TRNSYS 16

a TRaNsient SYstem Simulation program

Volume 5

Mathematical Reference

About This Manual

The information presented in this manual is intended to provide a detailed mathematical reference for the Standard Component Library in TRNSYS 16. This manual is not intended to provide detailed reference information about the TRNSYS simulation software and its utility programs. More details can be found in other parts of the TRNSYS documentation set. The latest version of this manual is always available for registered users on the TRNSYS website (see here below).

Revision history

- 2004-09   For TRNSYS 16.00.0000
- 2005-02   For TRNSYS 16.00.0037
- 2006-03   For TRNSYS 16.01.0000
- 2007-03   For TRNSYS 16.01.0003

Where to find more information

Further information about the program and its availability can be obtained from the TRNSYS website or from the TRNSYS coordinator at the Solar Energy Lab:

TRNSYS Coordinator Solar Energy Laboratory, University of Wisconsin-Madison 1500 Engineering Drive, 1303 Engineering Research Building Madison, WI 53706 – U.S.A.	Email: trnsys@engr.wisc.edu Phone: +1 (608) 263 1586 Fax: +1 (608) 262 8464
TRNSYS website: http://sel.me.wisc.edu/trnsys	

Notice

This report was prepared as an account of work partially sponsored by the United States Government. Neither the United States or the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or employees, including but not limited to the University of Wisconsin Solar Energy Laboratory, makes any warranty, expressed or implied, or assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TRNSYS Contributors

S.A. Klein	W.A. Beckman	J.W. Mitchell
J.A. Duffie	N.A. Duffie	T.L. Freeman
J.C. Mitchell	J.E. Braun	B.L. Evans
J.P. Kummer	R.E. Urban	A. Fiksel
J.W. Thornton	N.J. Blair	P.M. Williams
D.E. Bradley	T.P. McDowell	M. Kummert
D.A. Arias		

Additional contributors who developed components that have been included in the Standard Library are listed in their respective section.

Contributors to the building model (Type 56) and its interface (TRNBuild) are listed in Volume 6.

Contributors to the TRNSYS Simulation Studio are listed in Volume 2.

TABLE OF CONTENTS

5. MATHEMATICAL REFERENCE

This manual provides a detailed reference on each component model (Type) in TRNSYS. The information includes the mathematical basis of the model, as well as other elements that the user should take into consideration when using the model (e.g. data file format, etc.).

This guide is organized in 14 component categories that match the upper level directories in the Simulation Studio proformas. Those categories are:

Controllers

Electrical

Heat Exchangers

HVAC

Hydrogen Systems

Hydronics

Loads and Structures

Obsolete

Output

Physical Phenomena

Solar Thermal Collectors

Thermal Storage

Utility

Weather Data Reading and Processing

Within the categories, components are organized according to the models implemented in each component. This is different from the Simulation Studio structure, where components are first organized according to the function they perform, then according to the operation modes. An example is the mathematical model known as Type 1 (Solar Collector), which is the first component in the "Solar Thermal collectors" category in this manual. Type 1 is the underlying model for 5 different proformas listed in the "Solar Thermal Collectors\Quadratic Efficiency" category in the Simulation Studio. It is very frequent for one Type listed in this manual to be associated with several proformas which correspond to different modes of operation for the component.

Users looking for information on which components are included in those categories or which component to use have two sources of information:

- Each section starts with a short introduction that briefly explains the features of all components in that category
- Volume 03 of the documentation (Standard component library overview) also has a list of available components (based on the Studio's organization)

This manual does not provide a list of Inputs, outputs and parameters for each component. Such information can be found in the Simulation Studio proformas and in Volume 04, " Input - Output - Parameter Reference".

5.1. Controllers

There are two basic methods for controlling transient simulations of solar energy systems or components: energy rate control and temperature level control. These two strategies are discussed and compared in the introduction to Section 5.6, page 5–212, "Building Loads and Structures". The controllers in this section are designed primarily for implementing temperature level control.

Type 2 is most frequently used to control fluid flow through the solar collector loop on the basis of two Input temperatures. However, any system employing differential controllers with hysteresis can use Type 2. Type 8 and Type 108 implement respectively 3-stage and 5-stage room thermostats. Type 40, like the physical components it models, has considerable flexibility and can be used to implement a variety of relatively complex control strategies. Type 22 is a generic (single variable) feedback controller that tracks a setpoint by adjusting a control signal using the TRNSYS iterations. Type 23 has the same purpose but implements the well-known PID (Proportional, Integral and Derivative) algorithm.

Temperature level control in TRNSYS relies on a control function, γ, which is typically constrained to $[\gamma_{min};\gamma_{max}]$. Two types of temperature level control are commonly used: continuous (e.g. proportional) control and discrete (On/Off) control.

In continuous control, γ can take any value from γ_{min} to γ_{max}. Pure proportional control signals can be generated using simple Equations in the Input file or by using Type 23 in "P-only" mode. Type 22 and Type 23 provide continuous control signals.

In On/Off control, either $\gamma = 0$ or $\gamma = 1$. Types 2, 8 and 108 produce On/Off control signals. Like real controllers, these controller models use operational hysteresis to promote stability. For example, a heating system may be turned on ($\gamma = 1$) by a thermostat at a room temperature of 19°C, but not turned off ($\gamma = 0$) until the room reaches 21°C. In this case the controller has a "dead band" temperature difference (ΔT_{db}) of 2°C. When the difference between the set temperature (19°C) and the room temperature lies within this range, the controller remains in its previous state (either $\gamma = 1$ or $\gamma = 0$). Frequently the conditions used in making a control decision are changed by the control decision. For example, turning on a pump which moves fluid through a solar collector will change the temperatures on which the decision to turn on the pump was based. Careful selection of a dead band temperature difference can help to minimize a controller's tendency to oscillate between its on and off states. Beckman and Thornton (1) have shown that for stable operation of a controller in the solar collector loop, the following inequality must be satisfied:

$$\Delta T_1 \geq \frac{\varepsilon C_{min}}{A F_R' U_L} \Delta T_2$$

where ΔT_1 is the temperature difference at which the pump is turned on, and ΔT_2 is the temperature difference at which the pump is turned off. With ho heat exchanger in the solar collector loop, the above equation reduces to that found in Duffie and Beckman (2).

$$\Delta T_1 \geq \frac{\dot{m} C_p}{A F_R' U_L} \Delta T_2$$

However, the use of hysteresis in general, and satisfaction of this inequality in particular, does not guarantee convergence on an output state in a finite number of iterations. This is because control decisions can only be made at intervals of the simulation time step; thus, unlike real systems, a TRNSYS simulation involves dead bands in time as well as in temperature. To prevent an oscillating controller from causing the simulation to terminate in error, it was sometimes necessary to "stick" the controller in previous versions of TRNSYS. This prevents the pumps and/or other controlled subsystems from having step change outputs after NSTK oscillations, thereby hastening numerical convergence of the system. At a given time step, a controller may be stuck in the wrong state, but these errors will tend to cancel out over many time steps. To cancel these errors, it is necessary to set NSTK to an odd integer, typically 5 or 7. By setting NSTK to an odd integer, the controller will be OFF-ON-OFF for three successive time steps with no solution (cancellation of errors) as opposed to ON-ON-ON (summation of errors) with an even value of NSTK. A more complete discussion of controller stickiness is found in Reference (3). If a controller is stuck in more than 10% of the time steps during a simulation, a warning is issued.

Excessive controller sticking is indicative of instability. Several options exist for alleviating the problem:

- Increasing the dead band ΔT_{db}. This represents a change in the system being simulated, not just in the simulation of the system.

- Increasing the thermal capacitance associated with the controlled temperature. This improves stability and/or allows longer time steps to be used, but may decrease the accuracy of the simulation. For further discussion, see the introduction to Section 5.6, page 5–212 , "Building Loads and Structures".

- Decreasing the time step. This improves accuracy as well as stability, but increases the required computational effort and expense. Often this is the best approach.

Occasionally a time delay between control decisions, rather than (or in addition to) a temperature dead band, is used to promote controller stability. The Microprocessor Controller (Type 40) allows the output state to be "stuck" after each control decision for a user-specified number of time steps before another control decision can be made. Type 93 (Input value recall) may also be used to feed into the controller the outputs of some components at the previous time step instead of the current time step.

Types 22 and 23 produce a continuous control signal, hence they are not affected directly by "sticking". However, both Types can operate in an iterative mode while having some constraints operating in an "On/Off" mode. This might be the case if the controller On/Off signal is set by an external components that depends itself on the controller's output, or for a proportional controller with a very high gain which would oscillate between γ_{min} and γ_{max}. For that reason, both controllers also have a parameter that sets the maximum number of iterations after which the controller's output "sticks" to its value.

Because "sticking" a controller has no benefit besides promoting convergence and often causes incorrect short-term simulation results, a control strategy was developed for TRNSYS 14 and use with the Powell's Method solver (see Volume 07 – "TRNEdit: Editing the Input File and Creating TRNSED Applications"). The Powell's Method control strategy eliminates the "sticking" associated with control decisions by solving the system of equations at given values of the control variables. Upon convergence, the actual control states are compared to the desired control states at the converged solution. If the desired and actual control states are not equal, the TRNSYS calculations are repeated with the desired control states. The process is repeated until desired and calculated control states are equal, with no repeat calculations allowed. In some circumstances, there is not a physical solution to the set of equations. In this instance, the control state will be set to the previously solved control state. For these conditions, the Powell's Method controller acts similar to the old controller with an even value of NSTK. Currently, only Type 2 has a special mode to operate with Powell's solver. Other discrete (On/Off) controllers may work but

their operation will not be optimized for that solver. Continuous controllers can work with both solvers.

References

Beckman, W.A, Thornton, J.W, Long, S, and Wood, B.D., "Control Problems in Solar Domestic Hot Water Systems", Proceedings of the American Solar Energy Society, Solar   93 Conference, Washington D.C., 1993

Duffie, J.A. and Beckman, W.A., <u>Solar Engineering of Thermal Processes</u>, Wiley-   Interscience, New York (l980).

Piessens, L.P., "A Microprocessor Control Component for TRNSYS", MS Thesis, University of Wisconsin-Madison (l980).

5.1.1.   Type 2: Differential Controller

This controller generates a control function γ_o that can have values of 0 or 1. The value of γ_o is chosen as a function of the difference between upper and lower temperatures, T_H and T_L, compared with two dead band temperature differences, ΔT_H and ΔT_L. The new value of γ_0 is dependent on whether γ_i = 0 or 1. The controller is normally used with γ_0 connected to γ_i giving a hysteresis effect. For safety considerations, a high limit cut-out is included with the TYPE 2 controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded. Note that this controller is not restricted to sensing temperatures, even though temperature notation is used throughout the documentation.

5.1.1.1.   Nomenclature

ΔT_H	[C]	upper dead band temperature difference
ΔT_L	[C]	lower dead band temperature difference
T_H	[C]	upper Input temperature
T_{IN}	[C]	temperature for high limit monitoring
T_L	[C]	lower Input temperature
T_{MAX}	[C]	maximum Input temperature
γ_I	[0..1]	Input control function
γ_O	[0..1]	output control function

5.1.1.2.   Mathematical Description

Mathematically, the control function is expressed as follows:

IF THE CONTROLLER WAS PREVIOUSLY ON

If γ_i = 1 and $\Delta T_L \leq (T_H - T_L)$, γ_O = 1   **Eq. 5.1-1**

If γ_ι = 1 and $\Delta T_L > (T_H - T_L)$, γ_O = 0   **Eq. 5.1-2**

IF THE CONTROLLER WAS PREVIOUSLY OFF

If γ_i = 0 and $\Delta T_H \leq (T_H - T_L)$, γ_O = 1   **Eq. 5.1-3**

If γ_i = 0 and $\Delta T_H > (T_H - T_L)$, γ_O = 0   **Eq. 5.1-4**

However, the control function is set to zero, regardless of the upper and lower dead band conditions, if $T_{IN} > T_{MAX}$. This situation is often encountered in domestic hot water systems where the pump is not allowed to run if the tank temperature is above some prescribed limit.

The controller function is shown graphically as follows.
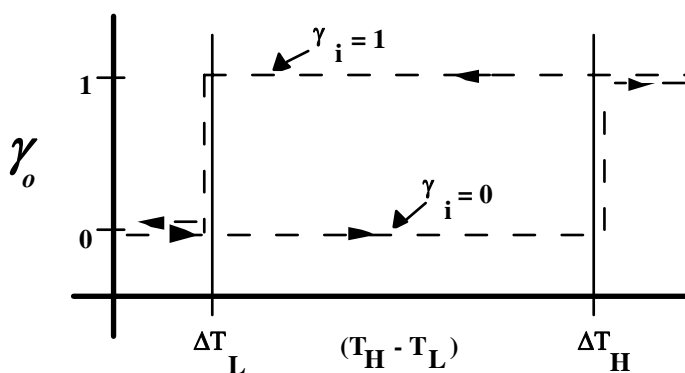
Figure 5.1.1–1: Controller Function

5.1.1.3. *Special considerations*

TYPE 2 INTERACTION WITH THE TRNSYS SOLVER

With the default TRNSYS solver (SOLVER 0, successive substitution), when (T_H-T_L) nears the upper or lower dead band in the normal mode of operation, γ_0 may sometimes oscillate between 1 and 0 for successive iterations at a given time step. This happens because T_H and T_L change slightly during each iteration, alternately satisfying and not satisfying the conditions for switching the controller. The value of PARAMETER 1, NSTK, is the number of oscillations permitted within a time step before the control function, γ_0, ceases to change. In general, it is recommended that NSTK be set to an odd number, typically five in order to encourage the controller to come to rest at a state different than at the previous time step.

With the release of TRNSYS version 14.1, an additional controller mode was added for use with the Powell's Method Solver. The Powell's Method control strategy is more robust in certain situations than the previous control strategy, solving the system of equations by not permitting the control variable to change during the iteration process. Upon convergence, the controller state is compared to the desired controller state at the converged solution and the calculations repeated if necessary. Please refer to section 5.1 of this document and see Volume 07 – "TRNEdit: Editing the Input File and Creating TRNSED Applications" for more information on the Powell's Method control strategy. It is important to note that if you use the Powell's Method control strategy, you must also use SOLVER 1 in your system.

For most simulations, use of the two control strategies will yield similar results. However, in short term simulations with unstable control behavior, the Successive Substitution (SOLVER 0) control strategy with an odd value of NSTK may yield quite different results from the Powell's Method control strategy.

5.1.2. Type 8: Three Stage Room Thermostat

A three-stage room thermostat is modeled to output three on/off control functions that can be used to control a system having a solar heat source, an auxiliary heater, and a cooling system. This controller is to be used to control systems on temperature levels (see Introduction to Section 4.8 "Building Loads and Structures"), and is compatible with the TYPE 12 mode 4 and the TYPE 19 mode 2 loads. The controller commands cooling at high room temperatures, first stage (solar source) heating at lower room temperatures, and second stage (auxiliary source) heating at even lower room temperatures. The user has the option, through parameter ISTG, to disable first stage heating during second stage heating and the capability, through parameter T_{min}, to disable first stage heating whenever the source temperature is too low. Although solar heating is specified in the description of this component, any three-stage heating system may be controlled using the TYPE 8 routine.

In many heating applications, the desired room temperature may depend on the time of day or the day of the week. This variation of the heating on/off temperatures is modeled here using an optional "set back" control function γ_{set} and "set back" temperature difference ΔT_{set}. When this option is used, the usual temperatures at which first and second stage heating are commanded are both reduced by $(\gamma_{set})(\Delta T_{set})$. Typically, γ_{set} is calculated by a TYPE l4 time-dependent function generator.

Hysteresis effects can be included in the model by supplying the optional "dead band" temperature difference ΔT_{db}. A single value of ΔT_{db}, if supplied, is applied to all three output control functions.

Parameter 1, NSTK, sets the number of oscillations permitted within a time step before the output state of the controller is "stuck". It is recommended that NSTK be set to 3 or 5. For a discussion of controller stability problems, see Section 5.1.

5.1.2.1. Mathematical Description

If hysteresis is not used, then ΔT_{db} is set to zero. Similarly, when the set back option is not used, γ_{set} and ΔT_{set} are zero. The heating and cooling on/off temperatures are set as follows:

FIRST HEAT SOURCE (SOLAR):

$$T_{H1}' = T_{H1} + \gamma_1 \cdot \Delta T_{db} - \gamma_{set} \cdot \Delta T_{set}$$
<div align="right">**Eq. 5.1-5**</div>

SECOND HEAT SOURCE (AUXILIARY):

$$T_{H2}' = T_{H2} + \gamma_2 \cdot \Delta T_{db} - \gamma_{set} \cdot \Delta T_{set}$$
<div align="right">**Eq. 5.1-6**</div>

COOLING SOURCE:

$$T_C' = T_C - \gamma_3 \cdot \Delta T_{db}$$
<div align="right">**Eq. 5.1-7**</div>

When the first stage source temperature T_h is greater than or equal to T_{min}, the first stage enable function γ_e is set to 1. Otherwise, $\gamma_e = 0$. The controller then functions as shown in the following diagram.

$$T_{H2}' \qquad T_{H1}' \qquad T_C'$$

Second Stage Heating

$$\gamma_1' = \gamma_e \cdot ISTG$$
$$\gamma_2' = 1$$
$$\gamma_3' = 0$$

First Stage Heating

$$\gamma_1' = \gamma$$
$$\gamma_2' = 0$$
$$\gamma_3' = 0$$

Idle

$$\gamma_1' = 0$$
$$\gamma_2' = 0$$
$$\gamma_3' = 0$$

Cooling

$$\gamma_1' = 0$$
$$\gamma_2' = 0$$
$$\gamma_3' = 1$$

$$T_R$$
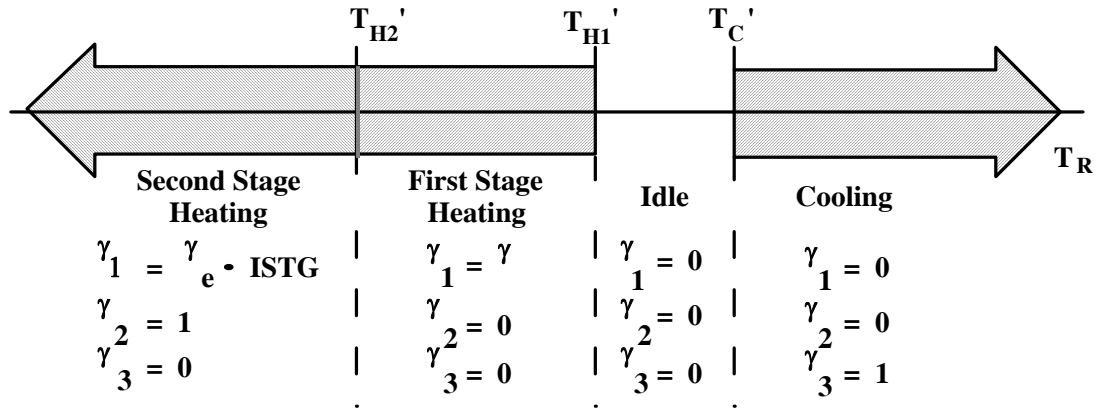
Figure 5.1.2–1: Controller Function

5.1.3. Type 22: Iterative Feedback Controller

The iterative feedback controller calculates the control signal (u) required to maintain the controlled variable (y) at the setpoint (y_{Set}). It uses TRNSYS iterations to provide accurate setpoint tracking. This controller can be used to model a real feedback controller (e.g. PID) that would adapt its control signal continuously or using a discrete time step much shorter than the TRNSYS simulation time step. The controller has an ON/OFF signal and bounds can be fixed for the control signal.

5.1.3.1. Nomenclature

y_{Set}	[any]	Setpoint for the controlled variable
y	[any]	Controlled variable that tracks the setpoint
u	[any]	Control signal (controller's output)
u_{min}	[any]	Minimum value of the control signal
u_{max}	[any]	Maximum value of the control signal
$u_{threshold}$	[any]	Threshold value for non-zero output (see text)
tol	[any]	Tolerance on tracking error
e	[any]	Tracking error

5.1.3.2. Mathematical description

The iterative feedback controller uses a secant method to calculate the control signal that zeroes (or minimizes) the tracking error e (e = ySet-y). The principle of operation is as follows:

- At the first 2 iterations in a time step, the controller outputs a control signal that is selected in order to provide a suitable starting point for the secant method search. The value used is different from the value at the previous call in order to prevent TRNSYS from considering that the simulation has converged, but not too far from that previous value in order to keep the system in a stable state.

- The controller stores the values of u it outputs and records the values of e that are measured when that control signal is applied. The controller operation can be interpreted in a (u,e) plane, where the solution is the value of u that zeroes e. Once the two initial points are obtained, the controller uses a secant method to search for the solution

The secant method is best described by an example (see Figure 5.1.3–1). The system's trajectory in the (u,e) plane is the thick, gray dotted line. The controller first outputs a control signal u_1. The system is then simulated using that value, which gives point 1. The controller then outputs signal u_2, which is chosen to be different but not too far apart from u_1. The system now outputs an error signal (e) that corresponds to point 2. The controller extrapolates the line between points 1 and 2 and calculates the u value that zeroes e. In this example, this value is outside the allowed range, so u_{min} is used. This gives point 3. A linear interpolation between points 2 and 3 gives point 4. Points 5 and 6 are obtained in a similar way and the controller stops iterating when the tolerance (tol) is reached or when TRNSYS stops iterating because the variation in the controller's output is within the global tolerances.
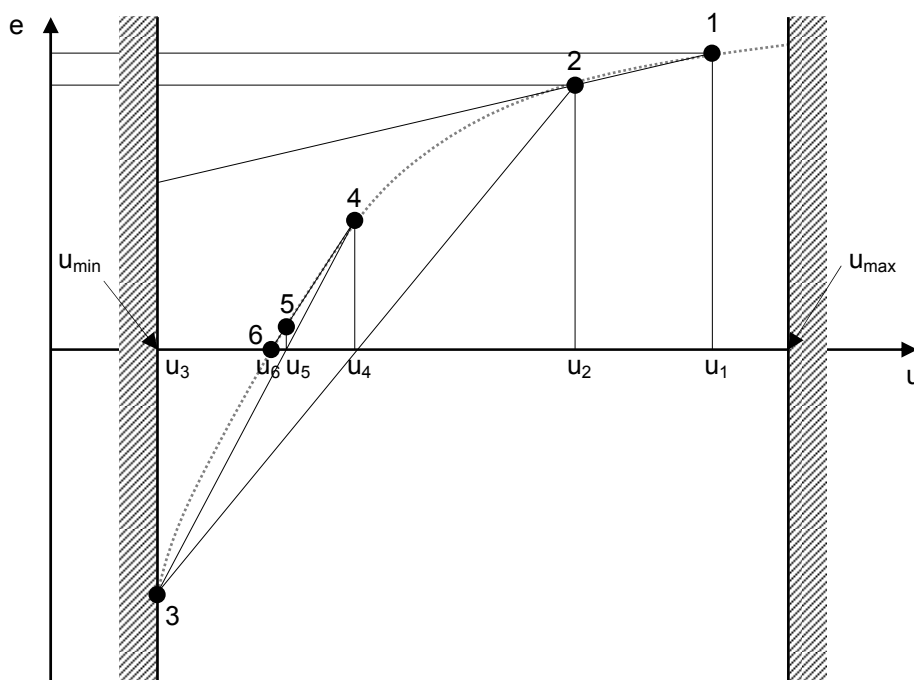
Figure 5.1.3–1: Secant method used in Type 22

The controller will also stop iterating when the number of iterations at a given time step reaches the maximum set by the nStick parameter. If you set this parameter to 0, the controller will stick a few iterations before the maximum number of iterations set in the general simulation parameters, so TRNSYS gets a chance to converge at the current time step.

CONSTRAINTS ON THE CONTROL SIGNAL

You can impose different constraints on the control signal:

u_{min} Minimum value (see Figure 5.1.3–1)

u_{max} Maximum value (see Figure 5.1.3–1)

$u_{threshold}$ Threshold value for non-zero output. This Input tells the controller that all calculated values that are less than $u_{threshold}$ (in absolute value) should be forced to zero. It is different from u_{min}. This can be used for example to model a pump that has a minimum operating flowrate: in that case $u_{threshold}$ should be set to the minimum flowrate and u_{min} should be set to 0. Another example is a control signal where u_{min} = -100, u_{max} = 100 and $u_{threshold}$ = 10. This means that values between -100 and 100 are acceptable but outputs lower than 10 (in absolute value) will be set to zero.

5.1.3.3.   Special considerations

Type 22 uses TRNSYS iterations to adjust the control signal. Its performance may be affected by different factors:

- Time step: Type 22 "solves" the control problem by attempting to zero the tracking error. It has no knowledge at all about the process dynamics, which may lead to oscillations. Changing the time step will have a strong influence on those oscillations. If you notice an "On-Off" behavior with poor setpoint tracking, you can try to adjust the simulation time step.

- Order of components in the Input file: it is recommended to start with the controller before the component(s) it controls and to keep components in a logical order. This will minimize the risk that TRNSYS "skips" time steps because the simulation appears to be converging. You can usually facilitate convergence and minimize simulation time by grouping all the controlled components and place them just after the controller. Please note that this is not an absolute rule and that we recommend that you experiment different component sequences, especially if the controller appears to be unresponsive.

- Simulation tolerances: often, small variations in a control signal have a very small effect on a controlled system, but users are expecting the controlled variable to follow the setpoint accurately. It is recommended to use stricter tolerances than the usual default values in simulations that make use of Type 22. Reducing tolerances usually minimizes the impact of component order

- TRNSYS solver: when using Solver 0 (successive substitution) with numerical relaxation, the convergence promotion algorithm may interact with the oscillations caused by Type 22. It is recommended to use Solver 0 without numerical relaxation (i.e. with a minimum and maximum relaxation factors equal to 1) with Type 22.

- Equation Solver: EQSolver 1 and above have been designed to speed up simulations by removing unnecessary calls to equations. If equations are used in an information loop that includes an iterative controller, those equations should always be called as soon as their Inputs have changed (as normal components are). This is the solving mode used by EQSolver 0 (the default), and Type 22 should be used with that equation solver

The factors discussed here above are the most likely causes of "unresponsive" iterative controllers. Please check the examples using Type 22 for additional information on how the good practice rules outlined here above can be implemented.

5.1.4.   Type 23: PID Controller

Type 23 implements a Proportional, Integral and Derivative (PID) controller. Type 23 calculates the control signal required to maintain the controlled variable at the setpoint. This control signal is proportional to the tracking error, as well as to the integral and the derivative of that tracking error. Type 23 implements a state-of-the-art discrete algorithm with anti windup.

5.1.4.1.   Nomenclature

y_{Set}	[any]	Setpoint for the controlled variable
y	[any]	Controlled variable (tracks the setpoint)
u	[any]	Control variable (controller's output)
v	[any]	Unsaturated control variable (before applying constraints)
u_{min}	[any]	Minimum value of the control variable
u_{max}	[any]	Maximum value of the control variable
$u_{threshold}$	[any]	Threshold value for non-zero output (see text)
e	[any]	Tracking error
K	[any]	Controller gain
T_i	[h]	Integral time (also called reset time)
T_d	[h]	Derivative time
b	[any]	setpoint weighting factor in Proportional action
c	[any]	setpoint weighting factor in Derivative action
N	[-]	High frequency limit for derivative action
T_t	[h]	Tracking time for integrator desaturation (anti wind-up)
h	[h]	TRNSYS time step

5.1.4.2.   Mathematical description

This section is a short description of the algorithm implemented in Type 23. The algorithm is presented in (Aström and Wittenmark, 1990) and (Aström and Hägglund, 1994).

The "textbook" PID algorithm is:

$$v(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt} \right) = P + I + D$$ **Eq 5.1.4-1**

There are 3 terms in Eq 5.1.4-1, which can easily be identified as the P-term (proportional to the error), the I-term (proportional to the integral of the error) and the D-term (proportional to the derivative of the error). Eq 5.1.4-1 is sometimes referred to as the non-interacting PID algorithm, or series PID algorithm.

There are many forms of the PID algorithm, and the optimal settings are different for the different algorithms. This should be kept in mind when transferring the parameters tuned in a simulation into a real-life controller. More information on the different algorithms and conversion factors between their parameters can be found in (Aström and Hägglund, 1994)

Several modifications have been made to the original algorithm in order to improve its performance and operability:

SETPOINT WEIGHTING

It is sometimes advisable to replace the tracking error (e) with a more general expression in both the P-Term and the D-term:

$$v(t) = K \left(e_p(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de_d(t)}{dt} \right)$$

Eq 5.1.4-2

where

$$e_p = b \, y_{set} - y \qquad (0 \le b \le 1)$$

Eq 5.1.4-3

$$e_d = c \, y_{set} - y \qquad (0 \le c \le 1)$$

Eq 5.1.4-4

Using b<1 allows to reduce overshoot during fast setpoint changes and, in a similar way, using c<1 will avoid large transients in the control variable due to sudden changes in the setpoint. In servo control (where the controller is supposed to respond quickly to changes in setpoint) b and c are usually close or equal to 1. In regulatory control (where one is more interested in responding to Input variations to bring the system back to a steady state), b and c are usually small (close or equal to 0).

LIMITATION OF THE DERIVATIVE GAIN

The derivative action may result is very large variation in the control variable and it is most often advisable to limit the high frequency gain of the derivative term. This can be done by replacing the D-term in Eq 5.1.4-1 with the following:

$$D = K \, T_d \, \frac{de_d(t)}{dt} - \frac{T_d}{N} \frac{dD}{dt}$$

Eq 5.1.4-5

This can be interpreted as the ideal derivative term, filtered by a first-order system with the time constant T_d/N. N is usually between 3 and 20, a value of 10 is usually a good compromise.

INTEGRATOR WINDUP

Control variables are usually limited by an upper and a lower bound that represent physical actuator limits. When the control variable reaches one of those limits, the feedback loop is broken because the actuator will remain at its limit independently of the system's output. A controller with integrating action will continue to integrate the error. In such a situation, the integral term may become very large (it "winds-up"). It is then necessary that the tracking error has an opposite sign for a very long time before the controller returns to a "normal" status.

Integrator wind-up can be prevented by back-calculating the integral value that would give a control variable exactly at the saturation limit. It is also advantageous to reset the integrator towards that back-calculated value not instantaneously but with a time constant (T_t):

$$v(t) = P + I + D \quad \text{(see Eq 5.1.4-1)}$$

$$u(t) = \text{saturate}(v(t))$$

$$I = I - \frac{1}{T_t} \int_0^t (u(\tau) - v(\tau)) d\tau \qquad \text{Eq 5.1.4-6}$$

Where the saturate() function applies minimum and maximum values and other constraints. It is generally recommended to have $T_t \in [0.1\, T_i \,;\, T_i]$.

DISCRETIZATION

The Proportional term is straightforward:

$$P(t_k) = K\, e_p(t_k) = K\, (b\, y_{set}(t_k) - y(t_k)) \qquad \text{Eq 5.1.4-7}$$

The Integral term is calculated using the backward difference approximation, which is consistent with the TRNSYS definition of variables (any variable reported at time t is the average between t_{k-1} and t_k) :

$$I(t_k) = I(t_{k-1}) + \frac{K\, h}{T_i}\, e(t_k) \qquad \text{Eq 5.1.4-8}$$

The Derivative term is approximated by a backwards difference:

$$D(t_k) = \frac{T_d}{T_d + N\, h} D(t_{k-1}) + \frac{K\, T_d\, N}{T_d + N\, h} \left(e_d(t_k) - e_d(t_{k-1}) \right) \qquad \text{Eq 5.1.4-9}$$

Finally, anti-windup desaturation is applied after calculating the saturated control variable by correcting the integral term as follows:

$$I(t_k) = I(t_k) - \frac{h}{T_t} \left(u(t_k) - v(t_k) \right) \qquad \text{Eq 5.1.4-10}$$

5.1.4.3.   Special considerations

TYPE 23 MODES

The PID controller can operate in two Modes: Mode 0 implements a "real life" (non-iterative) controller, and Mode 1 implements an iterative controller.

In Mode 0, Type 23 is only called after other TRNSYS components have converged (INFO(9) is set to 2). It then calculates the control variable based on the converged outputs, which is applied at the next simulation time step. This mimics the behavior of a real-life controller which uses the measured outputs at one point in time and calculates a control variable that is applied during the

next time step. Mode 0 typically requires short time steps (usually less than 1/10th of the dominant time constant in the system, although this is certainly not an absolute rule).

Mode 1 uses TRNSYS iterations to correct the control signal. It may lead to a faster response without requiring a short time step, but it is less stable and will generate more TRNSYS iterations. Please also note that Type 22 implements a generic feedback controller that is an interesting alternative to Type 23 in Mode 1 (see section 5.1.3 for more details).

TIME STEPS AND OTHER SETTINGS THAT MAY AFFECT TYPE 23'S PERFORMANCE

Type 23's performance depends on the simulation time step. It is generally recommended to keep the sampling time smaller than 10% of the dominant time constant of the process. Real-world controllers typically use very short time steps, which is not always practical in simulation studies. For that reason, it is not always possible to transfer the optimal parameters of a PID to a real application. Using Type 23 in Mode 1 (iterative) can improve the performance for relatively long time steps.

In Mode 1, Type 23 uses TRNSYS iterations to adjust the control signal. Its performance may be affected by different factors. Please check the Type 22 reference for more information (see section 5.1.3.3).

CHOOSING THE PID PARAMETERS

A discussion of PID parameters tuning is beyond the scope of this manual. The listed references are good examples of information sources on that topic.

It should be noted that the usual time steps used in TRNSYS simulations are typically much larger than the sampling time of commercial digital controllers (which are usually in the order of 200 ms). It may still be possible to achieve a satisfactory feedback control with a "typical" TRNSYS time step, but this might require some trial and error for parameter tuning. It is also likely that the optimal controller settings will be dependent on the simulation time step.

A final note on the transposition of parameter tuning to real-world controllers: even if your simulation uses a very short time step and if you use Mode 0, the tuned parameters may be different from the ones you would need to use in a real controller applied to the simulated system. Optimal parameters depend on the algorithm used in the PID, for which different implementations are available.

USING TYPE 23 IN HEATING ONLY, COOLING ONLY AND COMBINED HEATING AND COOLING APPLICATIONS

Unlike many of TRNSYS's controller components, Type 23 may be used in heating, cooling, and combined heating and cooling applications. Depending on the nature of the controlled variable (energy addition rate, mass flow rate, fraction), it may be appropriate to set up the controller with a negative proportional gain for cooling-only or combined heating and cooling applications. The examples here below illustrate a few typical uses of Type 23 for heating and cooling. The reader is also invited to refer to the corresponding standard examples (in Examples\Feedback Control).

Heating and/or cooling power (where heating power is positive, cooling power is negative)

When Type 23 is used to control the heating or cooling power that is provided to a room, a storage tank or any other device, the control signal must have the same sign as the tracking error (difference between the setpoint and the controlled variable): if the controlled temperature is below the setpoint, a positive power must be applied and if the temperature is above the setpoint

a negative power must be applied. In such cases, users should select a positive gain constant for the PID controller and set the minimum and maximum values to -(maximum cooling power) and +(maximum heating power) respectively.

Cooling power only (cooling power is positive)

If cooling only is required, the components or equations using the output of Type 23 might require positive values for cooling power. In that case the power should increase when the tracking error (difference between the setpoint and the controlled variable) decreases, i.e. more cooling should be provided when the temperature rises above the setpoint. Users should then use a negative gain constant and set the minimum and maximum control values to 0 and +(maximum heating power) respectively.

Heating flow rate

In this application, it is presupposed that a hot source is available and that heating is accomplished by increasing the flow rate from this hot source. The control signal must increase when the tracking error (setpoint – controlled temperature) increases, i.e. more heating should be provided when the temperature is below the setpoint. Users should then use a positive gain constant and set the minimum and maximum control values to 0 and (maximum flow rate) respectively.

Cooling flow rate

For this cooling application, it is presupposed that a cold source is available and that cooling is accomplished by increasing the flow rate from this cold source. The control signal must increase when the tracking error (setpoint – controlled temperature) decreases, i.e. more cooling should be provided when the temperature is above the setpoint. Users should then use a negative gain constant and set the minimum and maximum control values to 0 and (maximum flow rate) respectively.

5.1.4.4.   References

Aström, K.J. and Wittenmark, B. – Computer controlled Systems, 2nd Edition. Prentice Hall, Englewood Cliffs, NJ – 1990. ISBN 0-13-168600-3

Aström, K.J. and Hägglund, T. – PID Controllers: Theory, Design and Tuning, 2nd Edition. International Society for Measurement and Control – 1994. ISBN 1-55617-516-7

5.1.5. Type 40: Microprocessor Controller

The Microprocessor Controller component combines five differential comparators with a logic array to allow simulation of certain types of programmed controllers used in solar heating and cooling systems.

5.1.5.1. Nomenclature

NC	number of comparators (1 < NC $\leq$ 5)
C_i	output of comparator i
C_{i-1}	output of comparator i on previous call to component number of controller modes (1 < NMODE $\leq$ 12)
NMODE	number of outputs of component (1 < NOUTPUT $\leq$ 18)
NOUTPUT	number of parameters used to describe comparator functions (NPARS(A)=NC*2+1)
NPARS(A)	number of parameters used to describe mode array (NPARS(B)=NMODES*NC+1)
NPARS(B)	number of parameters used to describe output array (NPARS(C)=NMODES*NOUTPUT+1)
NPARS(C)	number of times mode may change in a time step before it is 'stuck' at its current value.
NSTK	number of time steps controller will remain in modeK before making next control decision.
MODE PRINT	number of times in a time step controller mode may change before diagnostic mode trace is printed

5.1.5.2. Mathematical Description

The controller is logically divided into four parts. The first part is concerned with conversion of Input signals into binary logic levels and consists of up to five comparators. Each comparator incorporates operational hysteresis based on user specified on and off dead bands. The state of comparator i at time t is described by the following equation:

$$C_{i,t} = \begin{cases} \text{ON if } (IN_{hi}\text{-}IN_{low}) > \Delta T_{on} \text{ and } C_{i,t-1} = \text{OFF} \\ \text{OFF if } (IN_{hi}\text{-}IN_{low}) \leq \Delta T_{off} \text{ and } C_{i,t-1} = \text{ON} \end{cases}$$

Eq. 5.1-8

The output of this part of the component is a binary word NC bits long in which each bit corresponds to a comparator state, 1 for on and 0 for off, with the LSB corresponding to the first comparator.

The second part of the controller is the mode array. This array consists of NC rows by NMODE columns. Each element of the array may assume a value of 0, 1 or -1. The current operating mode is determined by comparing the entries in each column with the word output by the comparator section. The comparison is done on a bit-by-bit basis, with no comparison made if the mode array entry is -1.

The mode array output is a single decimal number indicating the column in the array which matches the comparator output word. If no match is found, the output mode is set to -1. This is called the default mode and results in all outputs being set to 0. At the end of the simulation a message is printed which indicates the number of times the default mode occurred in the run.

The third part of the controller is the output array. This array consists of NOUTPUT rows by NMODE columns. The number output by the mode array is used to point to a specific column of the output array. The values contained in this column are transferred to the OUTPUTS of the controller, with the first value set as the first OUTPUT, the second value set as the second OUTPUT, etc.

The fourth part of this component is the control unit. This unit handles errors detected in other parts of the component as well as implementing the NSTCK, HOLD, and MODE PRINT options described below.

CONTROLLER OPTIONS NSTCK, HOLD AND MODE PRINT

NSTCK

Since a TRNSYS simulation involves dead bands in time as well as in temperature, it is possible for a system to experience instabilities that will result in a controller cycling between two or more different modes continuously. To limit this type of cycling, a TRNSYS control component incorporates 'stickiness'. A sticky controller is allowed to change state up to NSTK times in a given time step before its outputs are frozen in the current state. A recommended value for NSTCK is 4 or 5 for most long-term simulations. A more complete discussion of stickiness is found in Reference (1).

HOLD

This option is included to allow the simulation of time delays between control decisions. There are the NMODE and HOLD parameters in the controller. The value of the HOLD parameter associated with a particular mode specifies the number of time steps that the controller will stay in that mode before another control decision can be made.

MODE PRINT

This option allows the listing of successive controller modes in one time step after a specified number of iterations have occurred. This is useful in situations where excessive controller cycling occurs. MODE PRINT must be less than or equal to 40.

5.1.5.3. TRNSYS Component Configuration

> Type 40's flexibility results in a tremendous complexity in the cycles involving parameters. For that reason, type 40 is recommended for advanced users only and its Inputs, outputs and parameters are described in this manual (not in Volume 4)

PARAMETERS

The parameters used to describe the functions of the four internal parts of the controller are listed separately. Since this component may use more than 200 parameters, care must be used in constructing and documenting the parameter list used.

The first set of parameters, designated section A, relate to the number of comparators to be used and their on and off dead bands. This section may contain from three to eleven parameters. This number is represented in the following section by NPARS(A).

Parameter No.		Description
1	NC	number of comparators (up to 5)
2	ΔT_{ON}	on deadband, comp. 1 (° C)
3	ΔT_{OFF}	off deadband, comp. 1 (° C)
i * 2	ΔT_{ON}	on deadband comp. i (° C)
i * 2+1	ΔT_{OFF}	off deadband, comp. i (° C)

The second section of the parameter list, section B, contains parameters which relate to the determination of the controller mode. This section will contain parameters NC*2+2 through NMODES*NC+2NC+2. The number of parameters contained in this section is NPARS(B). All parameters in this section with the exception of the first, NMODES, must be either 0, 1 or -1.

Parameter No.	Description
NPARS(A)+1	NMODES, number of controller modes
NPARS(A)+2	Status of comparator 1 when in mode 1
NPARS(A)+3	Status of comparator 2 when in mode 1
NPARS(A)+(k-1)*NC+i	Status of comparator i when in mode k

The third section of the parameter list, designated Section C, relates to the specific output values set by a particular mode. This section contains NPARS(C) parameters.

Parameter No.	Description
NPARS(A)+NPARS(B)+1	NOUTPUT, number of outputs (1 ≤ NOUTS ≤ 18)
NPARS(A)+NPARS(B)+2	Output 1 of controller when in mode 1
NPARS(A)+NPARS(B)+(k-l)*NOUTS+i	Output i of controller when in mode k

The final section of the parameter list contains parameters which relate to overall controller operation. These include the values of NSTICK, HOLD, and MODE PRINT. Note that there must be NMODES HOLD parameters specified, one for each mode.

Parameter No.	Description
NPARS(A)+NPARS(B)+NPARS(C)+1	NSTICK, number of times controller mode may change in one timestep
NPARS(A)+NPARS(B)+NPARS(C)+2	HOLD1, number of timesteps before next mode change in mode 1
NPARS(A)+NPARS(B)+NPARS(C)+2+k	HOLDk, number of timesteps before next mode change when in mode k
NPARS(A)+NPARS(B)+NPARS(C)+NMODES+3	MODE PRINT, number of times in a timestep mode may change before mode trace is printed

INPUTS

Input No.	Description
1	Comparator 1 high Input
2	Comparator 1 low Input
2*(i-1)+1	Comparator i high Input
2*(i-1)+2	Comparator i low Input

OUTPUTS

Output No.	Description
1	Control function output 1
…	
N	Control function output N
…	
19	Controller status, 0=free, 1=stuck, 2=hold
20	Current mode

5.1.5.4. Example

The system to be controlled is shown in Figure 5.1.5–1. Three comparators are required: one to decide whether the pump in the collector-storage loop (I) should be on or off, one to determine whether useful energy is available in the storage tank, and one to determine whether heating is required by the house.
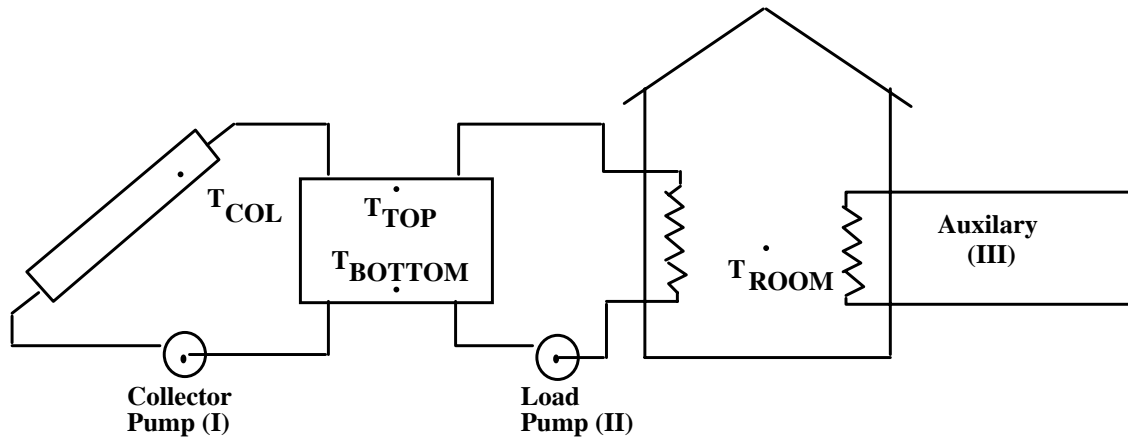
Figure 5.1.5–1: Type 40 – Example system

The three comparators are shown schematically in Figure 5.1.5–2. Six INPUTS are required: two for each comparator. The first group of 7 PARAMETERS specifies that 3 comparators are to be used and gives on and off dead bands for each comparator.
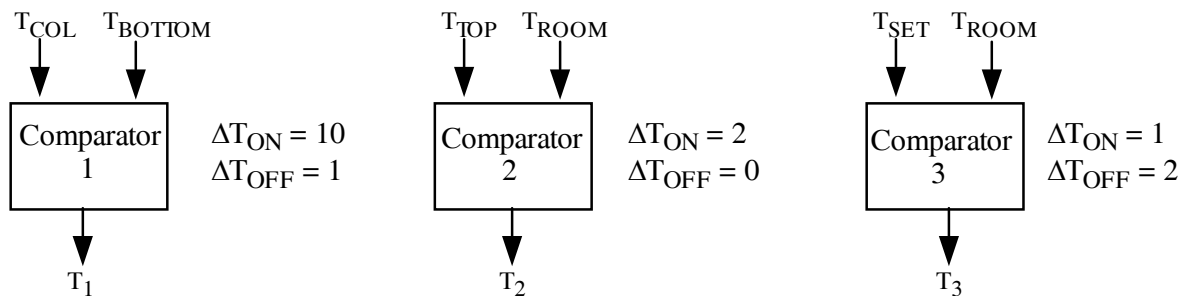
Figure 5.1.5–2: Type 40 – Example comparators

Three OUTPUTS are also required: one to control the pump in the collector storage loop (I), one to control the pump in the storage-load loop (II), and one to control the auxiliary heater (III). The values of the OUTPUTS will depend on the values of the control functions ($\gamma 1$, $\gamma 2$, and $\gamma 3$) generated by the 3 comparators.

The table here below gives the possible output states of the comparators and the corresponding Type 40 OUTPUTS desired. The second group of parameters specifies that 6 possible output states are of interest, and reproduce the left half of the table here below. The third group of parameters specifies that 3 OUTPUTS are required, and reproduces the right half of the table here below:

Comparator outputs				Type 40 outputs		
NMODE	γ_1	γ_2	γ_3	I	II	III
1	0	(0 or 1)	0	0	0	0
2	0	0	1	0	0	1
3	0	1	1	0	1	0
4	1	(0 or 1)	0	1	0	0
5	1	0	1	1	0	1
6	1	1	1	1	1	0

A final group of parameters is used to set NSTK = 3, HOLDk = 0 (for k = I, 6) and MODE PRINT = 4 (diagnostic printing turned on after four iterations for a given time step). Thus the following lines would be used in the Type 40 component description:

PARAMETERS 53

```
3    10 1      2 0       1 2
6    0 -1 0     0 0 1     0 1 1     0 -1 0    1 0 1     1 1 1
3    0 0 0      0 0 1     0 1 0     1 0 0     1 0 1     1 1 0
3    0 0 0 0 0 0         4
```

5.1.5.5.   References

1.   L.P. Piessens, "A Microprocessor Control Component for TRNSYS", M.S. Thesis, University of Wisconsin-Madison, 1980.

5.1.6.   Type 108: Five Stage Room Thermostat

This ON/OFF differential device models a five stage room thermostat which outputs five control signals that can be used to control an HVAC system having a three stage heating source and a two stage cooling source. The controller contains hysteresis effects and is equipped with a parameter that allows the user to set the number of controller oscillations permitted within a single time step before the output values "stick."

5.1.6.1.   Mathematical Description

CONTROLLER STABILITY

Very often, controllers pose difficulties in simulations because in defining a mathematical model of a piece of equipment, simplifying assumptions are inevitably made. These simplifying assumptions often disregard physical realities of the system components in order that they might actually be solvable. The side effect is that some of the component's robustness or insensitivity to Input changes disappears. Take the example of modeling a room in a building that is equipped with a thermostat and a heating device. The common way of modeling such a system would be for the thermostat to look at the difference between the room temperature and a set point temperature. If the room temperature is below the set point temperature, the heating device is turned on and energy is added to the space. The room model then recalculates its air temperature based on the new information about the addition of energy to the space. The thermostat then senses that the air temperature is higher and recalculates its decision and so on. Often ignored is the fact that the heater is placed within the room and that it does not add energy evenly to the space – it heats up the air in its immediate surroundings. Convection within the space develops and there is a time lag between when the heater begins adding energy to the space and when the air in the space is uniformly warmer enough that the thermostat would register a new temperature. While room models that perform convection calculations no doubt exist, they are often more detailed than is needed for the purposes of a building energy simulations. In an effort to slow down the reaction time of simulated systems, it is often necessary to add "stickiness" to controller components. In the case of this model and of many other controllers in TRNSYS, the stickiness comes in the form of a parameter that controls how many times a controller may change states within the iterations of a single time step before its newly calculated value sticks to one setting or another. As soon as the controller sticks, the system ought to get out of whatever iterative process it is in and converge upon a solution. Very often an odd number is chosen for the number of allowable state changes (NSTK) so that the controller makes altering decisions, turning equipment ON and OFF in such a way that the system moves away from its non convergent state. The second parameter in Type108 is the NSTK value that will be used throughout the simulation. If the controller was stuck for more than 10 % of the time steps in a given simulation, the actual percentage of stuck time steps will be reported to the TRNSYS list and simulation log files.

MULTIPLE STAGE HEATING AND COOLING

Type108 is designed to control up to three stages of heating equipment and two stages of cooling equipment. A stage might consist of a particular power setting on a furnace, or might consist of an entirely unique piece of equipment. For example, some furnaces are designed with a low and high burner setting. If the monitored temperature falls to a certain point, the low burner and fan come on. If the temperature continues to fall past a second set point, the furnace will switch over to high burner and fan speed, adding more energy to the space. Such a furnace would be referred to by this model as a two stage heating device. The same furnace could be used in such

a way that if even the high burner setting was still not sufficient to bring the zone temperature back up, an electric resistance heater (completely separate from the furnace) could be brought on as a third stage heating device. Type108 is able to control up to three stages of heating and two stages of cooling. Thus the user must specify three heating set points and two cooling set points as Inputs (since they may vary with time). Type108 checks to insure that the set point temperature are all realistic. That is to say that the second stage cooling set point much be higher than the first stage cooling set point, which in turn must be higher than the first stage heating set point, which must be higher than the second stage heating set point, which must be higher than the third stage heating set point temperature. The relative placement of the various set points is shown graphically on a temperature scale in Figure 5.1.6–1.
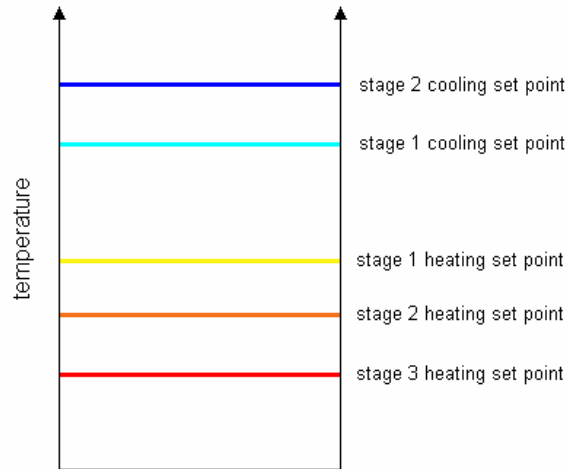
Figure 5.1.6–1: Set Point Definition

If the zone temperature goes above the stage two cooling set point temperature, it may be desirable for both the equipment associated with stage two and the equipment associated with stage 1 cooling to be ON simultaneously. Alternatively, it may be desirable for the stage 1 cooling equipment to shut OFF and for only the stage two equipment to be running. Similarly for heating it may be desirable for stage 1 heating equipment to shut off in stage 2 but to come back on in stage 3. To this end, Type108 requires the user to specify a series of parameter values to indicate exactly when a stage may be enabled and when it should be disabled. The following table summarizes the parameters, their values and the corresponding equipment enabling.

Table 5.1.6–1: Controller Stage Enabling

PARAMETER NUMBER	PARAMETER VALUE	INTERPRETATION
3	0	Stage 1 Heating will be DISABLED when Stage 2 Heating is ON
3	1	Stage 1 Heating will be ENABLED when Stage 2 Heating is ON
4	0	Stage 2 Heating will be DISABLED when Stage 3 Heating is ON
4	1	Stage 2 Heating will be ENABLED when Stage 3 Heating is ON
5	0	Stage 1 Heating will be DISABLED when Stage 3 Heating is ON
5	1	Stage 1 Heating will be ENABLED when Stage 3 Heating is ON
6	0	Stage 1 Cooling will be DISABLED when Stage 2 Cooling is ON
6	1	Stage 1 Cooling will be ENABLED when Stage 2 Cooling is ON

DEAD BANDS AND HYSTERESIS

Often times, controllers are designed with dead bands to prevent them from turning equipment ON and OFF in fast succession when the monitoring temperature and set point temperature are close to one another. Dead bands essentially replace a set point temperature with a bracketed range of set point temperatures. In heating mode, equipment would remain OFF until the monitored temperature had fallen to the specified set point minus the lower dead band temperature difference. Once ON, the equipment would remain ON until the monitored temperature exceeds the specified set point temperature plus the upper dead band. In some controllers, both upper and lower dead bands are specified. Type108 simply centers the specified heating and cooling dead band temperature differences on each set point. A heating set point temperature and its dead band temperature difference are shown graphically in Figure 5.1.6–2.
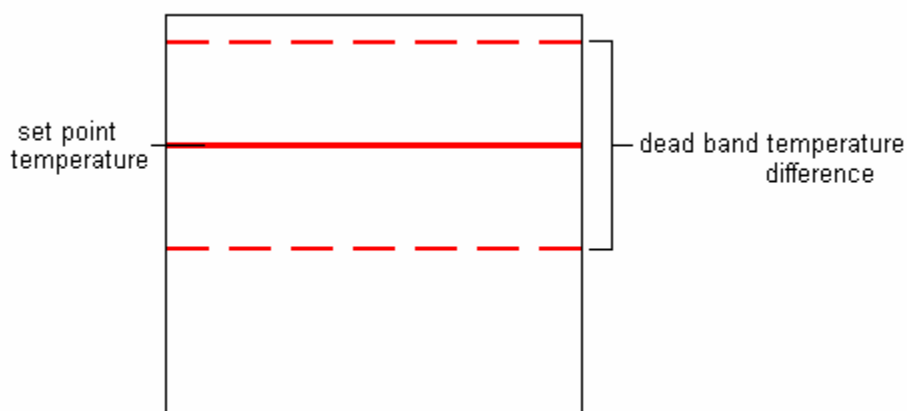
Figure 5.1.6–2: Type108 Dead Band Temperature Difference

COMPONENT OPERATION

At any given iteration, Type108 checks to note whether it has changed states more than the allowable number of times. If so, the state is stuck for all remaining iterations in the time step and will only be unstuck once a new time step has started. At the end of each iteration's calculations, the state of each controller is stored for comparison during the following iteration.

5.2. Electrical

This category contains components that generate or store electricity and their accessories: solar photovoltaic (PV) systems. Wind Energy Conversion Systems (WECS, or wind turbines), Diesel engines, Power conversion systems, batteries.

Type 90 models a Wind Energy Conversion System (WECS). Power versus wind speed data are read in a file. The impact of air density changes and wind speed increase with height are modeled.

Type 94 and Type 180 model PV arrays using the "one diode" model, also known as the "5-parameter" model. They allow to model crystalline PV cells, as well as amorphous cells. The main difference is that Type 180 reads the parameters of the PV array in a data file, while Type 94 parameters are to be provided in the Input file. Type 48 simulates a power regulator and inverter that can be used in conjunction with a PV array and a battery.

Type 47 provides a lead-acid battery model. Its different operation modes use different modeling assumptions, including Hyman and Shepherd equations. Type 185 provides an alternative and also models gassing effects. Type 185 also reads the battery parameters from a data file, while Type 47 reads them in the TRNSYS Input file.

Type 120 models Diesel Engine Generator Set(s). Several identical units can be simulated. Type 102 (Diesel Engine Dispatch Controller) can be used adapt the number of DEGS operating and their power to meet a given electrical load.

Type 175 simulates a power conversion device (AC/DC, DC/DC, etc.)

Type 188 provides a component to interface Renewable Energy Systems with an electric grid.

5.2.1. Type 47: Shepherd and Hyman Battery Models

This model of a lead-acid storage battery operates in conjunction with solar cell array and power conditioning components. It specifies how the battery state of charge varies over time, given the rate of charge or discharge. In the higher modes, this unit also utilizes formulas relating battery voltage, current and state of charge. The equations are those devised by Shepherd (1) (Modes 2 and 4) and recommended by Hyman (2) (Modes 3 and 5). The Shepherd model is simpler, while the Hyman version, a slight modification of the former model, is more realistic at very low currents.

5.2.1.1. Nomenclature

Q	State of Charge (Mode 1 - watt-hrs, Modes 2, 3, 4, 5 - amp hrs)
Q_m	Rated capacity of cell
Q_c, Q_d	Capacity parameters on charge; discharge
F	Fractional state of charge = Q/Qm (l.0 = full charge)
H	(1-F)
eff	Charging efficiency
I	Current
I_{max}, I_{min}	Maximum I (rate of charge), minimum I (rate of discharge)
P	Power
P_{max}, P_{min}	Maximum P, minimum P
V	Voltage
V_c	Cutoff voltage on charge
I_c, P_c	Charging current, power corresponding to Vc
I_c,tol, V_{tol}	Parameters used in iterative calculations
V_d	Cutoff voltage on discharge
e_d, r_d	Parameters used in calculating Vd
V_{zp}	Additional voltage term in Hyman model
I_{zp}, K_{zp}	Parameters used in calculating Vzp
V_{oc}	Open circuit voltage at full charge
e_{qc}, e_{qd}	Open circuit voltages at full charge, extrapolated from V vs I curves on charge; discharge
g_c, g_d	Small-valued coefficients of H in voltage-current-state of charge formulas
r_{qc} r_{qd}	Internal resistances at full charge when charging; discharging
m_c, m_d	Cell-type parameters which determine the shapes of the I-V-Q characteristics

5.2.1.2.   Mathematical Description

Shepherd originally devised his model to describe the discharge of a battery, but it is also applicable to battery charging, if different parameters are used. On <u>discharge</u> (I < 0), the Shepherd formula is:

$$V = e_{qd} - g_d H + I\ r_{qd}\left(1 + \frac{m_d H}{Q_d/Q_m - H}\right)$$

Eq. 5.2-1

and on <u>charge</u> (I > 0):

$$V = e_{qc} - g_c H + I\ r_{qc}\left(1 + \frac{m_c H}{Q_c/Q_m - H}\right)$$

Eq. 5.2-2

These equations are contained in Modes 2 and 4 of TYPE 47. The regulator/inverter component that works with this battery model never sets I = 0. Rather, when conditions on V_c, V_d, F_c, or F_d are such that charge or discharge should not be permitted, the regulator assigns the current some small positive or negative value depending on what condition (i.e. charging; discharging) would be desired if permitted. This fixes the system voltage on either the proper charge or discharge curve, rather than at some intermediate floating open circuit value.

Zimmerman and Peterson (3) describe a model which takes into account behavior at very low currents. Hyman recommends adding their expression to the Shepherd formula, thus providing a more realistic model at very low currents. On discharge, the formula is:

$$V = V_{oc} - V_{zp} - g_c H + I r_{qc}\left(1 + \frac{m_c H}{Q_c/Q_m - H}\right)$$

Eq. 5.2-3

and on charge, it is:

$$V = V_{oc} + V_{zp} - g_c H + I r_{qc}\left(1 + \frac{m_c H}{Q_c/Q_m - H}\right)$$

Eq. 5.2-4

where

$$V_{zp} = \frac{1}{k_{zp}}\ \ln\left(\frac{|I|}{I_{zp}} + 1\right)$$

Eq. 5.2-5

and

$$V_{oc} = \frac{1}{2}\left(e_{qd} + e_{qc}\right)$$

Eq. 5.2-6

One may recognize Eq. 5.2-5 and the V-I relationship for a semiconductor diode. These equations have been incorporated into Modes 3 and 5 of TYPE 47.

Figure 5.2.1–1and Figure 5.2.1–2 show the characteristics of both the Shepherd and the Shepherd-modified models for a 250 amp-hr. cell that are simulated by this component. Figure 5.2.1–2 also displays the I=50 and I= -50 (± $Q_m/5$) curves used in Reference 4.

To prolong battery life, the battery should not be charged to too high a voltage nor discharged to too low a voltage. The maximum charge voltage limit parameter, V_C, is set below the value at which appreciable gassing of the battery electrolyte commences. If the VCONTR parameter is negative the voltage limit on discharge, V_D is calculated from:

$$V_d = e_d - |I| r_d$$ **Eq. 5.2-7**

This last equation and the values of e_d and r_d used are from Hyman (2), who derived them from data of Vinal (5). If the VCONTR parameter is >0, then V_D is set to the constant value of VCONTR.

P_C and P_{Vd} are battery powers that correspond to V_c and V_d respectively. They are used in the regulator/inverter module so that constant voltage charging and discharging can be initiated to ensure V does not exceed V_c or V does not fall below V_d.

Modes 2, 3, 4 and 5 limit the current (per cell) to between I_{max} and I_{min}, which are Input as parameters. They also calculate the power corresponding to these two values of the current, for possible use in the regulator/inverter component.
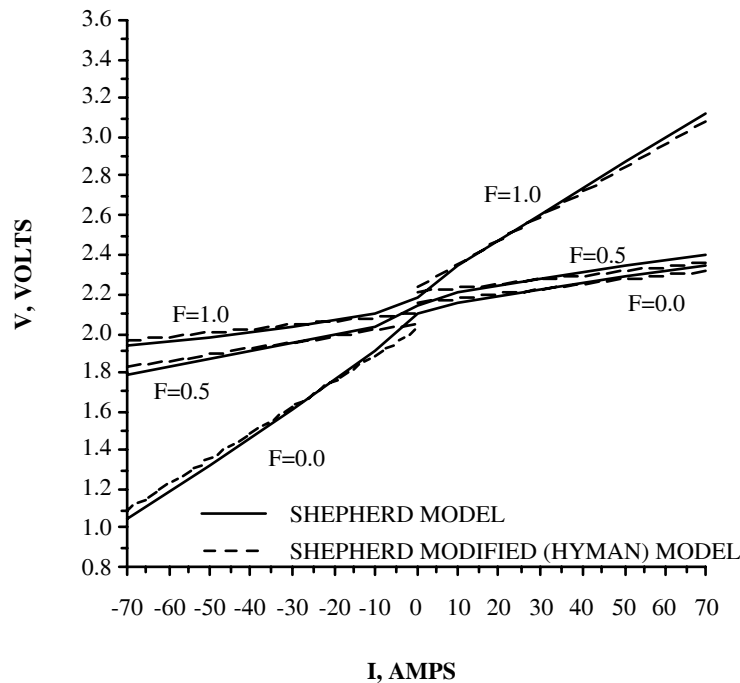
Figure 5.2.1–1: Voltage vs Current for a 250 Amp-Hr Cell

The calculations in every mode are performed on a single cell, but the power (in Modes 1, 2 and 3) or current (in Modes 4 and 5) Input to the component are for the entire battery. Therefore, P is divided by $(c_p)(c_s)$ or I by c_p before being used in the Mode calculation. P is divided by 3.6 in the program to convert from kJ/hr to watts. Upon output, all values of voltage (V, V_c, and V_d) are multiplied by c_s, powers (P, P_{max}, P_{min}, and P_c) by $(c_p)(c_s)(3.6)$, and the current by c_p.

Finally, each mode specifies how the state of charge changes during charge and discharge. In Mode 1, A is in terms of energy (watt-hrs), and

$$V = e_{qc} - g_c H + I\, r_{qc}\left(1 + \frac{m_c H}{Q_c/Q_m - H}\right)$$

Eq. 5.2-8

In the other modes, Q is the charge (amp-hrs) in the battery, so that

$$\frac{dQ}{dt} = \begin{cases} I & \text{if } I < 0 \\ I * \text{eff} & \text{if } I > 0 \end{cases}$$

Eq. 5.2-9

The eff factor is the charging efficiency.
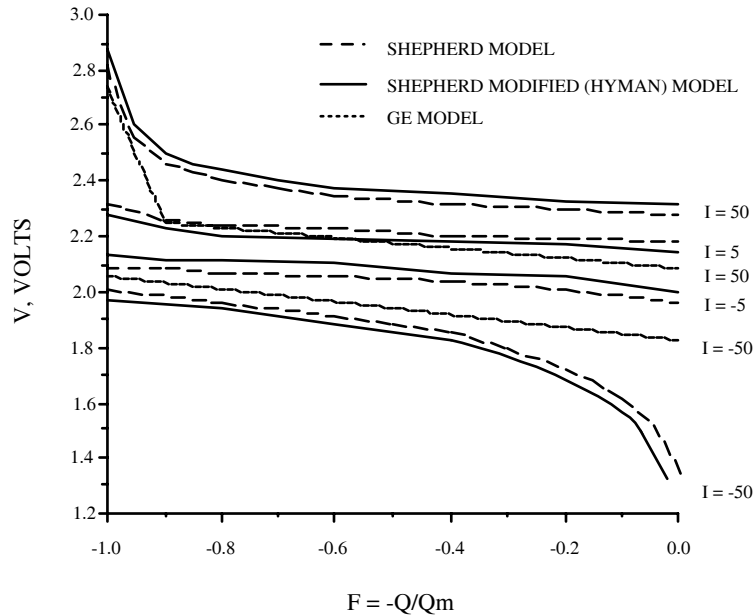
Figure 5.2.1–2: Voltage vs. State of Charge for a 250 Amp-Hr Cell

5.2.1.3. *References*

1.   Shepherd, C.M., "Design of Primary and Secondary Cells II. An Equation Describing Battery Discharge," Journal of Electrochemical Society, 112, 657 (1965).

2.   Hyman, E.A., "Phenomenological Cell Modelling: A Tool for Planning and Analyzing Battery Testing at the BEST Facility," Report RD77-1, Public Service Electric and Gas Company & PSE & G Research Corporation, Newark, (1977).

3.   Zimmerman, H.G. and Peterson, R.G., "An Electrochemical Cell Equivalent Circuit for Storage Battery/Power System Calculations by Digital Computer," Vol. 1 (1970), Intersociety Energy Conversion Engineering Conference, Paper 709071, 1970.

4.   "Conceptual Design and Systems Analysis of Photovoltaic Systems," Report No. ALO-3686-14, General Electric Co., Space Division, Philadelphia, (1977).

5.   Vinal, George W., Storage Batteries, Fourth Edition, 1955, John Wiley & Sons, Inc.

6.   Hyman, E.A., Public Service Electric and Gas Company, Newark, NJ, Private Communication

5.2.2.   Type 48: Regulator / Inverter

In photovoltaic power systems, two power conditioning devices are needed. The first of these is a regulator, which distributes DC power from the solar cell array to and from a battery (in systems with energy storage) and to the second component, the inverter. If the battery is fully charged or needs only a taper charge, excess power is either dumped or not collected by turning off parts of the array. The inverter converts the DC power to AC and sends it to the load and/or feeds it back to the utility.

Type 48 models both the regulator and inverter, and can operate in one of four modes. Modes 0 and 3 are based upon the "no battery/feedback system" and "direct charge system," respectively, in Reference 1. Modes 1 and 2 are modifications of the "parallel maximum power tracker system" in the same reference.

5.2.2.1.   Nomenclature

P_A	Power from solar cell array
P_D	Power demanded by load
P_L	(+) Power sent to load from array and battery (-) Power sent to battery from utility
$P_{L,MAX}$	Output capacity of inverter (or if negative, Input current limit)
P_R	Power "dumped" or not collected
P_U	Power supplied by (PU > 0) or fed back to (PU < 0) utility
P_B	Power to or from battery (+ charge, - discharge)
$P_{B,MAX}$	Maximum Input (charge)
$P_{B,MIN}$	Minimum output (discharge) of battery
P_C	Allowed charge rate when battery at high voltage limit VC
P_{Vd}	Allowed charge rate when battery is at low voltage limit VD
F	Fractional state of charge of battery (1.0 = full charge)
F_C	High limit on F, when battery charging
F_D	Low limit on F, when battery discharging
F_B	Limit on F, above which battery can begin to discharge after being charged
F_{BCH}	High limit on F, for charging from utility
V	Battery voltage (and solar cell array voltage, in mode 3)
V_C	High limit on V, when battery charging
V_D	Low limit on V, when battery discharging
$eff_{1,2,3}$	Power efficiencies of regulator and inverter (DC to AC and AC to DC)

TR   Time of day (0 to 24)

T_1, T_2 Times between which batteries should be charged at rate IBCH

5.2.2.2.   Mathematical Description

Mode 0 operates without a storage battery (TYPE 47) component. The power output by the array (P_A) is simply multiplied by eff_1 and sent to the load (as P_L), with any excess fed back to the utility ($P_U < 0$). When the load exceeds the array output, the utility furnishes the difference ($P_U < 0$). The present version places no limit on inverter size.

Mode 1 works with Mode 1 of TYPE 47, and monitors the battery's state of charge, which is Input as F. The subroutine performs tests of F against several parameters, the first being with respect to F_C. If $F < F_C$, the battery can either discharge (when $P_D > P_A$), or do nothing (when $P_D < P_A$). In the latter case, $P_R = P_A - P_L$. If $F < F_C$, the program determines if $F < F_B$ and the battery has been charging ($P_B > 0$). If these two conditions are met, then the battery must be on "total charge." On "total charge," first priority is given to recharging the battery with any array output, rather than sending the output to the load until $F > F_B$. "Total charge" can be avoided by setting $F_B < F_D$; in this case, the first priority for array output is always to meet the load. If $F > F_B$ or the battery has been discharging ($P_B < 0$), it can discharge (when $P_D > P_A$) or be placed on "partial charge" (when $P_D > P_A$), i.e., $P_B + P_A - P_L$. Finally, a check is made to ensure that $F > F_D$. If $F < F_D$ no further discharging is permitted.

Other conditional statements performed in mode 1 are with respect to the parameter $P_{L,MAX}$, the inverter power output capacity. The solar array and/or battery can never send more than this amount to the load, which means that $(P_L)(eff_2) < P_{L,MAX}$ where $P_{L,MAX}$ is the output power capacity of the inverter, and P_L is multiplied by eff_2 upon passing through the inverter.) The $P_{L,MAX}$ limit may require more power to be drawn from the utility, since $P_U = P_D – P_L (eff_2)$ or it may cause excess array output to be dumped into a resistor, with $P_R = P_A - P_L$.

Mode 2 monitors the battery's voltage level and charge/discharge rate as well as its state of charge. The additional limits are the Inputs V_D, V_C, P_B, $P_{B,MAX}$, and $P_{B,MIN}$.

In mode 2, inverter output power is limited to a maximum of $P_{L,MAX}$ if $P_{L,MAX} > 0$. If $P_{L,MAX} < 0$, the current Input to the inverter is limited to a maximum of - $P_{L,MAX}$.

Whenever the "F Tests" call for the mode 2 battery to discharge, the subroutine checks if $V < V_D$. If this is so, then a taper discharge is called for until $F = F_D$. During taper discharge, power is limited so as to never exceed P_{Vd}. If V remains above F_D, then discharge can proceed, as it would in mode 1.

When state of charge considerations imply charging, a test is performed against V_C. If $V < V_C$, charging can proceed. With $V > V_C$, the battery is put on "slow charge." This means that $P_B = P_C$, where P_C is the power that can be Input to the battery to keep V at V_C. (With the iterative procedure that is performed among the battery, regulator/inverter, and other components, V is effectively limited to exactly V_C.) Thus, the "finishing" charging of the battery is done at constant voltage.

After all "F Tests" and "V Tests," mode 2 checks the charge or discharge rate of the battery. These steps limit P_B to less than $P_{B,MAX}$ (on charge) and to greater than $P_{B,MIN}$ (on discharge). These correspond to the current limits I_{MAX} and I_{MIN} in the battery TYPE 47 subroutine. When P_A is large enough so that P_B would otherwise exceed $P_{B,MAX}$, this procedure carries out "constant current" charging of the battery (until V_C is reached, when "constant voltage" charging takes over).

Modes 0, 1 and 2 all operate with a maximum power mode of the TYPE 50 photovoltaic collector. They simply accept P_A as an Input and parcel it out among P_B, P_R and P_L. Mode 3 involves distributing current instead of power ("P" means "I" in this case), and the solar array voltage is clamped to that of the battery. It takes an initial P_A and sets P_B and the other currents accordingly. The voltage is calculated from the battery current in modes 3 or 4 of the TYPE 47 battery, then this value of V is fed into the TYPE 50 collector. This calculates a new P_A for the regulator. This sequence is repeated until, in effect, Kirchoff's Law for currents is satisfied, with the battery and array voltages equal to each other.

Mode 3 performs the same tests as the lower modes on F, V and P_B (now the battery current). It converts the Inputs $P_{L,MAX}$, P_C, P_D, $P_{B,MAX}$ and $P_{B,MIN}$ to currents by dividing by V and the kJ/hr to watt conversion factor 3.6. Mode 3 outputs P_A, P_B, P_L . eff_2, P_R and P_U as powers and currents, instead of just powers.

Modes 2 and 3 have the additional capability of charging the battery directly from the utility. Intended to simulate off-peak charging, this feature permits charging at a current I_{BCH}, up to an F limit of F_{BCH}, when the time of day is between T1 and T_2.

5.2.3. Type 50: PV-Thermal Collector

This write-up is a supplement to the TRNSYS Types for Solar Collectors (Types 1, 71, 72, 73), adding a PV module to the standard flat-plate collector. It describes the use of the modified version for combined collector simulation which incorporates both the analysis and work of Florschuetz (1) for flat plate collectors operated at peak power, and the analysis (2), for concentrating combined collectors. The latter analysis makes use of the I-V curves of the cells (or array) in solving for peak power or for current output at some imposed voltage.

MODES 1, 2, 3 and 4 of the modified collector are essentially similar to respectively Type 1, Type 72, Type 73 and Type 74 except that the work of Florschuetz is included. This necessitates the addition of a few extra PARAMETERS and INPUTS and provides for extra OUTPUTS. These are described in a very general nature below. The actual PARAMETER, INPUT, and OUTPUT lists can be found in Volume 04 of the TRNSYS documentation (Input, output, parameter reference).

5.2.3.1. Nomenclature

Please see the nomenclature for Type 1, Type 72, Type 73 and Type 74

5.2.3.2. Mathematical Description

MODE 1

Both U_L and τ in MODE 1 operate at the values supplied as PARAMETERs 6 and 7 respectively. Because a minimum of computational effort is required, the use of MODE 1 is recommended for all cases except those for which the assumption of constant U_L and/or may introduce significant error in the calculated performance. The numerical values of the PARAMETERS and INPUTS may be in any consistent set of units.

MODE 2

MODE 2 differs from MODE 1 in that U_L is calculated from Eq 5.10.5-3, page 5–358 as a function of the operating temperatures, the wind speed, and the collector construction details supplied as PARAMETERS.

MODE 3

MODE 3 differs from MODE 1 in that the angular dependence of τ is considered by the use of Eq 5.10.5-4, page 5–359. Note that the beam and diffuse components of the radiation incident on the (tilted) collector surface and the incident angle of the beam radiation must be supplied as INPUTS. As for MODE 1, any consistent set of units may be used for the numerical values of the PARAMETERS and INPUTS.

MODE 4

MODE 4 is essentially a combination of MODES 2 and 3, (i.e., U_L is calculated from Eq 5.10.5-3, page 5–358 and τ is calculated from Eq 5.10.5-4, page 5–359.

MODE 5

This mode can be used to model concentrating combined collectors. It uses the I-V curves through calls to SUBROUTINE SOLCEL to calculate solar cell performance at the peak power point. Therefore, data on the cells must be entered as called for by SOLCEL. (See the discussion of SOLCEL data in Volume 08, Programmer's guide) Both τ and U_T (the loss coefficient for thermal losses from the top of the solar cells) are considered to be constants.

MODE 6

This mode is the same as MODE 5 except that a temperature and wind dependent U_T is used. The expression developed by Klein (Eq 5.10.5-3, page 5–358) is assumed to apply; (this expression is the one used in MODE 2).

MODE 7

This mode is the same as MODE 5 (i.e., constant U_T and with solar cell output calculated from the I-V curves through SUBROUTINE SOLCEL) except that a cell operating voltage is specified (e.g., it may be imposed by a battery).

MODE 8

This mode is the same as MODE 6 (i.e., temperature and wind dependent top loss coefficient) except that a cell operating voltage is specified as in MODE 7. The units are also the same.

5.2.3.3.   References

1. Florschuetz L.W., "Extension of the Hottel-Whillier-Bliss Model to the analysis of Combined Photovoltaic/Thermal Flat Plate Collectors," Sharing the Sun Joint Conference Proceedings,Vol. 6, pg. 79, Winnipeg, (1976).

2. "Combined Photovoltaic/Thermal System Studies," Report ERC-R-78017, Arizona State University, Tempe, AZ (1978)

5.2.4. Type 90: Wind Energy Conversion System

TRNSYS Type 90 models a wind turbine. It makes use of some readily available manufacturer data as well as analytical solutions.

5.2.4.1. Nomenclature

U_0	Velocity in the free stream
P_0	Pressure in the free stream
A_1	Area of the c.v. far upstream of the rotor.
U_R	Velocity through the rotor
P_R^+	Pressure just upstream of the rotor
P_R^-	Pressure just downstream of the rotor
U_W	Velocity far downstream in the rotor wake
A_W	Area far downstream in the rotor wake
Q	Mass flux out the sides of the c.v.

5.2.4.2. Mathematical Description

FUNDAMENTALS OF WIND ENERGY SYSTEMS

Wind turbines transform the kinetic energy of moving air into useful work. In order to understand this process, a control-volume (*c.v.*) is constructed as shown in Figure 5.2.4–1 (page 5–50), representing a three-dimensional streamtube of air. The rotor is represented by an *actuator disk* interspersed in the flow.

The control volume method applied to wind turbine fluid dynamics is the *actuator disk model*, which was originally developed by Rankine (Spera, 1989) to model marine propellers. For wind turbines, the rotor is a homogeneous disk which removes energy from (rather than furnishing energy to) the moving fluid. Although insufficient for analysis of rotor geometry, the model is appropriate for analysis of axial mass, momentum, and energy balances. The following physical assumptions are employed:

- Constant, incompressible, non rotating, flow at constant temperature
- No mass flow across the streamtube boundary
- Point 1 is far upstream; point R is at the rotor, and point 2 is far downstream.

The position of point 2 is at the hypothetical point where the streamtube boundary is parallel to the horizontal c.v. boundary. At this point downstream the static pressure is constant and equals the free stream static pressure, P_O

The actuator disk approach to the momentum theory analysis of wind turbines does not include turbulent mixing between the air in the streamtube and the air in the balance of the c.v. Thus, the placement of the downstream boundary of the c.v. is arbitrary once the streamtube lines become parallel. When the condition that the streamtube lines are parallel is met, then the mass transfer Q (and the momentum associated with Q) leaving the c.v. due to the existence of the rotor is completed.
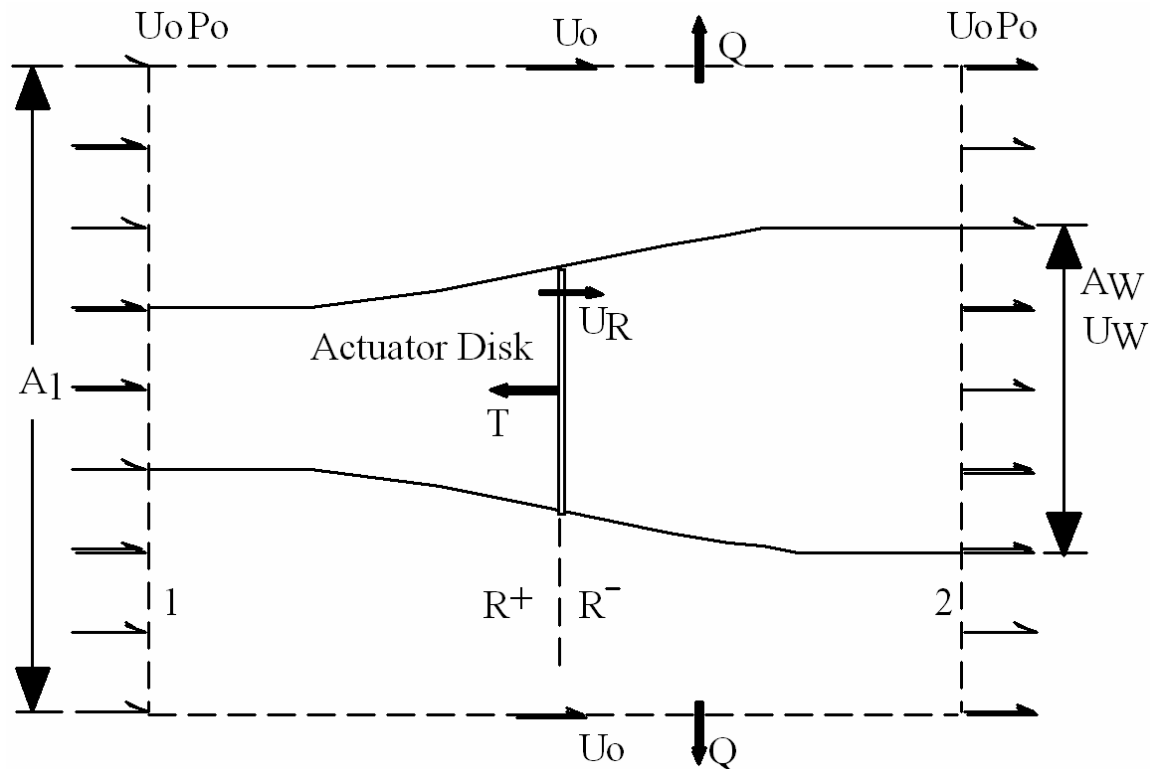
Figure 5.2.4–1: Streamtube Control Volume with Actuator Disk Wind Turbine Model

MOMENTUM THEORY

If it is assumed that the density of the air does not change, then mass continuity through the streamtube requires:

$$A_1 U_0 = A_R U_R = A_w U_w$$

Eq 5.2.4-1

Since $U_0 > U_R > U_W$ then it follows that   and the streamtube expands. The mass balance for the c.v. is:

$$A_1 U_0 - A_w U_w - (A_1 - A_w)U_0 - Q = 0$$

Eq 5.2.4-2

Rearranging Eq 5.2.4-2, and solving for Q yields an expression for the mass flow rate out of the control volume:

$$Q = A_w (U_0 - U_w)$$

Eq 5.2.4-3

Mass flow rate can be expressed as ρAU . Conservation of momentum in the horizontal direction results in:

$$\rho\, A_1 U_0^2 - \rho\, A_w U_w^2 - \rho\, (A_1 - A_2)U_0^2 - \rho\, U_0 Q - D = 0$$

Eq 5.2.4-4

or, after rearranging:

$$D = \rho\, A_w U_0^2 - \rho\, A_w U_w^2 - \rho\, U_0 Q$$ **Eq 5.2.4-5**

Substituting for Q by using Eq 5.2.4-3 results in:

$$D = \rho\, A_w U_0^2 - \rho\, A_w U_w^2 - \rho\, U_0 \left(A_w \left(U_0 - U_w \right) \right)$$ **Eq 5.2.4-6**

which, after rearranging, becomes

$$D = \rho\, A_w U_w \left(U_0 - U_w \right)$$ **Eq 5.2.4-7**

BERNOUILLI'S EQUATION

Figure 5.2.4–2 shows wind speed, plus static, dynamic and total pressure across the rotor.
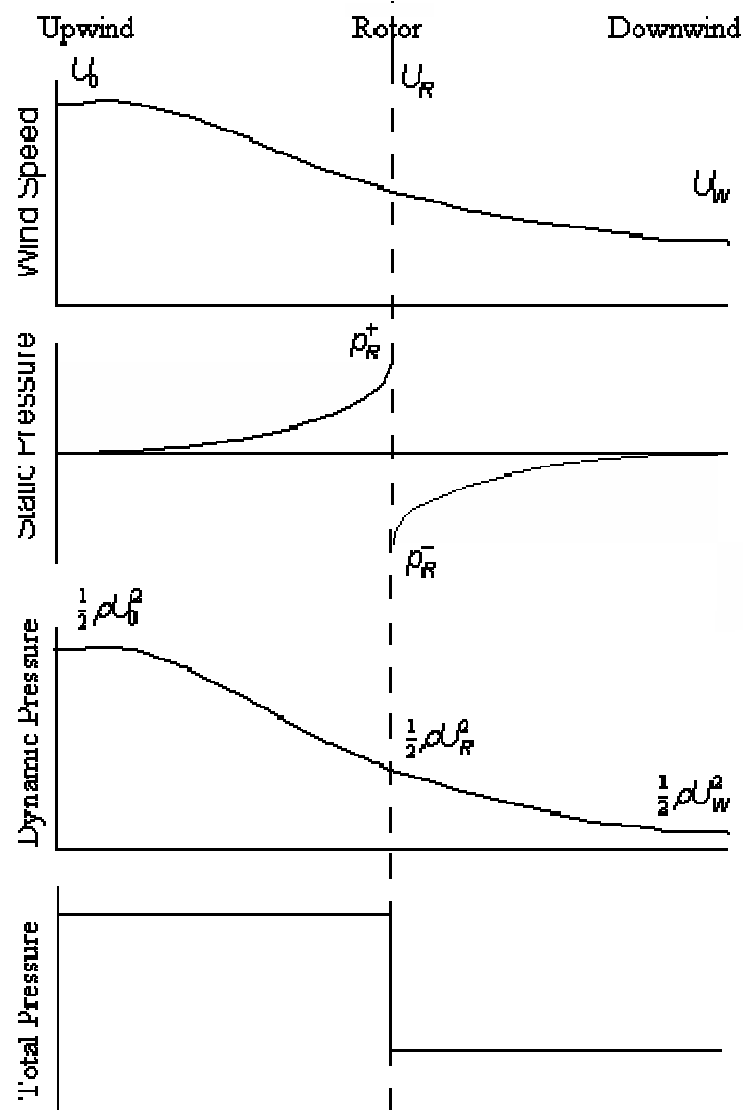
Figure 5.2.4–2: Wind speed, P, plus static, dynamic and total pressure across the rotor

Bernoulli's equation is next used to describe the pressure difference across the rotor. Upstream of the rotor:

$$p_0 + \frac{1}{2}\rho U_0^2 = p_R^+ + \frac{1}{2}\rho U_R^2 \qquad \textbf{Eq 5.2.4-8}$$

and downstream of the rotor:

$$p_0 + \frac{1}{2}\rho U_w^2 = p_R^- + \frac{1}{2}\rho U_R^2 \qquad \textbf{Eq 5.2.4-9}$$

The pressure difference across the rotor is then equivalent to the difference between Eq 5.2.4-8 and Eq 5.2.4-9, or:

$$p_R^+ - p_R^- = \frac{1}{2}\rho\left(U_0^2 - U_w^2\right) \qquad \textbf{Eq 5.2.4-10}$$

The thrust force, D can be expressed as the pressure difference applied to the rotor area (hence, *actuator disk*). The expression in this case is:

$$D = A_R\left(p_R^+ - p_R^-\right) \qquad \textbf{Eq 5.2.4-11}$$

It is then possible to combine Eq 5.2.4-10 and Eq 5.2.4-11 to create an expression for the thrust:

$$D = \frac{1}{2}\rho A_R\left(U_0^2 - U_w^2\right) \qquad \textbf{Eq 5.2.4-12}$$

WIND VELOCITY AT THE ROTOR AND AXIAL INDUCTION FACTOR

Combining the expression of thrust derived from Bernouilli's equation with the one that was derived from the momentum theory (Eq 5.2.4-7), we have:

$$\rho A_w U_w\left(U_0 - U_w\right) = \frac{1}{2}\rho A_R\left(U_0^2 - U_w^2\right) \qquad \textbf{Eq 5.2.4-13}$$

Recall that $A_w U_w = A_R U_R$, so that Eq 5.2.4-13 becomes

$$\rho A_R U_R\left(U_0 - U_w\right) = \frac{1}{2}\rho A_R\left(U_0^2 - U_w^2\right) \qquad \textbf{Eq 5.2.4-14}$$

Canceling out like terms and simplifying, results in

$$U_R\left(U_0 - U_w\right) = \frac{1}{2}\left(U_0^2 - U_w^2\right) \qquad \textbf{Eq 5.2.4-15}$$

Recalling that $\left(U_0^2 - U_w^2\right) = \left(U_0 - U_w\right)\left(U_0 + U_w\right)$, then Eq 5.2.4-15 reduces to an expression for the wind velocity at the rotor,

$$U_R = \frac{\left(U_0 + U_w\right)}{2} \qquad \textbf{Eq 5.2.4-16}$$

which means that the wind speed at the rotor is the average of the upstream and downstream wind speeds. The term **a** is defined as the *axial induction factor* (or the *retardation factor*) and is a measure of the influence of the rotor on the wind, such that:

$$U_R = U_0(1-a)$$

Eq 5.2.4-17

Eq 5.2.4-16 and Eq 5.2.4-17 can then be combined to yield an expression for the downstream wind speed in terms of the free stream wind speed, or:

$$U_w = U_0(1-2a)$$

Eq 5.2.4-18

The power output of a wind turbine can then be written as the product of the thrust times velocity:

$$P = D\, U_R$$

Eq 5.2.4-19

Eq 5.2.4-12 can be substituted into Eq 5.2.4-19 to create an expression for the power output

$$P = \left(\frac{1}{2}\rho A_R\left(U_0^2 - U_w^2\right)\right)U_R$$

Eq 5.2.4-20

Eq 5.2.4-17 can be used to replace U_R, and Eq 5.2.4-18 can be used to replace U_w in Eq 5.2.4-20, resulting in:

$$P = \rho A_R U_0 (1-a)\left(U_0^2 - \left(U_0(1-2a)\right)^2\right)$$

Eq 5.2.4-21

Simplifying Eq 5.2.4-21 yields

$$P = \frac{1}{2}\rho\, A_R\, U_0^3\, 4\, a(1-a)^2$$

Eq 5.2.4-22

The power coefficient for a wind turbine, C_P, is defined as the power of the turbine divided by the power in the wind, where the power in the wind is:

$$P = \frac{1}{2}\rho\, A_R\, U_0^3\, 4\, a(1-a)^2$$

Eq 5.2.4-23

Which yields an expression for the power coefficient as a function of the axial induction factor:

$$C_P = 4\, a\, (1-a)^2$$

Eq 5.2.4-24

The maximum power coefficient, C_{Pmax}, is found by finding dP/da = 0 and solving for a, where the solutions are a = 1 and a = 1/3. The solution for a = 1 results in the minimum value of C_P, 0, while a = 1/3 results in the maximum value of C_P, where:

$$C_{Pmax} = 4\,\frac{1}{3}\left(1-\frac{1}{3}\right)^2 = \frac{16}{27} = 59.3\%$$

Eq 5.2.4-25

The value of 59.3% as a maximum power coefficient was first derived by Betz in 1919, and has since been called Betz's limit.

The value of the coefficient is that, when multiplied by the area of the rotor and power in the wind, it describes the power output of the wind turbine, or:

$$P = C_P \, \rho \, A_R \, U_0^3$$

Eq 5.2.4-26

Figure 5.2.4–3 shows Cp as a function of the axial induction factor. The value of C_P for a wind turbine is determined by its tip-speed-ratio (the ratio of blade tip speed in the plane of the rotor to the free stream wind speed U_0). For variable pitch or variable speed wind turbines, tip-speed-ratio is selected by the turbine for maximum C_P up to the rated power output, then for operation at wind speeds above the rated wind speed, C_P falls in order to maintain constant rated power.
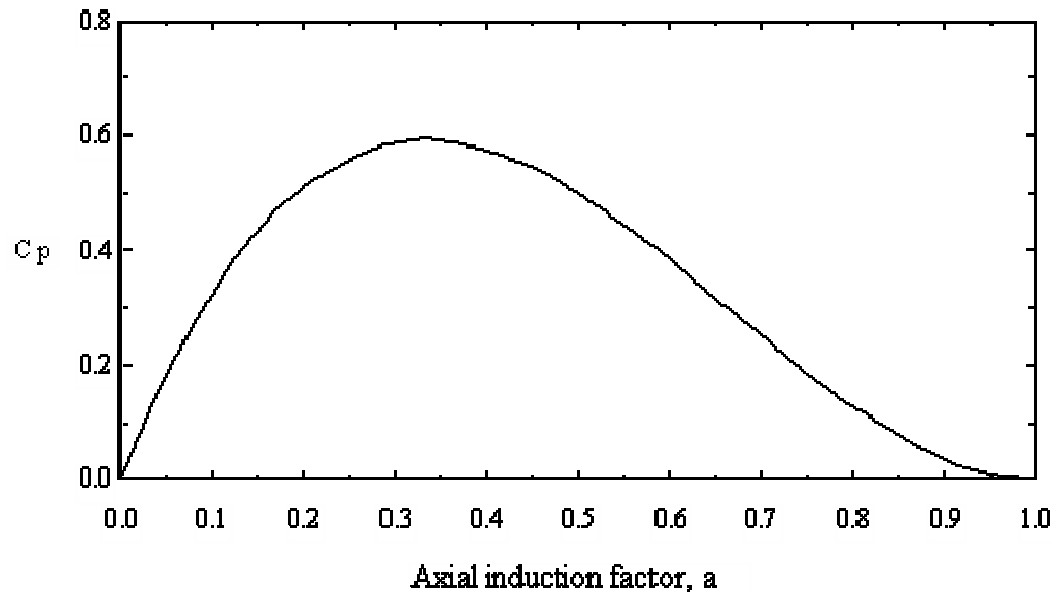
Figure 5.2.4–3: C_P as a Function of Axial Induction Factor

Figure 5.2.4–4 shows C_P as a function of wind speed for a typical stall-regulated wind turbine and power-regulated turbine. For stall-regulated turbines, rotational speed is fixed, so tip-speed-ratio is a measure of the ratio of free-stream wind velocity to the fixed rotor speed.
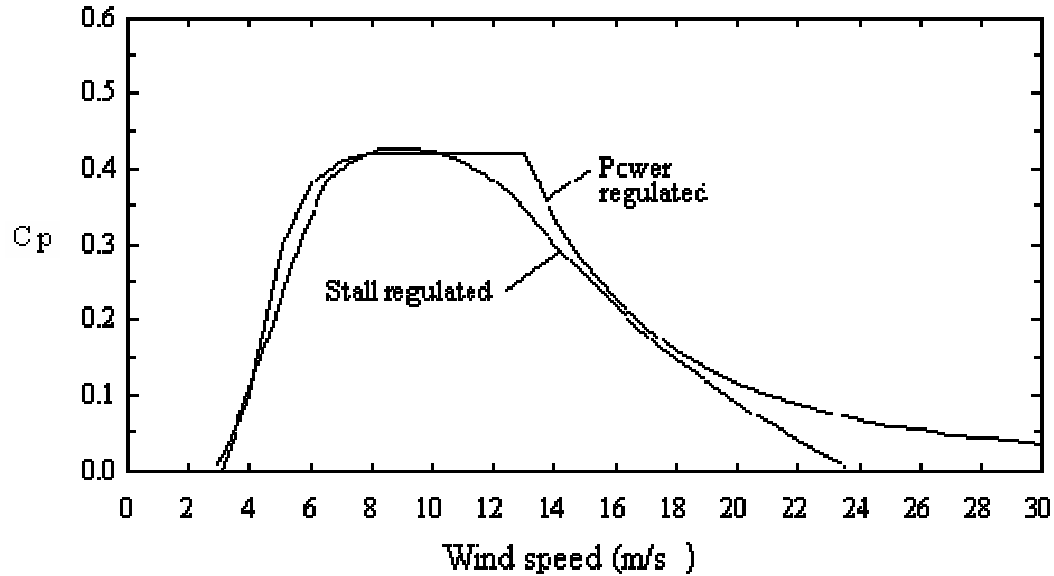
Figure 5.2.4–4: Typical C_P vs. wind speed curves for stall regulated and power regulated WECS

The C_P values applicable for most wind turbine applications are those associated with axial induction factors between 0 and 0.5; values less than 0 are associated with propeller operation, and values above 1.0 are associated with propeller brakes. For wind turbines, values between 0.5 and 1.0 are not encountered in practice because in this region, stall-regulated turbines have lower tip-speed-ratios and pitch-regulated wind turbines feather to lower, rather than higher thrust coefficients. Pitching to the lower thrust coefficient achieves lower structural loads than pitching to the higher thrust coefficient.

THRUST COEFFICIENT

The thrust coefficient, C_T, for a wind turbine is defined as the ratio of the wind turbine drag force divided by the force of the wind over an equivalent swept area. Determination of C_T is required for turbine wake and array calculations. The term "thrust" is commonly used instead of "drag" because turbine design shares a significant amount of its nomenclature and theoretical development with propeller theory. Most manufacturers do not explicitly publish thrust coefficient data. However, it is possible to derive the thrust coefficient at a given wind speed if the C_P or turbine power output is known, based on momentum theory.

Wilson and Lissaman (1974) developed a method for relating C_T to the axial induction factor. Recall from Eq 5.2.4-19 that $P = DU_R$. Substituting for P using Eq 5.2.4-17, and canceling like terms results in the expression:

$$D = \frac{1}{2}\rho A_R U_0^2 \left(4a(1-a)\right)$$

Eq 5.2.4-27

The thrust coefficient is the turbine thrust divided by the wind force applied to the rotor swept area, or:

$$C_T = \frac{D}{\frac{1}{2}\rho A_R U_0^2}$$

Eq 5.2.4-28

Eliminating D between the last two equations results in an expression for C_T as a function of a:

$$C_P = 4\,a\,(a-1)$$
Eq 5.2.4-29

Recalling from Eq 5.2.4-24 that C_P can also be expressed as a function of the axial induction factor, then it is possible to relate the thrust coefficient to the power coefficient through the axial induction factor.

Figure 5.2.4–5 shows C_T and C_P as a function of the axial induction factor in the a = 0 to 0.5 region. Figure 5.2.4–6 shows the curve of C_T as a function of C_P, for C_P between 0 and 0.593 and C_T between 0 and 1.0. The region C_T = 0 to 1.0 is appropriate for practical wind turbines because C_P cannot exceed Betz's limit and because commercial turbines, with low rotor solidities, do not commonly exhibit thrust coefficients greater than 1.0.
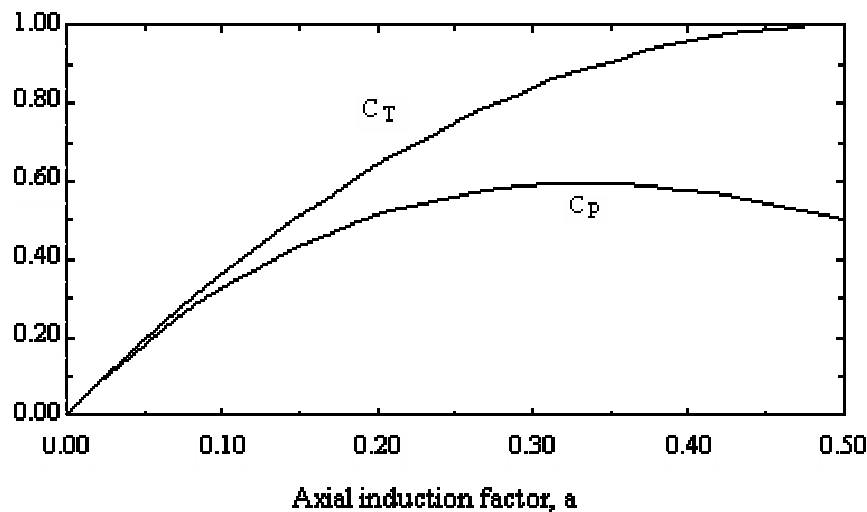
Figure 5.2.4–5: C_T and C_P as a Function of the Axial Induction Factor

Because Eq 5.2.4-16 is implicit, it is not possible to explicitly characterize C_P as a function of the axial induction factor. However, it is possible to determine a value for C_T by using the axial induction factor as a numeric solution parameter, as shown in Figure 5.2.4–6.
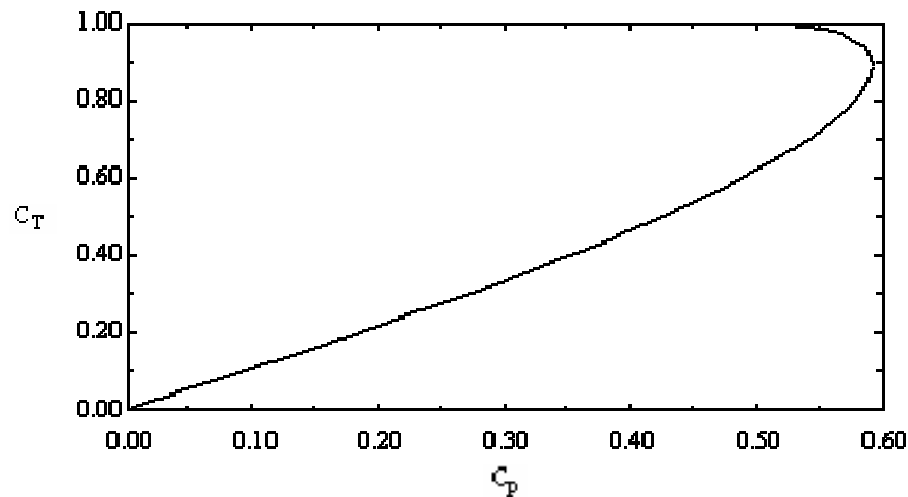
Figure 5.2.4–6: C_T as a function of C_P

5.2.4.3. Factors Influencing Wind System Performance

It has been shown earlier in this section that the energy extracted by a wind turbine results from a change in momentum of the air moving through the rotor plane. The mass flow rate of air is affected by its density, which is a function of temperature and pressure, and velocity. Estimated wind velocity at the turbine rotor is based on information concerning flow obstructions and assumptions made concerning speed-up with height above ground. In addition, the power conversion efficiency of a wind turbine is influenced by variance in the wind speed (turbulence), orthogonality to the flow (yaw error) and aerodynamic effects (blade cleanliness).

AIR DENSITY

The energy extracted by a wind turbine results from the change in momentum of the air moving through the rotor. The mass flow rate of air is a function of its density; therefore, the change in momentum is a function of the density of the air passing through the rotor. As described by the ideal gas law, the density of air is a function of its temperature and pressure. Air density is also dependent on humidity ratio, although Rohatgi and Nelson (1994) have shown that this influence is negligible for wind energy applications. In the atmosphere, the air density at a particular altitude is a function of the temperature and pressure of the air at the time and at that location. Both air pressure and temperature fall as a function of altitude. Hydrostatic pressure is commonly described as:

$$\frac{dp}{dz} = -\rho g \qquad \text{Eq 5.2.4-30}$$

so the pressure difference from one altitude to the next is:

$$\Delta p = -\int_1^2 \rho g \, dz \qquad \text{Eq 5.2.4-31}$$

Introducing the ideal gas law $p = \rho R T$, substituting for ρ in Eq 5.2.4-30, separating the variables, and integrating between two points yields:

$$\int_1^2 \frac{dp}{p} = \ln\left(\frac{p2}{p1}\right) = -\frac{g}{R}\int_1^2 \frac{dz}{T} \qquad \text{Eq 5.2.4-32}$$

Assuming constant temperature, integrating Eq 5.2.4-32 over z yields an expression for the pressure difference from point 1 to point 2 in elevation:

$$p_2 = p_1 \, e^{\left(-\frac{g(z_2 - z_1)}{RT}\right)} \qquad \text{Eq 5.2.4-33}$$

For elevations where wind energy applications apply, temperature decreases linearly with altitude. The temperature "lapse rate" (White, 1994) is:

$$T(z) \approx T_0 - B\,z \qquad \text{Eq 5.2.4-34}$$

where B = 6.5 K/km of altitude.

The expression for T(z) can be inserted into Eq 5.2.4-32 and integrated, resulting in an expression for pressure decrease with altitude, taking into account the temperature lapse rate

$$p_2 = p_1 \left(1 - \frac{B\,z}{T_0} \right)^{\frac{g}{RB}}$$ **Eq 5.2.4-35**

where the dimensionless exponent g/RB = 5.26 for air, and T_0 = 288K .

The air density at an elevation is a function of the combined effects of pressure and temperature, according to the ideal gas law. The air density at a given elevation, in kg/m3, is therefore:

$$\rho_{elev} = \frac{p_{elev}}{RT}$$ **Eq 5.2.4-36**

The resulting variation in air density is shown in. The left axis shows the percent of sea-level density, while the right axis shows the numeric value. At an altitude of 3,000 meters, the density has fallen to approximately 80 percent of sea-level density.

In most cases, wind turbine power output at a given wind speed is a linear function of air density. Wind turbines are usually not considered practical at high elevations, despite the stronger wind speeds. Since temperature and pressure also vary with weather, air density varies as well over time. Figure 5.2.4–8 shows percent of standard air density for weather conditions that are typical over the course of a year.
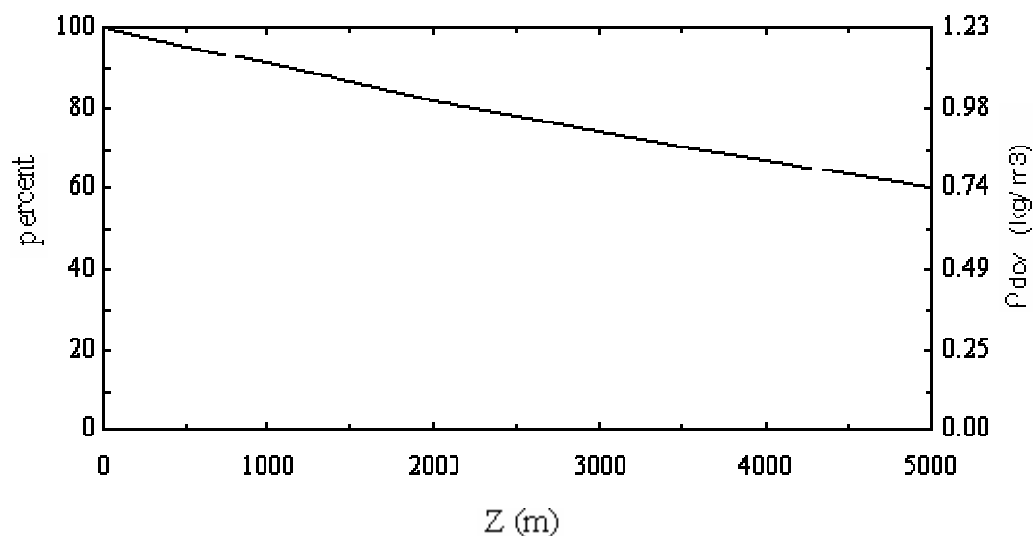
Figure 5.2.4–7: Air Density as a Function of Elevation
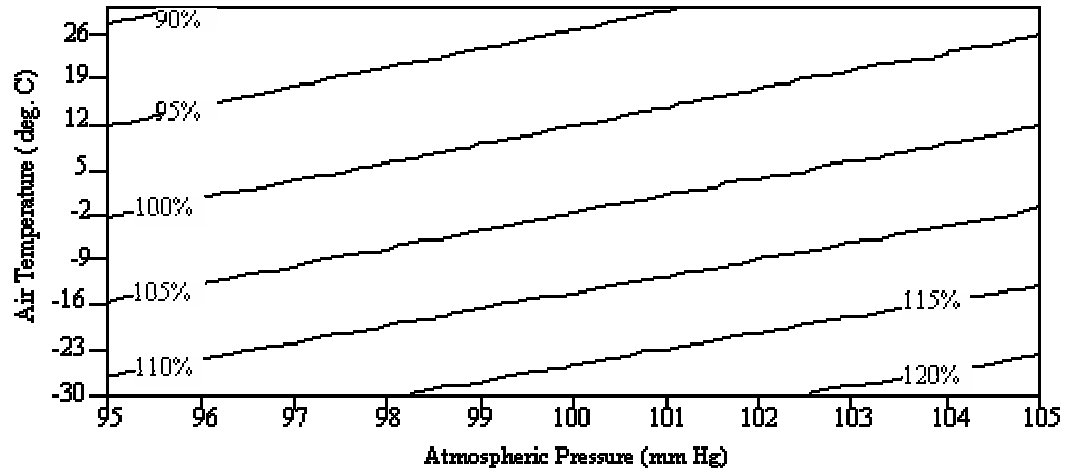
Figure 5.2.4–8: Percent of standard air density over the course of a year (typical weather conditions)

Wind turbine power output also varies slightly due to variations in air density because the Reynolds number, upon which airfoil performance depends, also depends on . However, the influence on power output at the variations in density occurring in the atmosphere is small, so that Reynolds effects are not usually considered in power output modeling.

Different types of turbines respond differently to air density changes depending on the method of power regulation employed. The output of fixed pitch wind turbines (stall-regulated and Darrieus vertical axis wind turbines) varies linearly with air density ratio. In this case, the vector addition of free-stream and rotor wind velocities results in an apparent airfoil angle of attack which moves into the "stalled" region of the airfoil lift-drag curve. Fixed pitch is problematic for commercial operators of wind turbines because the pitch of the turbine, as installed, is fixed and therefore based on a mean assumption for site air density. Since air density varies constantly, the turbine is rarely operating at an optimum. Fortunately, the range of "near-optimum" is broad. However, it is common practice to set conservative pitch angles on stall-regulated turbines to avoid overloading the turbine generator at times of high air density and high wind (typically, winter conditions).

Turbines with variable speed rotors and pitch-controlled blades are of a "power-regulation" class. For these turbines, output is linearly proportional to air density up to the maximum power rating of the turbine. Maximum power is achievable, albeit at a higher wind speed in low density conditions. The wind speed at which the rotor cuts-in and can reach its rated output occurs at a wind power density equivalent to the wind power density at standard conditions. Wind power density (W/m2) is a cubic function of wind speed, therefore

$$U_{rated,\rho} = U_{rated} \left(\frac{\rho_0}{\rho} \right)^{\frac{1}{3}}$$

Eq 5.2.4-37

Figure 5.2.4–9 shows power curve variations for a power-regulated turbine as a function of air density. Note that the turbine reaches a fixed maximum, but that the point at which it reaches the maximum depends on air density.
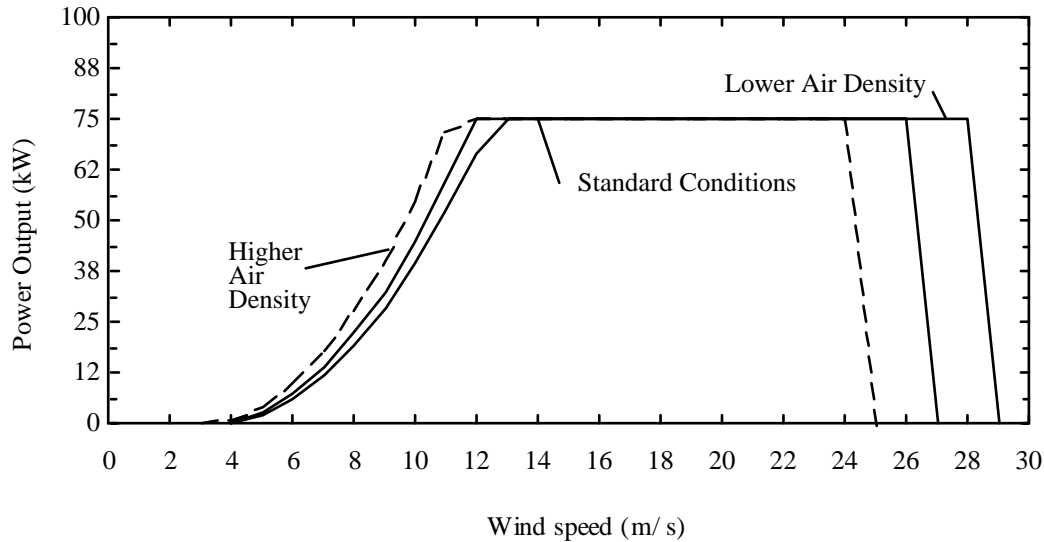
Figure 5.2.4–9: Output of a Power Regulated Wind Turbine as a Function of Air Density

VERTICAL WIND SHEAR

The modeling of vertical wind shear (the change in wind speed per change in height above the ground), is historically based on boundary layer theory applied to the atmosphere. Two vertical wind shear models are used in wind energy applications.

The first is the "one-seventh power law" model, based on the theoretical work of Von Karman (Koeppl, 1982):

$$\left(\frac{U_1}{U_2}\right) = \left(\frac{z_1}{z_2}\right)^\alpha$$

Eq 5.2.4-38

A single parameter, α, determines the rate of wind speed increase as a function of height. Under ideal boundary layer conditions, the value of alpha is taken to be 1/7 (0.14). However, under actual conditions, the value of alpha constantly varies, and depends on a variety of factors influencing vertical turbulence intensity, including:

- Local upwind surface roughness, determined by whether the air is moving over water, prairie, bushes or trees.
- Large scale surface characteristics in the "fetch", or upwind area, such as mountainous far upwind, or buildings and other structures nearby upwind.
- Atmospheric stability, as defined by the temperature gradient with height.
- Other wind turbines. Turbines increase turbulence due to vortex shedding.

Efforts to include these effects into more detailed, multiple-parameter shear models for wind energy applications have produced a variety of alternatives. The logarithmic profile

$$U_2 = U_1 \frac{\ln\left(z_2/z_0\right)}{\ln\left(z_1/z_0\right)}$$

<div align="right">**Eq 5.2.4-39**</div>

is incorporated in the WaSP computer model used in Europe. The value of   is the surface roughness length.

In some circumstances, a value for the surface roughness is not known, or is a source of subjectivity. For this reason, the power law model continues to be most often used by meteorologists, especially where multi-height wind data is obtainable from a site. In this case, the shear exponent, alpha, implicitly incorporates influences due to surface roughness. For this reason, many wind data collection sites monitor wind velocity at two or more heights, allowing the meteorologist to infer a vertical wind shear exponent between heights. Combined with the capability to disaggregate time series data into directional components, then it is possible to map the shear exponent by time and direction.

In time series modeling of wind turbine performance, vertical wind shear data is important in two cases. In the first case, the wind turbine power curve may have been collected at a height which was not the turbine hub height. For example, wind data may have been collected at ten meters for a wind turbine which was operating at a 25 meter height above the ground. Though not a common situation, power curve data have been published with this height mismatch, since it can misleadingly represent a more powerful turbine.

In the second case, it is more common that site wind data has been collected at a different height from the turbine hub height. In this case, a hierarchy of approaches is appropriate. The most rigorous approach is to utilize a time series of vertical wind shear values calculated from two wind speed data sets, each from a different height above ground bracketing the height of the wind turbine. The equation for determining the alpha value from heights 1 and 2 is obtained by solving the power law equation for α:

$$\alpha = \frac{\ln(U_2) - \ln(U_1)}{\ln(z_2) - \ln(z_1)}$$

<div align="right">**Eq 5.2.4-40**</div>

A less rigorous approach is to calculate wind speeds based on wind data where both heights were below the turbine hub height: in this case the very same model is employed, but for extrapolation, rather than interpolation. The least rigorous approach is to apply an alpha estimate which does not vary with time. Unfortunately, this is often the case with typical availability of historic wind data, where annual average alpha exponents for sites are often provided with average wind speed data and wind roses.

The sensitivity of hub height wind speed on the value of the vertical wind shear exponent is very strong. Figure 5.2.4–10 was prepared to present an "envelope" of possible variations in wind speed estimates, based on vertical wind shear assumptions, where the value of 1/7 was used as a baseline. The figure shows that an error of 10% in wind power output can occur with a five point error in shear exponent. Considering the fact that wind power is a cubic function of wind speed, the importance of vertical wind shear data is critical.
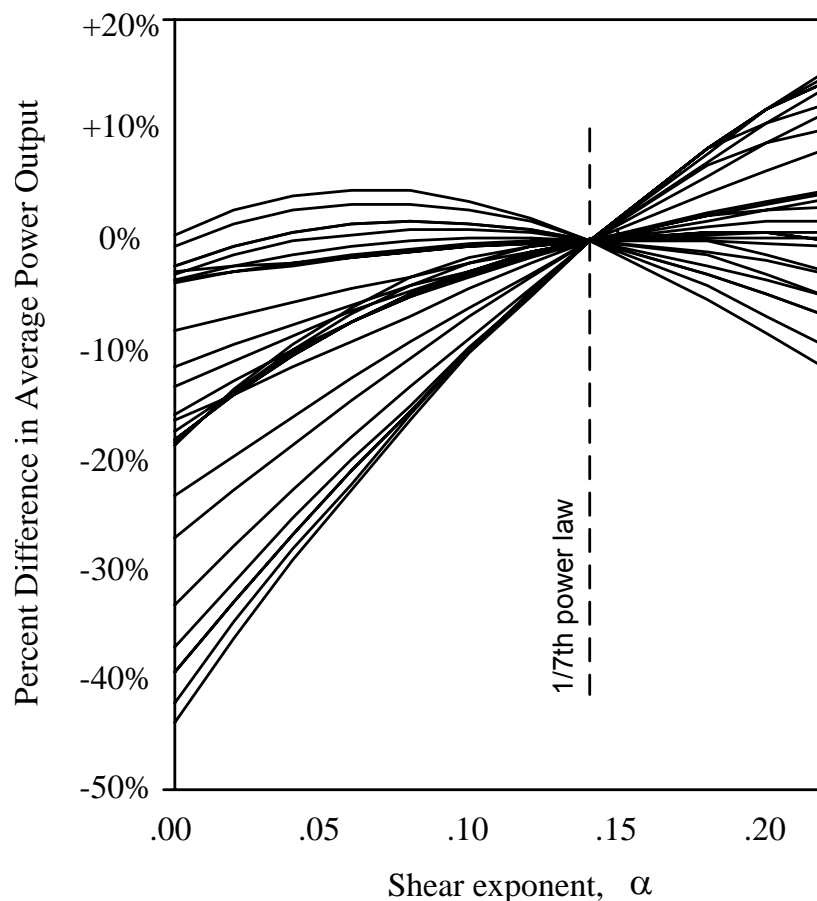
Figure 5.2.4–10: Example variation in wind turbine power output as a function of Shear exponent. (lines represent various typical data height and turbine height values across a probable range)

TURBULENCE

Turbulence has a variety of impacts in wind energy applications. As discussed earlier in this chapter, turbulence is major factor in contributing to the fatigue of turbine components. Turbulence is also important from an energy perspective. It contributes to errors in the preparation of power curves. Higher turbulence causes power fluctuations, since pitch controlled blades may not be able to adjust their blade pitch sufficiently quickly to follow the rapidly varying wind speeds, which can result in potentially unstable power output events. For stall-regulated wind turbines, turbulence has a similar effect, due to a hysteresis phenomenon, termed dynamic stall. Data from wind tunnel tests have confirmed the existence of dynamic stall; if the angle of attack of an airfoil is changed rapidly, stall is delayed. The same effect occurs as angle of attack is returned from the stall condition; stall is maintained for a brief amount of time before settling back.

When a turbine airfoil encounters turbulence, the effect is a change in apparent angle of attack. This effect has been one of the areas NREL (The National Renewable Energy Laboratory, USA) has attempted to mitigate in its development of airfoils designed specifically for wind turbines.

The U component is downwind, the V component is vertical, and the W component is the crosswind component of the wind velocity vector. Turbulence is described as the variation in wind

velocity, where the associated turbulence intensities are defined as U', V' and W'. The only component which is actually measured in most wind energy site assessments is U', based on the variation in the wind speed measurements from a cup anemometer or propeller anemometer mounted on the front of a wind vane. U' is important from an energy perspective because of its role in airfoil aerodynamics, such as dynamic stall. W' is important because it influences the horizontal component of the rotor wake structure, and V' influences vertical wind shear and the vertical component of the rotor wake structure.

The time base for turbulence data is usually over an hour, with measurements stored at 1 Hz. A turbulence intensity of 10% is equivalent to a standard deviation of 1m/s in an hour with a mean value of 10 m/s.

Connell (1986, 1988) has investigated turbulence in the atmosphere, as it relates to wind power applications. His research revealed that turbine blades pass through a combination of turbulence components as a rotation is completed. This mixing effect was simulated by computer re-sampling of turbulence data from a ring of anemometers, using a rotational approach. Veers (1994) has made important contributions in the characterization of the turbulent flow field, especially as it applies to fatigue damage, to the extent of creating algorithms based on Connell's findings for synthesizing turbulent flow fields with properties similar to observed data.

WAKES

When installed in multiple-unit arrays, wind turbines have the potential to interact with each other when a downwind turbine is in the wake of an upwind wind turbine. The wake of the upwind turbine can be visualized as a plume of reduced flow having a generally Gaussian shape and boundary-layer characteristics in the radial crosswind direction. The extent of the wake interaction is dependent on the general wind direction (placement), turbulence intensity in the radial crosswind direction (mixing), and distance between turbines (strength), the number of upwind turbines (superposition), and whether wind speeds are reduced below the turbines rated speed (sensitivity). Figure 5.2.4–11 shows a typical wake interaction situation for a hypothetical wind array.

In general, the impact of wake effects on a wind turbine array is a reduction in power output for certain wind speeds and directions. Knowledge of the wind speed by direction distribution at a site results in a determination of an efficiency factor associated with the layout of the wind array. Thus, it is possible to perform scenario analyses of possible array layouts in order to minimize wake effects. In real life projects, the easiest approach is to increase the distances between turbines. This can increase the cost of a project, however. The costs per land area are then introduced in the analysis to seek an optimum.
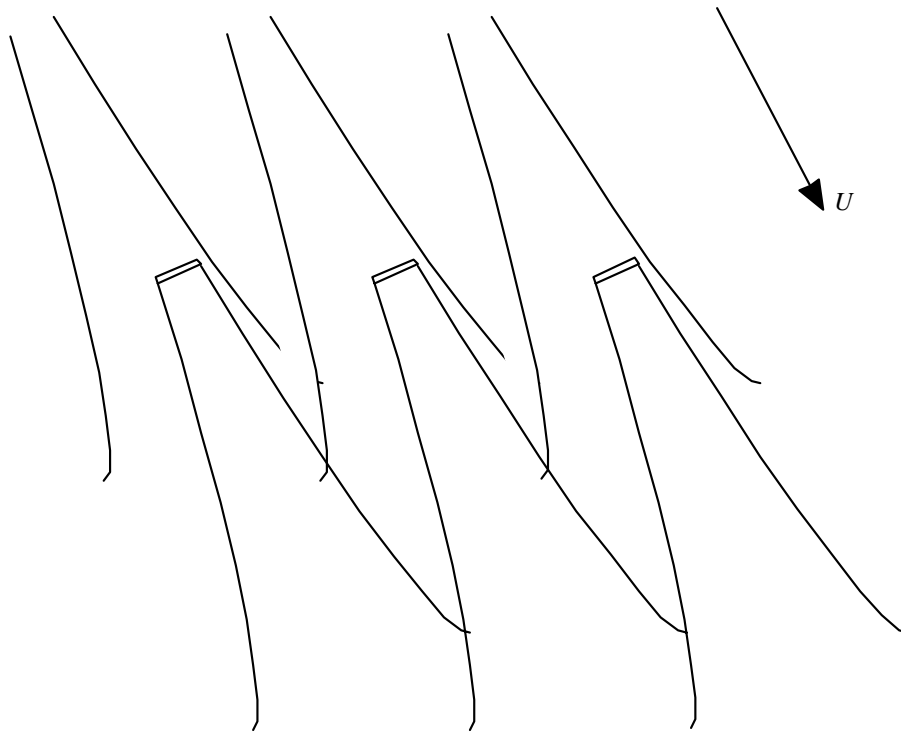
Figure 5.2.4–11:Wake Interactions in a Hypothetical Wind Array

In the case of wind turbines arranged along ridge lines, some wind project operators have shut off wind turbines along the rows. This has had two effects: the first influences the apparent turbine distances. The second (and most important to the operator) is the reduced in-flow turbulence (and resulting increase in service-life) experienced by the operating wind turbines.

OTHER FACTORS

A variety of other factors influence wind turbine power output. These can be divided into two categories: aerodynamic and operational. Aerodynamic impacts are those influences on the aerodynamic performance of the rotor airfoils. The most important aerodynamic impacts are the sources of increased surface roughness of the blades, and the prime cause is dead insects built up on the leading edges of the blades. Also recognized are ultra-violet light degradation of the surfaces of the blades, and air pollution. Installations near highways have reported that turbine blades had been soiled by aerosols from the exhaust of diesel engines powering trucks on the highway.

Operational influences are either external- or control-system sources of sub-optimal operation. External causes include power outages or inadvertent shut-down. Control-system causes include sub-optimal cut-in of the rotor due to anemometer or software error. A common cause of sub-optimal operation of horizontal axis turbines is yaw-error: the misalignment of the rotor to the wind which can happen when variation in wind direction occurs faster than the response rate of the yaw drive. Operational factors are commonly lumped into a percent-loss factor or efficiency factor.

5.2.4.4. External data file

Type 90 reads the wind turbine performance data from a data file. Table 5.2.4–1 describes the required data in the file. An example is available in "Example\Data Files". In Table 5.2.4–1, the text that must appear literally is printed in **bold italics**, while the variables that must be provided (mostly numbers) are within brackets <>.

Table 5.2.4–1: Type 90, External data file

line	Data	Comments
1	**WECS_Typ** <WECS Type>	String (for information only)
2	**WECS_REF** <origin of data>	String (for information only)
3	**Len_Unit m**	Do not edit
4	**Spd_Unit m/s**	Do not edit
5	**Pwr_Unit kW**	Do not edit
6	**Ctl_mode** <control mode>	Control mode is ONE CHARACTER, and there must be ONE SPACE between "Ctl_mode" and the character. Valid choices: S, P, V (S=stall; P=pitch; V=variable speed)
7	**Rotor_Ht** <rotor height>	Rotor center height, meters
8	**Rotor_Di** <rotor diameter>	Rotor diameter, meters
9	**Sensr_Ht** <sensor height>	Sensor Height for data pairs given here below, meters (often rotor center height)
10	**Sher_Exp** <wind shear exponent>	Power-law exponent for vertical wind profile
11	**Turb_Int** <turbulence intensity>	Turbulence intensity valid for this curve
12	**Air_Dens** <air density>	Power curve air density, kg/m3
13	**Pwr_Ratd** <rated power>	Rated power of the turbine, kW
14	**Spd_Ratd** <rated wind speed>	Rated wind speed, m/s
15	**Num_Pair** <NP>	Number of (wind speed, power) pairs in the file (Max 100)
16	<wind speed 1> <power 1>	1st data pair (wind speed, power) - Free format (space separated) – ALWAYS START AT 0.0
…	<wind speed> <power>	Additional data pairs
15+ NP	<wind speed NP> <power NP>	Last data pair. Use maximum 100 points

EXAMPLE

```
WECS_Typ Bonus 2MW (60)              ! Wind Turbine type
WECS_REF www.bonus.dk                ! Data source
Len_Unit m                           ! Length unit, must be m (do NOT edit)
Spd_Unit m/s                         ! Speed unit, must be m/s (do NOT edit)
Pwr_Unit kW                          ! Power unit, must be m (do NOT edit)
Ctl_mode P                           ! Control mode (S, P, V)
Rotor_Ht   60.00                     ! Rotor center height, meters
Rotor_Di   76.0                      ! Rotor diameter, meters
Sensr_Ht   60.00                     ! Sensor Height for curve
Sher_Exp    0.16                     ! Power-law exp. for wind profile
Turb_Int    0.10                     ! Turbulence intensity for this curve
Air_Dens    1.225                    ! Power curve air density, kg/m3
Pwr_Ratd 2000.00                     ! Rated power of the turbine, kW
Spd_Ratd   15.00                     ! Rated wind speed, m/s
Num_Pair   26                        ! Number of data pairs in the file
    0    0.00                        ! First data pair (wind speed, power)
    1    0.00                        ! Second data pair - Free format
    2    0.00                        ! Other data pairs
    3    9.6

   ...   ...                         ! Other data pairs (max 100 total)

   24    2000
   25    2000                        ! Last data pair - Free format.
```

5.2.4.5. References

Connel J. 1985. A primer on turbulence at the wind turbine rotor. In proceedings of Wind Power 1985, pp. 57-66. Washington DC. American Wind Energy Association.

Connel J. 1988. The wind lumps that bump a rotor. In proceedings of Wind Power 1988, pp. 452-461. Washington DC. American Wind Energy Association.

Koepll G.W. 1982. Putnam's power from the wind: Second Edition. Van Nostrand Reinhold Company, New-York.

Rohatgi J. and Vaughn N. 1974. Wind characteristics: an analysis for the generation of wind power. Alternative Energy Institute. West Texas A&M university.

Spera, D.A. 1986. Overview of the new ASME performance test code for wind turbines. Proceedings of Joint ASME/IEEE power generation conference, 1986. ASME, New-York

Veers P.S. et al. 1994. User's manual for FAROW: Fatigue and reliability of wind turbine components, Version 1.1. Sandia National Laboratories, Albuquerque, NM, USA.

White F. 1994. Fluid Mechanics, Third Edition. Mc Graw Hill, New-York, USA.

Wilson R.E. and Lissaman P.B.S. 1994. Applied aerodynamics of wind power machines. National Science Foundation, Washington DC, USA.

5.2.5.   Type 94: Photovoltaic array

This component models the electrical performance of a photovoltaic array. Type 94 may be used in simulations involving electrical storage batteries, direct load coupling, and utility grid connections. It employs equations for an empirical equivalent circuit model to predict the current-voltage characteristics of a single module. This circuit consists of a DC current source, diode, and either one or two resistors. The strength of the current source is dependent on solar radiation and the IV characteristics of the diode are temperature-dependent. The results for a single module equivalent circuit are extrapolated to predict the performance of a multi-module array.

For crystalline modules (either single crystal or polycrystalline technology), Type 94 employs a "four-parameter" equivalent circuit. The values of these parameters (not to be confused with formal component PARAMETERS in TRNSYS) cannot be obtained directly from manufacturers' catalogs. However, Type 94 will automatically calculate them from available data. A second equivalent circuit model involving five mathematical parameters is available for amorphous/thin-film PV modules. Again, the component will determine these values from manufactures' catalog data. Type 94 also includes an optional incidence angle modifier correlation to calculate how the reflectance of the PV module surface varies with the angle of incidence of solar radiation.

Type 94 determines PV current as a function of load voltage. Other OUTPUTS include current and voltage at the maximum power point along the IV curve, open-circuit voltage, and short circuit current.

5.2.5.1.   Modeling options

A number of simulation options are available for the Type 94 Photovoltaic Array. The first of these is the mathematical model used to predict the electrical performance of the array. The "four-parameter" model should be used to for single crystal or polycrystalline PVs. This assumes that the slope of the IV curve at short-circuit conditions is zero. The four-parameter model is enabled whenever zero or a positive value is entered for PARAMETER 18. The second PV model, the "five-parameter model" is intended for amorphous or thin-film PVs. This produces a finite negative slope in the IV characteristic at the short-circuit condition. When a negative value is entered for PARAMETER 18, Type 94 takes this value to be the short-circuit IV slope and enables the five-parameter model. Sections 5.2.5.3 and 0 address the four-parameter model and five-parameter model.

The second option is whether or not the simulation should call the "incidence angle modifier" correlation. This correlation accounts for the increased reflective losses when   radiation is incident on the module at large angles. **If PARAMETER 16 is a positive value, TRNSYS will not call the incidence angle modifier**. In this case, PARAMETER 16 is the value of the transmittance-absorptance product ($\tau\alpha$) for all angles of incidence. **The angle modifier correlation is enabled when a negative value is entered for PARAMETER 16.** The magnitude of PARAMETER 16 is then the $\tau\alpha$ product for normal incidence; $\tau\alpha$ for other angles are calculated based on the normal value and an empirical correlation as described in Section 4 of the Mathematical Description.

Finally, the user may choose to enter a value for the module series resistance R_s or to call on Type 94 to calculate R_s from other manufacturers' data. **Type 94 reads the series resistance directly from PARAMETER 19 whenever a positive value is given. Zero of a negative value indicates that Type 94 should calculate R_s; the magnitude of PARAMETER 19 is irrelevant in this case.**

5.2.5.2. *Nomenclature*

β	Slope of PV array [degrees]
γ	Empirical PV curve-fitting parameter
ε_g	Semiconductor bandgap [eV]
η_c	Module conversion efficiency
μ_{Isc}	Temperature coefficient of short-circuit current [A/K]
μ_{Voc}	Temperature coefficient of open-circuit voltage [V/K]
θ	Angle of incidence for solar radiation [degrees]
$\tau\alpha$	Module transmittance-absorptance product
$\tau\alpha_{normal}$	Module transmittance-absorptance product at normal incidence
FLAG	Flag for PV convergence promotion algorithm
G_T	Total radiation incident on PV array
$G_{T,beam}$	Beam component of incident radiation
$G_{T,diff}$	Diffuse component of incident radiation
$G_{T,gnd}$	Ground-reflected component of incident radiation
$G_{T,NOCT}$	Incident radiation at NOCT conditions
$G_{T,ref}$	Incident radiation at reference conditions
I	Current
I_L	Module photocurrent
$I_{L,ref}$	Module photocurrent at reference conditions
I_o	Diode reverse saturation current
$I_{o,ref}$	Diode reverse saturation current at reference conditions
I_{sc}	Short-circuit current
$I_{sc,ref}$	Short-circuit current at reference conditions
I_{mp}	Current at maximum power point along IV curve
$I_{mp,ref}$	Current at maximum power point along IV curve, reference conditions
IAM	Dimensionless incidence angle modifier
k	Boltzmann constant [J/K]
NP	Number of modules in parallel in array
NS	Number of modules in series in array
N_s	Number of individual cells in module
P	PV output power
P_{max}	PV output power at maximum power point along IV curve
q	Electron charge constant
R_s	Module series resistance [Ω]
R_{sh}	Module shunt resistance [Ω]
T_c	Module temperature [K]
$T_{c,NOCT}$	Module temperature at NOCT conditions [K]
$T_{c,ref}$	Module temperature at reference conditions [K]
U_L	Array thermal loss coefficient
V	Voltage
V_{mp}	Voltage at maximum power point along IV curve
$V_{mp,ref}$	Voltage at maximum power point along IV curve, reference conditions
V_{oc}	Open-circuit voltage
$V_{oc,ref}$	Open-circuit voltage at reference conditions [V]

5.2.5.3. *Mathematical description (4-parameter model)*

The four-parameter equivalent circuit model was developed largely by Townsend [1989] and also detailed by Duffie and Beckman [1991]. The model was first incorporated into a TRNSYS component by Eckstein [1990], and much of the code in Type 94 comes from Eckstein's work. Type 94 employs this model for crystalline PV modules. **This model is used whenever TRNSYS PARAMETER 19 (the module's short-circuit IV slope) is set to zero or a positive value.**

The four parameter model assumes that the slope of the IV curve is zero at the short-circuit condition:

$$\left(\frac{dI}{dV}\right)_{v=0} = 0$$

Eq 5.2.5-1

This is a reasonable approximation for crystalline modules. The "four parameters" in the model are $I_{L,ref}$, $I_{o,ref}$, γ, and R_s. These are empirical values that cannot be determined directly through physical measurement. Type 94 calculates these values from manufactures' catalog data; these calculations are discussed in the following. The four-parameter equivalent circuit is shown in Figure 5.2.5–1.
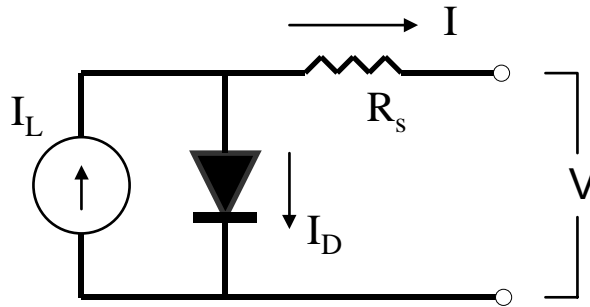
Figure 5.2.5–1: Equivalent electrical circuit in the 4-parameter model

DETERMINING PERFORMANCE UNDER OPERATING CONDITIONS

The IV characteristics of a PV change with both insolation and temperature. The PV model employs these environmental conditions along with the four module constants $I_{L,ref}$, $I_{o,ref}$, γ, and R_s to generate an IV curve at each timestep.

The current-voltage equation of circuit shown in Figure 5.2.5–1 is as follows:

$$I = I_L - I_o\left[\exp\left(\frac{q}{\gamma k T_c}(V + IR_s)\right) - 1\right]$$

Eq 5.2.5-2

R_s and γ are constants. The photocurrent I_L depends linearly on incident radiation:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}}$$

Eq 5.2.5-3

The reference insolation G_{ref} is given as TRNSYS PARAMETER 4. It is nearly always defined as 1000 W/m². The diode reverse saturation current I_o is a temperature dependent quantity:

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3$$

Eq 5.2.5-4

Eq 5.2.5-2 gives the current implicity as a function of voltage. Once I_o and I_L are found from Eq 5.2.5-3 and Eq 5.2.5-4, Newton's method is employed to calculate the PV current. In addition, an iterative search routine finds the current (I_{mp}) and voltage (V_{mp}) at the point of maximum power along the IV curve.

CALCULATING $I_{L,REF}$, $I_{O,REF}$, γ, AND R_S

The PARAMETERS for Type 94 include several values which must be read from manufacturers' PV module catalogs. The manufactures' values are used to determine the equivalent circuit characteristics $I_{L,ref}$, $I_{o,ref}$, γ, and R_s. These characteristics define an equivalent circuit that is employed to find the PV performance at each timestep, as described in Section 1.1. This section describes the algebra and calculation algorithms used to solve for the four equivalent circuit characteristics.

Three of these values, $I_{L,ref}$, $I_{o,ref}$, γ, may be isolated algebraically. The first step is to substitute the current and voltage into Eq 5.2.5-2 at the open-circuit, short circuit, and maximum power conditions:

$$0 = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{q}{\gamma k T_{c,ref}}V_{oc,ref}\right) - 1\right] - \frac{V_{oc,ref}}{R_{sh}}$$

Eq 5.2.5-5

$$I_{sc,ref} = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{qI_{sc,ref}R_s}{\gamma k T_{c,ref}}\right) - 1\right] - \frac{I_{sc,ref}R_s}{R_{sh}}$$

Eq 5.2.5-6

$$I_{mp,ref} = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{q}{\gamma k T_{c,ref}}\left(V_{mp,ref} + I_{mp,ref}R_s\right)\right) - 1\right] - \frac{V_{mp,ref} + I_{mp,ref}R_s}{R_{sh}}$$

Eq 5.2.5-7

In each case the "-1" term is may be dropped to simplify the algebra. This approximation has little influence on the right side of the equations since because the magnitude of I_o is very small, generally on the order of 10^{-6} A. Some rearrangement then yields the following three expressions which isolate $I_{L,ref}$, $I_{o,ref}$, γ:

$$I_{L,ref} \approx I_{sc,ref}$$

Eq 5.2.5-8

$$\gamma = \frac{q\left(V_{mp,ref} - V_{oc,ref} + I_{mp,ref}R_s\right)}{kT_{c,ref}\ln\left(1 - \frac{I_{mp,ref}}{I_{sc,ref}}\right)}$$

Eq 5.2.5-9

$$I_{o,ref} = \frac{I_{sc,ref}}{\exp\left(\dfrac{qV_{oc,ref}}{\gamma k T_{c,ref}}\right)}$$

Eq 5.2.5-10

At this point an additional equation is needed in order to determine the last unknown parameter. The fourth equation is derived by taking the analytical derivative of voltage with respect to temperature at the reference open-circuit condition. This analytical value is matched to the open-circuit temperature coefficient, a catalog specification:

$$\frac{\partial V_{oc}}{\partial T_c} = \mu_{voc} = \frac{\gamma k}{q}\left[\ln\left(\frac{I_{sc,ref}}{I_{o,ref}}\right) + \frac{T_c \mu_{isc}}{I_{sc,ref}} - \left(3 + \frac{q\varepsilon}{AkT_{c,ref}}\right)\right]$$

Eq 5.2.5-11

where $A = \dfrac{\gamma}{N_s}$

Type 94 uses an iterative search routine in these four equations to calculate the equivalent circuit characteristics. The first step is to set upper and lower bounds for the series resistance parameter R_s: physical constraints require the R_s value to lie between 0 and the value such that $\gamma = N_s$. The initial guess for R_s is midway between these bounds. γ and $I_{o,ref}$ are found from Eq 5.2.5-9 and Eq 5.2.5-10, while Eq 5.2.5-8 gives a trivial solution for $I_{L,ref}$. Type 94 then employs Eq 5.2.5-11 to compare the analytical and catalog values for μ_{voc}. When all other variables are held constant, the analytical value for μ_{voc} increases monotonically with series resistance [Townsend, 1989]. If the analytical voltage coefficient is less than the catalog value, the lower bound for R_s is reset to the present guess value. Likewise, the upper bound is set to the current value if the calculated μ_{voc} is too large. After resetting the upper or lower bound for R_s, a new guess value is found by averaging the bounds. This procedure repeats until R_s and γ converge. Note that for $I_{L,ref}$, $I_{o,ref}$, γ, and R_s are assumed to be constant and are calculated only on the first call in the simulation. Alternatively, the user may enter a known series resistance by entering a **positive** value for TRNSYS PARAMETER 18. In this case the iterative routine described above is skipped and the 3 equations mentioned here above allow to calculate $I_{L,ref}$, $I_{o,ref}$, and γ directly from the given value of R_s.

5.2.5.4. Mathematical description (5-parameter model)

The four-parameter model described here above does not adequately describe the current-voltage characteristics of amorphous silicon or thin-film PV modules. There is one major qualitative difference between the IV curves of crystalline and amorphous PVs. The short-circuit slope of the IV curve for crystalline modules is very close to zero, while slope for amorphous modules is generally finite and negative. **The five parameter model is called whenever TRNSYS PARAMETER 19 (the short-circuit IV slope) is set to a negative value.** This slope is not generally included in the list of module catalog specifications. However, it may be measured (e.g. with a ruler) if the manufacturer provides a module IV curve at reference conditions.

The five-parameter model adds a shunt resistance R_{sh} to the equivalent circuit used in the four-parameter model. This circuit is illustrated in Figure 5.2.5–2.
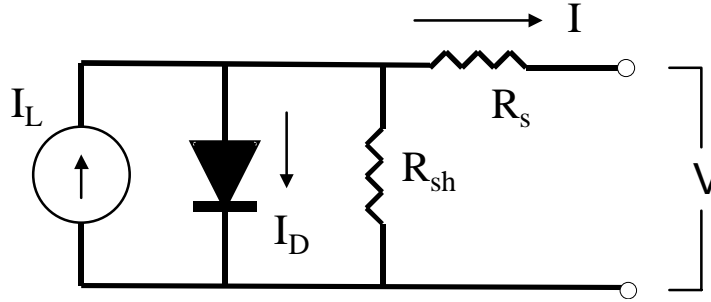
Figure 5.2.5–2: Equivalent electrical circuit in the 5-parameter model

The four-parameter model may be considered a special case of the five-parameter model in which R_{sh} is infinite. All the equations employed in the five-parameter model reduce to those described for the four-parameter model as the shunt resistance approaches infinity.

The current-voltage equation for the equivalent circuit in Figure 5.2.5–1 is:

$$I = I_L - I_o \left[\exp\left(\frac{q}{\gamma k T_c} \left(V + I R_s \right) \right) - 1 \right] - \frac{V + I R_s}{R_{sh}}$$

Eq 5.2.5-12

The algorithms and behavior of the five-parameter model are discussed in detail by Fry [1999].

DETERMINING PERFORMANCE UNDER OPERATING CONDITIONS

As in the four-parameter model, the insolation and temperature dependence of the PV module are given by:

$$I_L = I_{L,ref} \frac{G_T}{G_{T,ref}}$$

Eq 5.2.5-13

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}} \right)^3$$

Eq 5.2.5-14

However, the five-parameter model uses different equations to find the reference values $I_{o,ref}$ and $I_{L,ref}$. These equations are discussed in the following section.

CALCULATING $I_{L,REF}$, $I_{O,REF}$, γ, R_{SH}, AND R_S

The five-parameter model adds another equivalent circuit characteristic to the four-parameter model: the shunt resistance R_{sh}. The addition of this circuit element changes the equations used to find the other values ($I_{L,ref}$, $I_{o,ref}$, γ, and R_s) from available manufacturers' data.

Fry [1999] has shown that the negative reciprocal of the short-circuit IV slope closely approximates the shunt resistance:

$$R_{sh} \approx \frac{-1}{\left(\dfrac{dI}{dV}\right)_{V=0}}$$

Eq 5.2.5-15

This expression reduces the number of unknown quantities to four: $I_{L,ref}$, $I_{o,ref}$, γ, R_s. Rearranging Eq 5.2.5-12 (and neglecting the "-1") at open-circuit, short-circuit, and maximum power conditions yields the following expressions for $I_{L,ref}$, $I_{o,ref}$, γ:

$$I_{L,ref} = I_{sc,ref}\left(1 + \frac{R_s}{R_{sh}}\right)$$

Eq 5.2.5-16

$$I_{o,ref} = \frac{I_{L,ref} - \dfrac{V_{oc,ref}}{R_{sh}}}{\exp\left(\dfrac{q}{k\gamma T_{c,ref}}V_{oc,ref}\right)}$$

Eq 5.2.5-17

$$\gamma = \frac{\left(q\left(V_{mp,ref} - V_{oc,ref} + I_{mp,ref}R_s\right)\right)}{kT_{c,ref}\ln\left(\dfrac{I_{L,ref} - I_{mp,ref} - \dfrac{V_{mp,ref} + I_{mp,ref}R_s}{R_{sh}}}{I_{sc,ref} - \dfrac{V_{oc,ref}}{R_{sh}}}\right)}$$

Eq 5.2.5-18

At this point only R_s is needed to solve the system. An iterative search routine is used to find the correct values for R_s and γ by matching the analytical value for μ_{voc} to that given in the catalog. Differentiating Eq. 4.11.5.12 with respect to temperature at the open-circuit condition yields:

$$\frac{\partial V_{oc}}{\partial T_c} = \mu_{Voc} = \frac{\mu_{Isc} - \dfrac{I_{o,ref}}{T_c}\left(3 + \dfrac{q\varepsilon}{AkT}\right)\exp\left(\dfrac{q}{k\lambda T_{c,ref}}\right)}{\dfrac{q}{k\lambda T_{c,ref}}I_{o,ref}\exp\left(\dfrac{q}{k\lambda T_{c,ref}}V_{oc,ref}\right) + \dfrac{1}{R_{sh}}}$$

Eq 5.2.5-19

The search algorithm is similar to that described above for the four-parameter model.

5.2.5.5. *Module Operating Temperature (Thermal model)*

Type 94 uses temperature data from the standard NOCT (Nominal Operating Cell Temperature) measurements to compute the module temperature T_c at each timestep. The NOCT temperature ($T_{c,NOCT}$) is the operating temperature of the module with a wind speed of 1 m/s, no electrical load, and a certain specified insolation and ambient temperature [Beckman and Duffie, 1991]. The values for insolation $G_{T,NOCT}$ and ambient temperature $T_{a,NOCT}$ are usually 800 W/m^2 and 20° C. Type 94 uses the NOCT data to determine the ratio of the module transmittance-reflectance product to the module loss coefficient:

$$\frac{\tau\alpha}{U_L} = \frac{\left(T_{c,NOCT} - T_{a,NOCT}\right)}{G_{T,NOCT}}$$

<div align="right">Eq 5.2.5-20</div>

Assuming that this ratio is constant, the module temperature at any timestep is:

$$T_c = T_a + \frac{\left(1 - \dfrac{\eta_c}{\tau\alpha}\right)}{\left(\dfrac{G_T \tau\alpha}{U_L}\right)}$$

<div align="right">Eq 5.2.5-21</div>

η_c is the convesion efficiency of the module, which varies with ambient conditions. $T_{c,NOCT}$, $T_{a,NOCT}$, and $G_{T,NOCT}$ are set in PARAMETERS 12, 13, and 14 respectively. $\tau\alpha$ may be either a constant or the a value calculated from an incidence angle correlation, as described here below.

5.2.5.6.   Incidence Angle Modifier Correlation

Type 94 includes an optional "incidence angle modifier" routine. If this routine is used, an empirical correlation determines the transmittance-reflectance product ($\tau\alpha$) of the module at each timestep. This calculation is based on the module slope, and the angle of incidence and intensity of each radiation component (direct, diffuse, and ground-reflected). **TRNSYS PARAMETER 16 should be set to a negative value (between 0 and –1) to enable the incidence angle corrleation.** In this case, the *magnitude* of PARAMETER 16 equals $\tau\alpha$ at normal incidence. **PARAMETER 16 is set to a positive value (between 0 and 1) to disable the incidence modifier.** If the incidence angle modifier is disabled, PARAMETER 16 sets $\tau\alpha$ for all angles of incidence. For a given magnitude of PARAMETER 16, using the incidence angle modifier will always produce more a more conservative (and probably more accurate) estimate of system performance. For most locations, a given PV array will generate about 10% less energy over the course of a year when the incidence anlge routine is enabled. $\tau\alpha$ at normal incidence is not usually included in the list of manufacturer's parameters, although 0.9 is usually a good estimate.

Whether or not the modifier is used, the radiation incident on the PV is always multiplied by $\tau\alpha$ to account for reflective losses before Eq 5.2.5-3 is used to determine the photocurrent. The expression for the incidence angle modifier, taken from King et. al [1997] is:

$$IAM = 1 - \left(1.098x10^{-4}\right)\theta - \left(6.267x10^{-6}\right)\theta^2 + \left(6.583x10^{-7}\right)\theta^3 - \left(1.4272x10^{-8}\right)\theta^4$$

where $IAM \equiv \dfrac{\tau\alpha}{\tau\alpha_{normal}}$

<div align="right">Eq 5.2.5-22</div>

Here, θ is the angle of incidence in degrees, with θ = 0 indicating normal incidence. plots *IAM* as a function of θ.
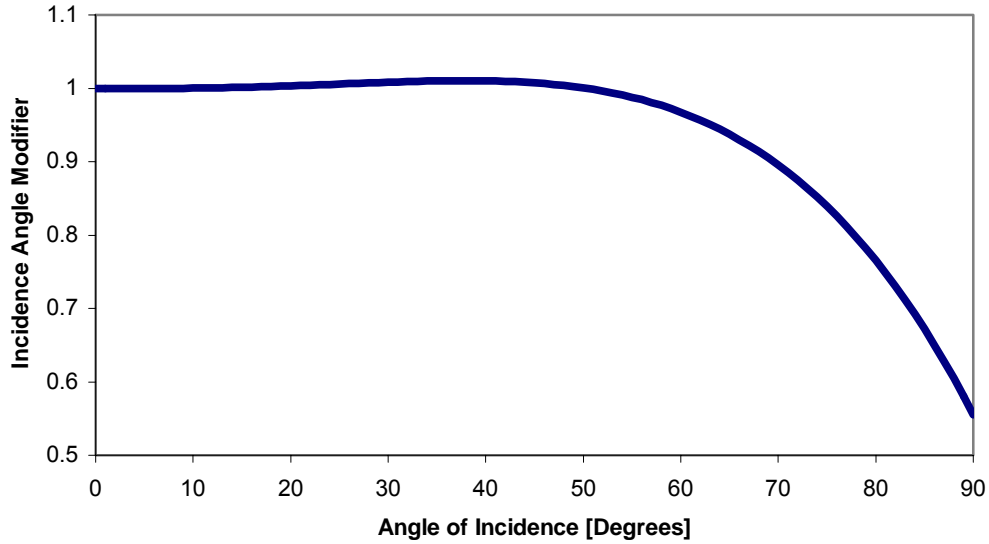
Figure 5.2.5–3: Incidence Modifier Angle of King et al., [1997]

The angle of incidence for the beam component of the solar radiation is obtained directly as an output from the Type 16 Solar Radiation Processor. However, Type 16 does not calculate effective angles of incidence for the diffuse and ground-reflected radiation components. Type 94 uses two additional correlations to find these effective angles of incidence. These correlations, developed by Duffie and Beckman [1991], are:

$$\theta_{eff,diff} = 59.7 - 0.1388\beta + 0.001497\beta^2 \qquad \textbf{Eq 5.2.5-23}$$

$$\theta_{eff,gnd} = 90 - 0.5788\beta + 0.002693\beta^2 \qquad \textbf{Eq 5.2.5-24}$$

β is the slope of the PV array in degrees. The total insolation on the array is found by summing the individual radiation components and multiplying them by their appropriate incidence angle modifiers:

$$G_{T,eff} = \tau\alpha_{norm}\left(G_{T,beam}IAM_{beam} + G_{T,diff}IAM_{diff} + G_{T,gnd}IAM_{gnd}\right) \qquad \textbf{Eq 5.2.5-25}$$

5.2.5.7.   Multi-Array Modules

The electrical calculations discussed for the four-parameter and five-parameter PV models deal only with a single module. Type 94 may be used to simulate arrays with any number of modules. TRNSYS PARAMETERS 10 and 11 define the number of modules in series (NS) and modules in parallel (NP) for the entire array. The total number of modules in the array is the product of NS and NP. When simulating a single module only, both NS and NP are set to 1. The single-module values for all currents and voltages discussed here above are multiplied by NP or NS to find values for the entire array. This approach neglects module mismatch losses.

5.2.5.8.   Convergence Issues for Various Applications

Type 94 may be used in direct-coupled systems in which the PV array is connected directly to a load or is linked to a battery to provide daily energy storage. In both of these applications, system performance at each timestep depends on the point of intersection between the IV graphs of the photovoltaic array and the load or battery. Alternatively, the maximum power output of Type 94 may be used in systems employing maximum power point tracking devices. One example of such an application is a grid-tied building-integrated PV system [Fry, 1999].

Eckstein [1990] has shown that in direct coupled systems the normal TRNSYS equation solvers sometimes fail to converge on the point of intersection between the PV array and load. He developed an alternative "convergence promoting algorithm," contained in Type 94, for applications in which the PV array is connected directly to a pump motor or other load. This algorithm uses a bisection search method to find the point at which the voltages of the PV and load are equal. It differs significantly from the standard "modified Euler" sequential substitution method TRNSYS employs to solve the system of equations produced by linking component INPUTS and OUTPUTS. **The PV convergence promotion algorithm may be activated by setting INPUT 4 of Type 94 to any nonzero value**. This is advisable for all direct-coupled systems.

INPUT 4 should be set to zero to disable the alternative convergence promotion. **The convergence promotion should always be disabled when the PV is charging a battery or when using a deck employing a TRNSYS ACCELERATE statement** (See Volume 07 for more details on the Accelerate statement)**.** In some systems, a controller component may direct the PV array to charge a battery at some times and to connect directly to a load at others. In this case, it is necessary for the controller to have an OUTPUT flag which may be connected to INPUT 4 of Type 94. Such a scheme will activate and deactivate convergence promotion appropriately.

Many applications employ maximum power point tracking (MPPT) devices which force the PV array to always operate at the point of maximum power along its IV curve. MPPTs are generally included in all grid-interactive inverters. When an MPPT is being used, some arbitrary load voltage must be chosen for INPUT 3 of Type 94. This voltage should be greater than zero and less than the open-circuit voltage of the array. OUTPUT 1, the PV current, is always calculated based on the load voltage Input. However, the maximum power point (OUTPUT 4) should be used for PV generation in MPPT systems. The value for OUTPUT 4 does not depend on the Input load voltage. **INPUT 4, the convergence promotion flag, should be set to zero for MPPT systems.**

5.2.5.9.   References

Duffie, John A. and William A. Beckman. *Solar Engineering of Thermal Processes*. New York: John Wiley & Sons, Inc., 1991.

Eckstein, Jürgen Helmut. *Detailed Modeling of Photovoltaic Components*. M. S. Thesis – Solar Energy Laboratory, University of Wisconsin, Madison: 1990.

Fry, Bryan*. Simulation of Grid-Tied Building Integrated Photovoltaic Systems.* M. S. Thesis – Solar Energy Laboratory, University of Wisconsin, Madison: 1999.

King, David L., Jay A. Kratochvil, and William E. Boyson. "Measuring the Solar Spectral and Angle-of-Incidence Effects on Photovoltaic Modules and Irradiance Sensors." *Proceedings of the 1994 IEEE Photovoltaics Specialists Conference*. Sept 30-Oct 3, 1997. pp. 1113-1116.

Townsend, Timothy U. *A Method for Estimating the Long-Term Performance of Direct-Coupled Photovoltaic Systems*. M. S. Thesis – Solar Energy Laboratory, University of Wisconsin, Madison: 1989.

5.2.6. Type 102: DEGS Dispatch controller

Type 102 calculates the number of Diesel Engine Generator Sets (DEGS) that have to operate and the power that each DEGS must provide to meet a given load.

5.2.6.1. Nomenclature

P_{Load}	[W]	Power required by the load
$P_{DEGS,max}$	[W]	Rated Power generated by one DEGS (all DEGS are identical)
$P_{DEGS,set}$	[W]	Power setpoint for each DEGS
X_{Low}	[-]	Minimum power ratio (P_{DEGS} / $P_{DEGS,max}$) for one DEGS
X_{Up}	[-]	Maximum power ratio (P_{DEGS} / $P_{DEGS,max}$) for one DEGS
N_{DEGS}	[-]	Number of operating DEGS
$N_{DEGS,min}$	[-]	Minimum number of DEGS operating at any time
$N_{DEGS,max}$	[-]	Maximum number of DEGS operating at any time
$P_{up,i}$	[W]	"call up" power level for DEGS i (see text)
$P_{down,i}$	[W]	"call down" power level for DEGS i (see text)

5.2.6.2. Mathematical description

DEGS are controlled in a master-slave setup. DEGS i can only be switched ON if DEGS (i-1) is ON. For each DEGS, a "call up" and "call down" power level can be defined (the load power at which the corresponding DEGS is respectively switched ON or OFF):

$$P_{up,i} = i \; P_{DEGS,max} \; X_{Low} \qquad \qquad \textbf{Eq 5.2.6-1}$$

$$P_{down,i} = i \; P_{DEGS,max} \; X_{Up} \qquad \qquad \textbf{Eq 5.2.6-2}$$

The dispatch controller simply loops through the DEGS and compare the power required by the load to $P_{up,i}$ and $P_{down,i}$.

NUMBER OF DEGS ON AND OFF

First DEGS:

- If P_{Load} > 0 then switch ON

Other DEGS (i = 2.. $N_{DEGS,max}$):

- If DEGS i was OFF and P_{Load} > $P_{up,i}$ then switch DEGS i ON
- If DEGS i was ON and P_{Load} < $P_{down,i}$ then switch DEGS i OFF

Note that the rules here above are overruled to have the number of operating DEGS between $N_{DEGS,min}$ and $N_{DEGS,max}$:

$$N_{DEGS,min} \leq N_{DEGS} \leq N_{DEGS,max} \qquad \textbf{Eq 5.2.6-3}$$

POWER OF EACH DEGS

The power of each DEGS is simply calculated as:

$$P_{DEGS,set} = P_{Load} / N_{DEGS} \qquad \textbf{Eq 5.2.6-4}$$

5.2.7. Type 120: Diesel Engine Generator Set

Type 120 is a mathematical model for a diesel engine generator set (DEGS). The model is based on an empirical relation (1st order polynomial) for the fuel consumption expressed as a function of the electrical power output (normalized). Electrical and fuel efficiencies are both calculated. The model can simulate a number of identical DEGS units.

Type 120 can be used to predict the performance of a specific DEGS, provided a fuel consumption curve is supplied. Alternatively, a generic model can be used to predict the performance of any DEGS in the power range 5-500 kW.

The generic model extrapolates from a reference fuel efficiency curve (average of 5 different DEGS). The generic model incorporates a correction factor derived from actual data measurements on DEGS for 20 remote area power systems (RAPS) with average operating powers in the range 5-186 kW [1].

The default fuel is diesel (liquid), but a database with fuel properties [2,3] included in Type 120 make it possible to calculate the equivalent fuel flow rates (liquid or gas) for 5 alternative fuels: liquefied gas (LPG), propane (C3H8), methane (CH4), natural gas, or hydrogen (H2). In the following, "diesel" is used to refer to the fuel.

Figure 5.2.7–1 shows an example of typical fuel efficiency and fuel consumption curves for Diesel Engine Generator Sets.
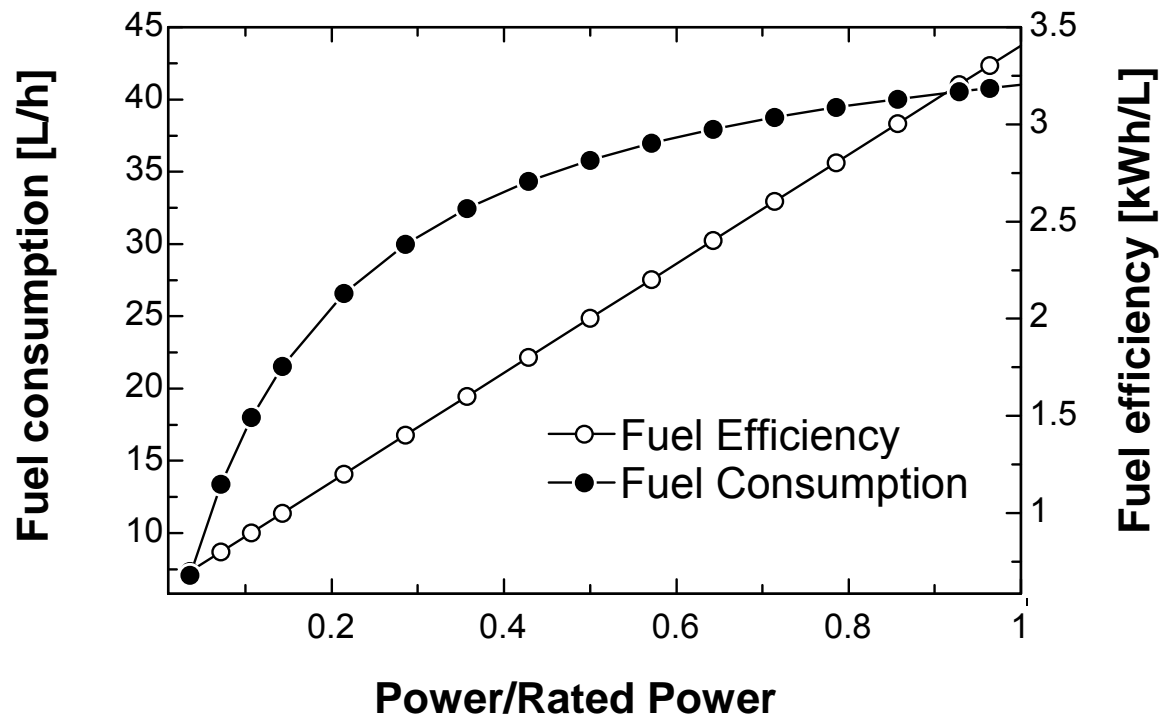
Figure 5.2.7–1: Typical fuel efficiency and fuel consumption curves for DEGS

5.2.7.1. Nomenclature

P_{DEGS}	[W]	DEGS Rated Electrical Power
$P_{DEGS,rated}$	[W]	DEGS Rated Electrical Power
N_{DEGS}	[-]	Number of identical DEGS units
X	[-]	Normalized power
$\dot{V}$	[m³/s]	Fuel volumetric flowrate
ρ	[kg/m³]	Fuel density
LHV	[J/kg]	Lower Heating Value of the fuel

5.2.7.2. Electric model

The normalized power is defined as:

$$X = P_{DEGS} / P_{DEGS,rated}$$

Eq 5.2.7-1

The electrical efficiency is:

$$\eta_{el} = \frac{P_{DEGS}}{\rho_{diesel} \cdot \dot{V}_{diesel`} \cdot LHV_{diesel}}$$

Eq 5.2.7-2

The Total Power output is:

$$P_{total} = N_{DEGS} P_{DEGS}$$

Eq 5.2.7-3

5.2.7.3. Fuel consumption

The fuel consumption is given as a curve fit:

$$\dot{V}_{diesel} = a + b \cdot X$$

Eq 5.2.7-4

The fuel efficiency is:

$$\eta_{fuel} = \frac{P_{DEGS}}{\dot{V}_{diesel}}$$

Eq 5.2.7-5

And the total fuel consumption is:

$$\dot{V}_{total} = N_{DEGS} \dot{V}_{diesel}$$

Eq 5.2.7-6

5.2.7.4. Thermal model

Total Thermal losses (wasted energy):

$$Q_{waste} = N_{DEGS} \; P_{DEGS} \; (100 - \eta_{el}) \, / \, \eta_{el}$$

<div align="right">**Eq 5.2.7-7**</div>

5.2.7.5. External data file

Type 120 optionally reads a fuel consumption curve from a data file. An example is provided in "Examples\Data Files". The data file should have the following information:

```
<Nb of DEGS>

<No of the DEGS>, <Name of DEGS>
<Rated power> <coefficient A [l/h]> <coefficient B [l/h]>
```
For each DEGS

EXAMPLE

```
3
  1,Generic Model Reference Curve (40 kW) (DEGS2.EES)
  40.0     2.0780  9.2521
  2,Volvo Penta D 100 B Gen Set (72 kW) (Neumann, 1987)
  72.0     4.2419  16.4926
  3,MAN Diesel-Motor D 0224 ME (32 kW) (Pryor, 2001)
  32.0     1.2945  7.4180
```

5.2.7.6. References

1. Lloyd C. R. (1999) Assessment of diesel use in remote area power supply. Internal report prepared for the Australian Greenhouse Office, Energy Strategies, Canberra.

2. Adler U., Bauer H., Bazlen W., Dinkler F. and Herwerth M. (Eds) (1986) Automotive Handbook. 2nd edn, Robert Bosch GmbH, Stuttgart.

3. McCarthy R. D. (1982) Mathematical models for the prediction of liquefied-natural-gas densities. Thermophysical Properties Division, National Bureau of Standards, USA.

5.2.8.   Type 175: Power conditioning unit

Type 165 is a mathematical model for a power conditioning unit. The model is based on empirical efficiency curves for electrical converters (DC/DC) or inverters (DC/AC or AC/DC). The empirical relationship used in Type 175 was first proposed by [1] and further improved by [2]. The model is in agreement with related literature [3].

5.2.8.1.   Nomenclature

P_{in}	[W]	Power entering the conditioner
P_{out}	[W]	Power leaving the conditioner
P_{loss}	[W]	Power losses of the conditioner
P_0	[W]	Idling power
P_n	[W]	Nominal (rated) power
U_s	[V]	Setpoint voltage
U_{out}	[V]	Output voltage
R_i	[Ω]	Internal resistance
R_{ipn}	[V²]	Internal resistance constant = $R_i P_n$
η	[-]	Electric efficiency
I_{out}	[A]	Output current

5.2.8.2.   Electrical model

The power conditioner can have either output or Input power as Input for the calculations (output if the system is connected to a load, or Input if the system is connected to an electric power source). MODE=1 indicates that the power source is known, while MODE=2 indicates it is an output.

Power conditioners are devices that can invert DC power to AC power, and/or vice versa, or they function as DC/DCconverters. In a Stand Alone Power Systems (SAPS) consisting of both DC power producing and DC power consuming components, DC/DCconverters are sometimes needed to transfer DC power from one voltage to another. This is particularly true if there is a large mismatch between the I-U characteristics of the various components.

In a SAPS based on a natural energy source, such as solar or wind energy, the system Input power varies continuously with time. The output characteristics of a PV array, wind turbine, or hydro turbine (run off river) have peak power points that depend on solar insolation and cell temperature, wind speeds, and water flow rates, respectively. Therefore, it may be advantageous to use a maximum power point tracker (MPPT) to utilize the Input power source to its fullest capability [3].

The power loss (P_{loss}) for a power conditioner is mainly dependent on the electrical current running through it. Laukamp, [1], proposed a three-parameter expression to describe the power loss for a power conditioner:

$$P_{loss} = P_{in} - P_{out} \qquad\qquad\qquad \text{Eq 5.2.8-1}$$

$$P_{in} - P_{out} = P_0 + (U_S / U_{out}) P_{out} + (R_{ipn} / U_{out}{}^2) P_{out}{}^2 \qquad\qquad \text{Eq 5.2.8-2}$$

A convenient relationship between the Input power P_{in} and output power P_{out} can be derived by normalizing Eq 5.2.8-2 with respect to the nominal (maximum) power P_n of the power conditioner:

$$\frac{P_{in}}{P_{nom}} = \frac{P_0}{P_{nom}} + \left[1 + \frac{U_s}{U_{out}} \right] \cdot \frac{P_{out}}{P_{nom}} + \frac{R_{ipn}}{U_{out}{}^2} \cdot P_{nom} \cdot \left[\frac{P_{out}}{P_{nom}} \right]^2 \qquad \text{Eq 5.2.8-3}$$

In Type 175, either the Input power P_{in} or the output power P_{out} can be specified as Inputs. If P_{out} is Input, then Eq 5.2.8-3 is used directly. However, if P_{in} is Input, then an expression analytically derived from Eqn.3 is used. This makes the model numerically very robust. The efficiency of the power conditioner is simply:

Electric efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \qquad\qquad\qquad \text{Eq 5.2.8-4}$$

Current ouput:

$$I_{out} = \frac{P_{out}}{U_{out}} \qquad\qquad\qquad \text{Eq 5.2.8-5}$$

5.2.8.3.   Additional information

Type 175 is also described in an EES-based executable program distributed with TRNSYS 16: %TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.2.8.4.   References

1. Laukamp H. (1988) Inverter for photovoltaic systems (in German). User-written TRNSYS source code., FraunhoferInstitute für Solare Energiesysteme, Freiburg im Breisgau, Germany.

2. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

3. Snyman D. B. and Enslin J. H. R. (1993) An experimental evaluation of MPPT converter topologies for PV installations. Renewable Energy 3 (8), 841-848.

5.2.9.   Type 180: Photovoltaic array (with data file)

Type180 is a mathematical model for a photovoltaic (PV) generator, based on an equivalent circuit of a one-diode model, also known as the 5-parameter model (see Figure 5.2.9–1). The model is primarily intended for PV-arrays consisting of silicon cells, but can also be used for other types of materials. The electrical model used in Type180 is described in [1]. A dynamic thermal model has also been included [2,3].
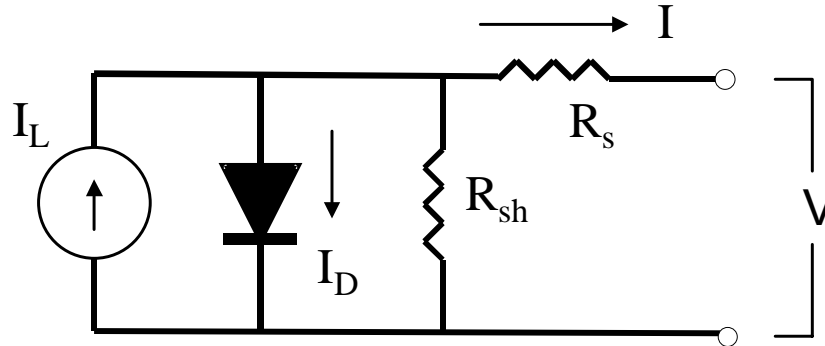
Figure 5.2.9–1: PV cell equivalent electrical circuit (one diode model)

The non-linear equations in section 5.2.9.6 can be solved for any cell temperature Tcell and irradiance GT. In the Type180 model this is done numerically by using the Newton-Raphson iteration [4] - for a given voltage U, the model calculates the current I. A maximum power point tracker (MPPT) algorithm which finds the maximum power point automatically is also included in Type180. Since the P-U curve of a PV generator is a unimodal function, a golden section search algorithm [9] can be used to find the maximum power point. This makes the MPPT algorithm in Type180 very robust.

The main difference between Type 180 and Type 94 is that the parameters of the PV array are read in a data file (see section 5.2.9.3).

5.2.9.1.   Electrical model

CURRENT – VOLTAGE CHARACTERISTIC

The PV generator model developed for this study (Type180) is based on the findings of [5, 6, 7] on PV array modeling. Detailed examples and methods on how to apply these models are found in [1]. An equivalent circuit of the one-diode model [8] can be used in the modeling of an individual cell, of a module consisting of several cells, or of an array consisting of several modules. The electrical model described in this context is for a module with a number of cells in series.

In practice, PV arrays often consist of modules in series and parallel. Hence, Type180 is configured so that the user must specify the number of cells in series per module, the number of modules in series in the array, and the number of modules in parallel per array.

The relationship between the current I_{cell} and voltage U of the equivalent circuit can be found by equating the light current I_L, diode current I_D, and shunt current I_{sh} to the operation current I [1]:

CELL CURRENT

$$I_{cell} = I_L - I_D - I_{sh}$$

Eq 5.2.9-1

With:

$$I_L = \frac{G_T}{G_{T,ref}} \cdot (I_{L,ref} + \mu_{Isc} \cdot (T_{cell} - T_{cell,ref}))$$

Eq 5.2.9-2

$$I_{sh} = \frac{U_{cell} + I_{cell} \cdot R_s}{R_{sh}}$$

Eq 5.2.9-3

$$I_D = I_o \cdot \left[\exp\left(\frac{U_{cell} + I_{cell} \cdot R_s}{a} \right) - 1 \right]$$

Eq 5.2.9-4

See the appendix (section) for more details on the electrical model.

OPEN CIRCUIT VOLTAGE

$$U_{oc} = a \cdot \ln\left[\frac{I_L}{I_o} \right]$$

Eq 5.2.9-5

CELL POWER

$$P_{cell} = I_{cell} \cdot U_{cell}$$

Eq 5.2.9-6

ARRAY POWER

$$P_{tot} = N_s \cdot I_{cell} \cdot U_{cell}$$

Eq 5.2.9-7

A measure of performance of the PV cell, is defined as the ratio of the electric energy produced over the incident of solar energy (G_T is the incident solar radiation):

CELL EFFICIENCY

$$\eta = \frac{P_{cell}}{A_{cell} \cdot G_T}$$

Eq 5.2.9-8

5.2.9.2. Thermal model

The temperature T_{cell} of the PV cell(s) depends mainly on the ambient conditions, but also on the operation of the PV module. In principle, the solar energy that is absorbed by the module is converted partly into thermal energy and partly into electrical energy, which is removed through the external circuit. The thermal energy is dissipated by a combination of convection, conduction, and radiation. The rate at which these heat transfer processes occur depends largely on the design of the PV system. For instance, the cells may be cooled artificially by passing air or water on the backside of the module. If a PV module is mounted directly onto the top of a roof, less natural cooling on the backside occurs compared to when it is mounted on a structure at some distance away from the roof. The thermal model for the PV generator developed and incorporated into Type180 was based on the energy balance proposed by [1]. The advantage of this model, as opposed to more detailed models, is that relatively little information is needed about the design of the PV system. This is because all of the heat losses to the surroundings are lumped together

into an overall heat loss coefficient U_L. A heat balance of a PV cell can be determined using simple or complex thermal models, depending on the need for accuracy. Assuming a lumped thermal capacitance model, the overall thermal energy balance can be expressed as a linear, first order, non-homogeneous differential equation.

Type 180 can operate in 3 modes for the cell temperature:

- TCMODE=1: The temperature of the PV-array is given as an Input
- TCMODE = 2: The cell temperature is calculated using an overall heat loss coefficient (U_L)
- TCMODE = 3: The cell temperature is calculated based on an overall heat loss coefficient (U_L) and a lumped thermal capacitance (C_T)

OVERALL HEAT LOSS COEFFICIENT

In TCMODE = 2, U_L is calculated form the NOCT (Normal Operating Cell Temperature) conditions:

$$U_L = taualpha \cdot \left[\frac{G_T}{T_{c,NOCT} - T_{amb,NOCT}} \right]$$
Eq 5.2.9-9

In TCMODE = 3, U_L is given as an Input

ENERGY BALANCE

$$C_t \cdot dTdt = \dot{Q}_{rad} - \dot{Q}_{el} - \dot{Q}_{loss}$$
Eq 5.2.9-10

$$\dot{Q}_{rad} = taualpha \cdot G_T$$
Eq 5.2.9-11

$$\dot{Q}_{el} = \eta \cdot G_T$$
Eq 5.2.9-12

$$\dot{Q}_{loss} = U_L \cdot (T_{cell} - T_{amb})$$
Eq 5.2.9-13

The term on the left-hand side of Eq 5.2.9-10 is the thermal energy stored in the PV module. The three terms on the right hand side are the heat gains due to absorption of solar radiation (Q_{rad}), electrical energy produced by the PV module (Q_{el}), and heat losses to the ambient (Q_{loss}), respectively.
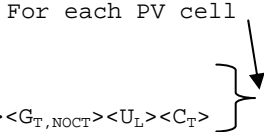
5.2.9.3. External data file

Type 180 reads the PV cell parameters in a data file. The data file should have the following information:

For each PV cell

```
<Nb of PV cells>

<No of the PV cell>, <Name of PV cell>
<I_sc,ref><U_oc,ref><T_c,ref><G_T,ref><I_mp><U_mp><μ_I,sc><μ_U,oc><T_a,NOCT><T_c,NOCT><G_T,NOCT><U_L><C_T>
```

The parameters that must be provided are described here below (note: see section 5.2.9.6, here below, for an explanation of the parameters):

No	Parameter	Units	Description
1	$I_{sc,ref}$	A	Short circuit current at reference
2	$U_{oc,ref}$	V	Open circuit voltage at reference
3	$T_{c,ref}$	°C	Reference cell temperature
4	$G_{T,ref}$	W/m²	reference solar radiation
5	I_{mp}	A	Maximum Power Point current at reference
6	U_{mp}	V	Maximum Power Point voltage at reference
7	$\mu_{I,sc}$	A/K	Short circuit current temperature coefficient
8	$\mu_{U,oc}$	V/K	Open circuit voltage temperature coefficient
9	$T_{a,NOCT}$	°C	Ambient temperature at NOCT – used in TCMODE 2
10	$T_{c,NOCT}$	°C	Cell temperature at NOCT– used in TCMODE 2
11	$G_{T,NOCT}$	W/m²	Solar radiation at NOCT– used in TCMODE 2
12	U_L	W/m²-K	Overall Loss coefficient– used in TCMODE 3
13	C_T	J/m²-K	Thermal capacitance (per unit area) – used in TCMODE 3

EXAMPLE

```
3
  1,Solarex MSX-64
  4.00 21.30 25.0 1000.0 3.66 17.50 3.0E-3 -0.0730 20.0 49.0 800.0 0.0 0.0
  2, Kyocera LA 44/63S (IFE)
  3.30 25.91 25.0 1000.0 3.03 20.7 2.20E-3 -0.095  20.0 50.0 800.0 0.0 0.0
  3, Flagsol (KFA) 150 cell module (29.06.97)
  2.66 87.72 25.0 1000 2.448 70.73 1.48E-3 -0.332 20.0 44.0 800.0 30.0  50000.0
```

5.2.9.4. Additional information

Type 180 is also described in an EES-based executable program distributed with TRNSYS 16: %TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.2.9.5. References

1. Duffie J. A. and Beckman W. A. (1991) Solar Engineering of Thermal Processes. 2nd edn, Wiley Interscience, New York.

2. Ulleberg Ø. (1997) Simulation of autonomous PV-H2 systems: analysis of the PHOEBUS plant design, operation and energy management. In Proceedings of ISES 1997 Solar World Congress, August 24-30, Taejon.

3. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

4. Cheney W. and Kincaid D. (1985) Numerical Mathematics and Computing, 2nd edn. Brooks/Cole Publishing Co., Monterey, California

5. Rauschenbach H. S. (1980) Solar Cell Array Design Handbook: the Principles and Technology of Photovoltaic Energy Conversion, Van Nostrand Reinhold, New York.

6. Townsend T. U. (1989) A Method for Estimating the Long-term Performance of Direct-Coupled Photovoltaic Systems, M.Sc. thesis, University of Wisconsin-Madison, U.S.A.

7. Eckstein J. H. (1990) Detailed Modelling of Photovoltaic System Components, M.Sc. thesis, University of Wisconsin- Madison, U.S.A.

8. Loferski J. J. (1972) An introduction to the physics of solar cells. In Solar Cells-Outlook for Improved Efficiency, pp. 47-53, National Academy of Sciences-Space Science Board, Washington, DC.

9. Mathews J. H. (1992) Numerical Methods for Mathematics, Science, and Engineering, 2nd edn. Prentice-Hall, New Jersey.

5.2.9.6. Appendix: Electrical model

Light current = short circuit current at reference conditions:

$$I_{L,ref} = I_{sc,ref}$$ **Eq 5.2.9-14**

Diode reverse saturation current:

$$I_{o,ref} = I_{L,ref} \cdot \mathbf{exp}\left[\frac{-U_{oc,ref}}{a_{ref}}\right]$$ **Eq 5.2.9-15**

Ideality factor at reference conditions:

$$a_{ref} = \frac{\mu_{Uoc} \cdot T_{cell,ref} - U_{oc,ref} + e_{gap} \cdot N_s}{\mu_{Isc} \cdot \dfrac{T_{cell,ref}}{I_{L,ref}} - 3}$$ **Eq 5.2.9-16**

Series resistance (assumed independent of temperature, $R_s = R_{s,ref}$):

$$R_s = \frac{a_{ref} \cdot \mathbf{ln}\left[1 - \dfrac{I_{mp,ref}}{I_{L,ref}}\right] - U_{mp,ref} + U_{oc,ref}}{I_{mp,ref}}$$ **Eq 5.2.9-17**

Temperature dependence:

$$\frac{a}{a_{ref}} = \frac{T_{cell}}{T_{cell,ref}}$$ **Eq 5.2.9-18**

$$\frac{I_o}{I_{o,ref}} = \left[\frac{T_{cell}}{T_{cell,ref}}\right]^3 \cdot \mathbf{exp}\left[e_{gap} \cdot \frac{N_s}{a_{ref}} \cdot \left(1 - \frac{T_{cell,ref}}{T_{cell}}\right)\right]$$ **Eq 5.2.9-19**

$$\eta_{mp} = \eta_{mp,ref} + \mu_{P,mp} \cdot (T_{cell} - T_{cell,ref})$$ **Eq 5.2.9-20**

$$\mu_{P,mp} = \eta_{mp,ref} \cdot \frac{\mu_{Uoc}}{U_{mp,ref}}$$ **Eq 5.2.9-21**

Maximum power point:

$$\eta_{mp,ref} = I_{mp,ref} \cdot \frac{U_{mp,ref}}{A_{cell} \cdot G_{T,ref}}$$ **Eq 5.2.9-22**

$$\eta_{mp} = \frac{P_{mp}}{A_{cell} \cdot G_T}$$ **Eq 5.2.9-23**

$$P_{mp,approx} = I_{mp} \cdot U_{mp}$$ **Eq 5.2.9-24**

$$I_{mp} = I_L - I_o \cdot \left[\mathbf{exp}\left(\frac{U_{mp} + I_{mp} \cdot R_s}{a}\right) - 1\right] - \left[\frac{U_{mp} + I_{mp} \cdot R_s}{R_{sh}}\right]$$ **Eq 5.2.9-25**

$$\delta_{P,mp} = P_{mp,approx} - P_{mp}$$ **Eq 5.2.9-26**

5.2.10. Type 185: Lead-acid battery with gassing effects

Type185 is a quasi-static mathematical model of lead-acid battery, or Pb-accumulator. The model uses a simple equivalent circuit that relates the electrical currents, voltages, resistance (related to the concentration-overvoltage), and capacity. The main features of the model include gassing current losses, polarization effects (during charging and discharging), and calculation of equilibrium voltage at various states of charge [1, 2].

A secondary lead-acid battery, or Pb-accumulator, is an electrochemical device that can transform electrical energy into stored chemical energy (charge) and by reversing the process, release the energy again (discharge). In a lead-acid battery this is mainly possible due to the transfer of lead ions to and from the electrodes.

Figure 5.2.10–1 shows an example of typical current – voltage curves for lead-acid batteries.
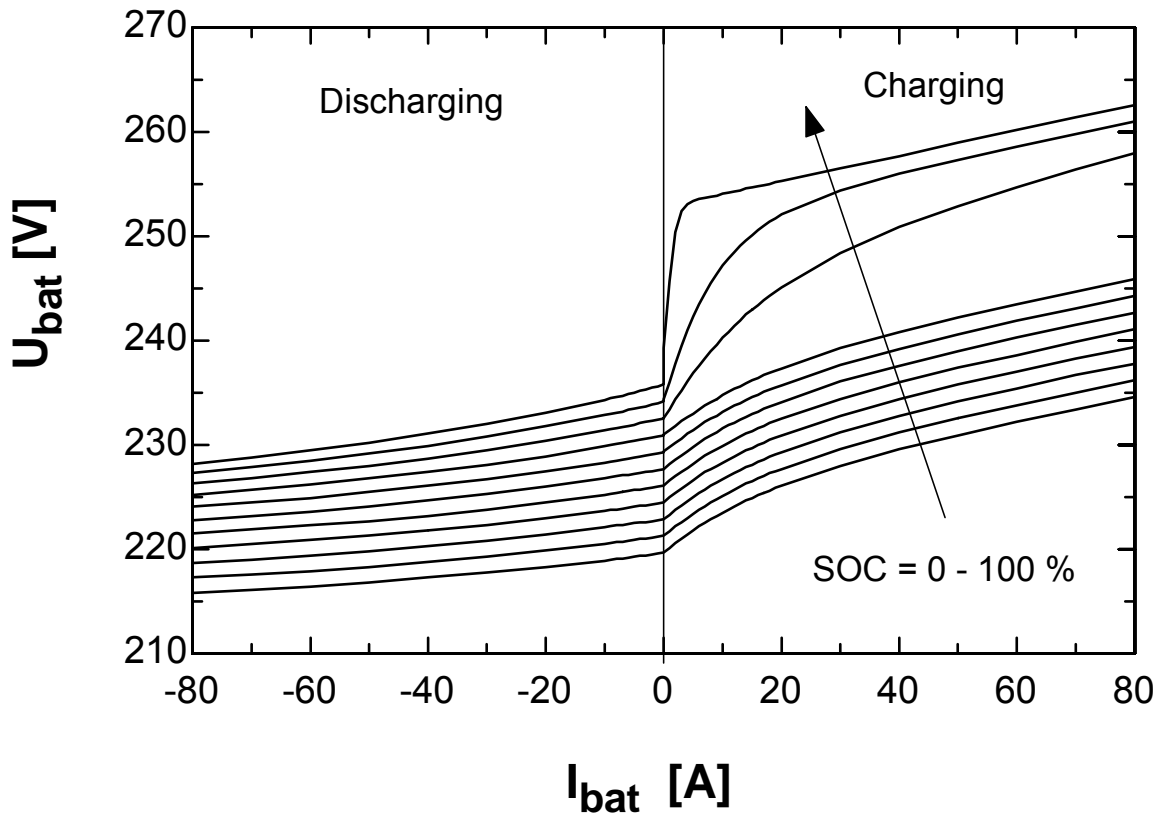
Figure 5.2.10–1: Typical current-voltage curves for a lead-acid battery

5.2.10.1. Chemical reactions

At discharge (the direction of the chemical reactions described below are for discharge, unless stated otherwise), the total reaction for the lead-acid battery is:
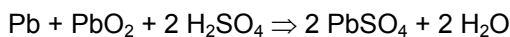
$$Pb + PbO_2 + 2\,H_2SO_4 \Rightarrow 2\,PbSO_4 + 2\,H_2O$$ **Eq 5.2.10-1**

In reality, this discharge reaction (Eq 5.2.10-1) is the sum of the reactions occurring at the negative and positive electrodes. The basic charge transfer reactions and the complete reactions taking place at the electrodes during discharging of a lead battery with sulfuric acid (H_2SO_4) as electrolyte.

Anode: $Pb + HSO_4^- \Rightarrow PbSO_4 + 2\ e^- + H^+$ **Eq 5.2.10-2**

Cathode: $PbO_2 + HSO_4^- + 2\ e^- + 3\ H^+ \Rightarrow PbSO_4 + 2\ H_2O$ **Eq 5.2.10-3**
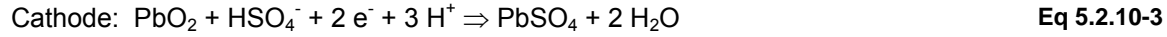
During discharging, lead ions (Pb^{2+}) are dissolved at the negative electrode, and a corresponding number of electrons ($2e^-$) are removed from the electrode as negative charge. Due to the limited solubility of Pb^{2+} ions in sulfuric acid (H_2SO_4), the dissolved ions form lead sulfates ($PbSO_4$) on the electrode. This occurs immediately after the dissolution process.

The discharging process at the positive electrode proceeds in a similar manner. That is, Pb^{2+} ions are formed by Pb^{4+} ions by adding a negative charge ($2e^-$). These lead ions are dissolved immediately to form lead sulfate ($PbSO_4$). In addition, water (H_2O) is formed at the positive electrode during discharging, because oxygen ions (O^{2-}) are released from the lead dioxide (PbO_2) and they combine with the protons (H^+) of the sulfuric acid.

5.2.10.2. Voltage model

In a battery that consists of several cells in series the individual cell U_{cell} voltage is simply the terminal voltage $U_{bat} = n_{cells}\ U_{cell}$, where n_{cells} is the number of cells in series. The cell voltage U_{cell} is found by adding the equilibrium voltage U_{equ} and the polarization voltage U_{pol}.

$$U_{cell}\ =\ U_{eq}\ +\ U_{pol}$$ **Eq 5.2.10-4**

The equilibrium voltage is defined as the resting voltage (across the terminals) after no current has passed in/out of the battery for a substantial period of time (several hours). This voltage can be assumed to be a linear function of the state of charge SOC of the battery:

$$U_{eq}\ =\ U_{eq,0}\ +\ U_{eq,1}\ \cdot\ SOC`$$ **Eq 5.2.10-5**

The polarization, or overvoltage, depends heavily on whether the battery is being charged or discharged. These effects can be estimated by non-linear expressions using empirically derived battery parameters. The polarization during charging (ch) can be expressed as:

$$U_{pol,ch}\ =\ U_{ch}\ \cdot\ a_{ch}\ \cdot\ \left[1\ -\ \exp\left(\frac{-I_{q,n}}{b_{ch}}\right)\ +\ c_{ch}\ \cdot\ I_{q,n}\right]$$ **Eq 5.2.10-6**

where U_{ch} is a constant, a_{ch}, b_{ch}, and c_{ch} are coefficients that are dependent on SOC, and $I_{q,n}$ is described in Eqn.7. (Note that the Eqn.3 and Eqn.4 both are functions of the normalized main reaction current $I_{q,n}$ and the SOC). Saupe [1] found a set of empirical expressions for a_{ch}, b_{ch}, and c_{ch} based on battery experiments performed on a solar battery.

The polarization, or overvoltage, during discharging (dch) , which is dependent on the main current Iq,norm and the state of charge SOC, can be calculated from:

$$U_{pol,dch}\ =\ U_{dch}\ \cdot\ f_{dch}\ \cdot\ g_{dch}$$ **Eq 5.2.10-7**

Where U_{dch} is a constant, while f_{dch} and g_{dch} are dimensionless coefficients dependent on $I_{q,n}$ and SOC, respectively:

$$f_{dch} = 1 - \exp\left[\frac{-I_{q,n}}{b_{dch}}\right] + c_{dch} \cdot I_{q,n} \qquad \textbf{Eq 5.2.10-8}$$

$$g_{dch} = 1 + (g_{100} - 1) \cdot \exp\left[\frac{SOC - 100}{k_{100}}\right] \qquad \textbf{Eq 5.2.10-9}$$

5.2.10.3. Current model

The main reaction current I_q is simply the difference between the current at the battery terminal I_{bat} and the gassing current I_{gas}. The battery current is an Input and the gassing current can be found by the following expression proposed by Schöner [3]:

$$I_{gas} = I_{10} \cdot g_0 \cdot \exp\left[\frac{U_{cell}}{g_1} - \frac{g_2}{T_{bat}}\right] \qquad \textbf{Eq 5.2.10-10}$$

The main reaction current is then normalized with respect to the 10-hour discharge current of the battery I_{10}, where $I_{10} = Q_{bat,nom}/10h$ and $Q_{bat,nom}$ is the nominal battery capacity in Ah. Since the charging current is positive and the discharge current is negative, the absolute value of the normalized current is used in the calculations:

$$I_{10} = \frac{Q_{bat,nom}}{10} \qquad \textbf{Eq 5.2.10-11}$$

$$I_{q,n} = \left|\frac{I_q}{I_{10}}\right| \qquad \textbf{Eq 5.2.10-12}$$

$$I_q = I_{bat} - I_{gas} \qquad \textbf{Eq 5.2.10-13}$$

$$I_{bat} = \frac{Bat_{load`}}{U_{bat}} \qquad \textbf{Eq 5.2.10-14}$$

Power dissipated as a result of gassing:

$$P_{gas} = I_{gas} \cdot U_{bat} \qquad \textbf{Eq 5.2.10-15}$$

Power of charge (+) or discharge (-):

$$P_{bat} = U_{bat} \cdot I_{bat} \qquad \textbf{Eq 5.2.10-16}$$

5.2.10.4. Battery capacity

The battery capacity Q_{bat} for a given time step, can simply be found from the main current I_q and the battery capacity from the previous time step ($Q_{bat,ini}$). Alternatively, $Q_{bat,ini}$ can be derived from the state of charge for the previous time step SOC_{ini} and the nominal battery capacity $Q_{bat,nom}$ (given in Ah). That is,

Previous capacity:

$$Q_{bat,ini} = Q_{bat,nom} \cdot SOC_{ini`} \qquad \textbf{Eq 5.2.10-17}$$

Current capacity

$$Q_{bat} = Q_{bat,ini} + I_q \cdot \Delta t$$ **Eq 5.2.10-18**

Battery state of charge

$$SOC = \frac{Q_{bat`}}{Q_{bat,nom}}$$ **Eq 5.2.10-19**

5.2.10.5. External data file

Type 185 reads the battery parameters in a data file. The data file should have the following information:

```
<Nb of batteries>

<No of the battery>, <Name of battery>
<g₀><g₁><g₂><Uequ,0><Uequ,1><Uch><Udch><bdch><cdch><g₁₀₀><k₁₀₀>
```
For each battery

The parameters that must be provided are described here below (see text for an explanation of the parameters):

No	Parameter	Units	Description
1	g_0	-	Gassing current constant
2	g_1	V	Gassing current constant
3	g_2	K	Gassing current constant
4	$U_{equ,0}$	V	Equilibrium cell voltage at SOC = 0
5	$U_{equ,1}$	V/dec	Equilibrium cell voltage gradient
6	U_{ch}	-	Parameter for overvoltage during charging
7	U_{dch}	-	Parameter for overvoltage during discharging
8	b_{dch}	-	Discharge overvoltage constant
9	c_{dch}	-	Discharge overvoltage constant
10	g_{100}	-	Parameter for overvoltage at SOC = 1 (100%)
11	k_{100}	-	Parameter for overvoltage at SOC = 1 (100%)

EXAMPLE

```
4
  1,Pb-Accumulator Hagen-CSM Type OCSM (KFA)
  1.6E-6 81.2E-3 6000. 1.997 0.1464 52.0E-3 -27.03E-3 0.4085 0.5610 2.36 53.0
  2,Solar Battery Tubular plate 50 Ah (Saupe)
  2.162E-4 86.5E-3 6273. 2.007 0.098 48.92E-3 -27.03E-3 0.4085 0.5610 2.36 8.7
  3,Varta Bloc 428 (Lyklingholmen)
  2.162E-4 86.5E-3 6273. 1.968 0.112 75.0E-3 -40.0E-3 0.4085 0.5610 2.36 10.0
  4,Varta Bloc 428 (Lyklingholmen)
  2.162E-4 86.5E-3 6273. 1.85 0.25 75.0E-3 -40.0E-3 0.4085 0.5610 2.36 10.0
```

5.2.10.6. Additional information

Type 185 is also described in an EES-based executable program distributed with TRNSYS 16: %TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.2.10.7. References

1. Saupe G. (1993) Photovoltaic Power Supply System with Lead-Acid Battery Storage: Analysis of the Main Problems, System Improvements, Development of a Simulation Model for a Battery (in German). PhD thesis, University of Stuttgart, Germany.

2. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

3. Schöner H. P. (1988) Evaluation of the Electrical Behavior of Lead-Batteries during Discharging and Charging (in German). Ph.D. thesis, Technical University of Aachen, Germany.

5.2.11. Type 188: AC-busbar

The AC-busbar is a simple power balance between the different components of a renewable energy / Hydrogen power system and the electric grid. Its Inputs are the power from / to different components of the system, and its output is the power from / to the grid. The grid voltage is assumed to be constant.

5.2.11.1. Nomenclature

P_{WECS}	[W]	Power from the Wind Energy Conversion System (wind turbine)
P_{PV}	[W]	Power from the Photovoltaic (PV) system
P_{FC}	[W]	Power from the Fuel cell
P_{RE}	[W]	Power from additional (unspecified) Renewable Energy sources
P_{other}	[W]	Power from other sources (e.g. Diesel Generator Sets, etc.)
P_{ely}	[W]	Power to the electrolyzer (Hydrogen generation)
P_{load}	[W]	Power to the (local) load
P_{aux}	[W]	Power to (local) auxiliary systems (compressors, pumps, etc.)
P_{grid}	[W]	Power to the electric grid
U_{grid}	[V]	Grid voltage

Notes:

- Any power units can be substituted for W as long as all values are expressed using the same units
- For power sources (WECS, PV, FC, RE, other), power values are positive from the RE sources to the grid. For the electrolyzer, the load and the auxiliary power consumption, power values are positive from the grid (i.e. from the busbar) to the components. Pgrid is positive when power is fed to the grid

5.2.11.2. Mathematical description

The power balance is written as:

$$P_{grid} = P_{WECS} + P_{PV} + P_{FC} + P_{RE} + P_{other} - P_{ely} - P_{load} - P_{aux}$$ **Eq. 5.2-10**

The grid voltage is given as a parameter and is assumed to be constant.

5.2.12. *Type 194: Photovoltaic array*

This component determines the electrical performance of a photovoltaic array. The model is based on the calculation method presented by DeSoto et al (2005). Type 194 may be used in simulations involving electrical storage batteries, direct load coupling, and utility grid connections. The model determines the current and power of the array at a specified voltage. Other OUTPUTS include current and voltage at the maximum power point.

5.2.12.1 *Nomenclature*

β	Slope of PV array [degrees]
ε_g	Semiconductor bandgap [eV]
η_c	Module conversion efficiency
α_{Isc}	Temperature coefficient of short-circuit current [A/K]
β_{Voc}	Temperature coefficient of open-circuit voltage [V/K]
θ	Angle of incidence for solar radiation [degrees]
$\tau\alpha$	Module transmittance-absorptance product
$\tau\alpha_n$	Module transmittance-absorptance product at normal incidence
a	Parameter in the model defined in equation 5.1.3-2)
G_T	Total radiation incident on PV array
$G_{T,beam}$	Beam component of incident radiation
$G_{T,diff}$	Diffuse component of incident radiation
$G_{T,gnd}$	Ground-reflected component of incident radiation
$G_{T,NOCT}$	Incident radiation at NOCT conditions
$G_{T,ref}$	Incident radiation at reference conditions
I	Current
I_L	Module photocurrent
$I_{L,ref}$	Module photocurrent at reference conditions
I_o	Diode reverse saturation current
$I_{o,ref}$	Diode reverse saturation current at reference conditions
I_{sc}	Short-circuit current
$I_{sc,ref}$	Short-circuit current at reference conditions
I_{mp}	Current at maximum power point along IV curve
$I_{mp,ref}$	Current at maximum power point along IV curve, reference conditions
IAM	Dimensionless incidence angle modifier
k	Boltzmann constant [J/K]
KL	Product of extinction coefficient and thickness for cover
NP	Number of modules in parallel in array
NS	Number of modules in series in array
N_s	Number of individual cells in series within a module
P	PV output power
P_{max}	PV output power at maximum power point along IV curve
q	Electron charge constant
R_s	Module series resistance [Ω]
R_{sh}	Module shunt resistance [Ω]
T_c	Module temperature [K]

$T_{c,NOCT}$	Module temperature at NOCT conditions [K]
$T_{c,ref}$	Module temperature at reference conditions [K]
U_L	Array thermal loss coefficient
V	Voltage
V_{mp}	Voltage at maximum power point along IV curve
$V_{mp,ref}$	Voltage at maximum power point along IV curve, reference conditions
V_{oc}	Open-circuit voltage
$V_{oc,ref}$	Open-circuit voltage at reference conditions [V]

5.2.12.2   Mathematical description

The model used in Type 194 is based on the five-parameter equivalent circuit model that is presented in Duffie and Beckman [1991]. However, the method for determining the parameters differs from what is presented by Duffie and Beckman. The main thrust of this model is to reliably extrapolate performance information provided by the manufacturer at standard rating conditions (1,000 W/m^2, 25°C) to other operating conditions. The model, as described by Desoto et al, (2005) is based on the equivalent circuit diagram shown in Figure 5.2.12–1.
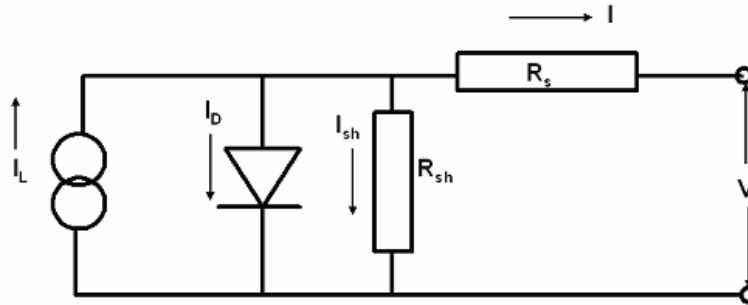
Figure 5.2.12–1: Equivalent electrical circuit

The current-voltage (I-V) characteristics of a PV array change with both insolation and array temperature. The PV model determines the current-voltage curve as a function of these environmental conditions using five array that are deduced from rating information provided by the manufacturer. The current-voltage equation for the circuit shown in Figure 5.2.12–1 is as follows:

$$I = I_L - I_o \left[e^{\frac{V+IR_s}{a}} - 1 \right] - \frac{V+IR_s}{R_{sh}}$$

Eq 5.2.12-1

where

$$a \equiv \frac{N_s\, n_I\, k T_c}{q}$$

Eq 5.2.12-1

Five parameters must be known in order to determine the current and voltage, and thus the power delivered to the load. These are: the light current I_L, the diode reverse saturation current I_o, the series resistance R_s, the shunt resistance R_{sh}, and the modified ideality factor a defined in Eqn. (5.2.12-2).

To evaluate the five parameters in Eqn. (5.2.12-1), five independent pieces of information are needed. In general, these five parameters are functions of the solar radiation incident on the array and array temperature. Reference values of these parameters are determined for a standard rating condition (SRC) which is almost always 1,000 W/m^2 and 25°C. Three current-voltage pairs are normally available from the manufacturer at SRC: the short circuit current, the open circuit voltage and the current and voltage at the maximum power point. A fourth piece of information results from recognizing that the derivative of the power at the maximum power point is zero. Although both the temperature coefficient of the open circuit voltage (β_{Voc}) and the temperature coefficient of the short circuit current (α_{Isc}) are known, only β_{Voc} is used to find the five reference parameters. α_{Isc} is used when the cell is operating at conditions other than reference conditions.

The Reference Parameters

The five parameters appearing in Eqn. (5.2.12-1) corresponding to operation at SRC are designated: a_{ref}, $I_{o,ref}$, $I_{L,ref}$, $R_{s,ref}$, and $R_{sh,ref}$. To determine the values of these parameters, the 3 known *I-V* pairs at SRC are substituted into Eqn. (5.2.12-1) resulting in Eqns. (5.2.12-3 to 5).

For short circuit current: *I=I$_{sc,ref}$, V=0*

$$I_{sc,ref} = I_{L,ref} - I_{o,ref}\left[e^{\frac{I_{sc,ref}R_{s,ref}}{a_{ref}}} - 1\right] - \frac{I_{sc,ref}R_{s,ref}}{R_{sh,ref}} \tag{5.2.12-3}$$

For open circuit voltage: *I=0, V=V$_{oc,ref}$*

$$0 = I_{L,ref} - I_{o,ref}\left[e^{\frac{V_{oc,ref}}{a_{ref}}} - 1\right] - \frac{V_{oc,ref}}{R_{sh,ref}} \tag{5.2.12-4}$$

At the maximum power point: *I=I$_{mp,ref}$, V=V$_{mp,ref}$*

$$I_{mp,ref} = I_{L,ref} - I_{o,ref}\left[e^{\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}} - 1\right] - \frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{R_{sh,ref}} \tag{5.2.12-5}$$

The derivative with respect to power at the maximum power point is zero.

$$\left.\frac{d(IV)}{dV}\right|_{mp} = I_{mp} - V_{mp}\left.\frac{dI}{dV}\right|_{mp} = 0 \tag{5.2.12-6a}$$

where $\left.dI/dV\right|_{mp}$ is given by:

$$\left.\frac{dI}{dV}\right|_{mp} = \frac{\dfrac{-I_o}{a}e^{\frac{V_{mp}+I_{mp}R_s}{a}} - \dfrac{1}{R_{sh}}}{1 + \dfrac{I_oR_s}{a}e^{\frac{V_{mp}+I_{mp}R_s}{a}} + \dfrac{R_s}{R_{sh}}} \tag{5.2.12-6b}$$

The temperature coefficient of open circuit voltage is given by:

$$\mu_{Voc} = \left. \frac{\partial V}{\partial T} \right|_{I=0} \approx \frac{V_{oc,ref} - V_{oc,T_c}}{T_{ref} - T_c} \qquad (5.2.12\text{-}7)$$

To evaluate μ_{Voc} numerically, it is necessary to know V_{oc,T_c}, the open circuit voltage at some cell temperature near the reference temperature. The cell temperature used for this purpose is not critical since values of T_c ranging from 1 to 10 K above or below T_{ref} provide essentially the same result. V_{oc,T_c} can be found from Eqn. (5.2.12-4) if the temperature dependencies for parameters I_o, I_L, and a, are known. The shunt resistance, R_{sh} was assumed to be independent of temperature. Therefore, in order to apply Eqn. (5.2.12-7), it is necessary to obtain expressions for the temperature dependence of the three parameters a, I_o and, I_L. The dependence of all of the parameters in the model on the operating conditions is considered next.

Dependence of the Parameters On Operating Conditions

From the definition of a, the modified ideality factor is a linear function of cell temperature (assuming n_I is independent of temperature) so that:

$$\frac{a}{a_{ref}} = \frac{T_c}{T_{c,ref}} \qquad (5.2.12\text{-}8)$$

where $T_{c,ref}$ and a_{ref} are the cell temperature and modified ideality factor for reference conditions, while T_c and a are the cell temperature and modified ideality factor parameter for the new operating conditions.

The diode reverse saturation current, I_o is related to temperature and reference conditions with the following relation,

$$\frac{I_o}{I_{o,ref}} = \left[\frac{T_c}{T_{c,ref}} \right]^3 \exp\left[\frac{1}{k} \left(\left. \frac{E_g}{T} \right|_{T_{ref}} - \left. \frac{E_g}{T} \right|_{T_c} \right) \right] \qquad (5.2.12\text{-}9)$$

where k is Boltzmann's constant and E_g is the material band gap. E_g exhibits a small temperature dependence (Van Zeghbroeck, 2004) which, for silicon, can be represented as indicated in Eqn. (5.2.12-10) where $E_{g,T_{ref}}$ =1.121 eV for silicon cells.

$$\frac{E_g}{E_{g,T_{ref}}} = 1 - 0.0002677\left(T - T_{ref} \right) \qquad (5.2.12\text{-}10)$$

The light current, (I_L), is assumed to be a linear function of incident solar radiation. The light current (I_L) is observed to depend on the absorbed solar irradiance (S), the cell temperature (T_c), the short circuit current temperature coefficient (α_{Isc}), and the air mass modifier (M). The light current I_L for any operating conditions is related to the light current at reference conditions by:

$$I_L = \frac{S}{S_{ref}} \frac{M}{M_{ref}} [I_{L,ref} + \alpha_{Isc}(T_c - T_{c,ref})] \qquad (5.2.12\text{-}11)$$

where S_{ref}, M_{ref}, $I_{L,ref}$, $T_{c,ref}$ are the parameters at reference conditions, while S, M, I_L, and T_c are the values for specified operating conditions. When using Eqn. (5.2.12-11) to find the reference parameters, $S = S_{ref}$ and $M = M_{ref}$. The air mass modifier is assumed to be a function of the local zenith angle and is discussed below. R_s is assumed constant at its reference value, $R_{s,ref}$.

The shunt resistance (R_{sh}) controls the slope of the I-V curve at the short circuit condition; large shunt resistances result in a horizontal slope. Desoto et al (2005) empirically propose Eqn (5.2.12-12) to describe the observed effect of solar radiation on the shunt resistance.

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{S_{ref}}{S} \qquad (5.2.12\text{-}12)$$

The Incidence Angle Modifier, $K_{\tau\alpha}$

The incidence angle, θ, is directly involved in the determination of the radiation incident on the surface of the PV device. In addition, the incidence angle affects the amount of solar radiation transmitted through the protective cover and converted to electricity by the cell. As the incidence angle increases, the amount of radiation reflected from the cover increases. Significant effects of inclination occur at incidence angles greater than 65°. The effect of reflection and absorption as a function of incidence angle is expressed in terms of the incidence angle modifier, $K_{\tau\alpha}(\theta)$, defined as the ratio of the radiation absorbed by the cell at some incidence angle θ divided by the radiation absorbed by the cell at normal incidence.

The incidence angle modifier for a PV panel differs somewhat from that of a flat-plate solar collector in that the glazing is bonded to the cell surface, thereby eliminating one air-glazing interface and the glazing surface may be treated so as to reduce reflection losses. Equations (5.2.12-13) and (5.2.12-14), based on Snell's and Bougher's laws as reported in Duffie and Beckman (1991), are used to calculate the incidence angle modifier for one glass-air interface. The angle of refraction (θ_r) is determined from Snell's law

$$\theta_r = \arcsin\left(n\sin\theta\right) \qquad (5.2.12\text{-}13)$$

where θ is the incidence angle and n is an effective index of refraction of the cell cover. A good approximation of the transmittance of the cover system considering both reflective losses at the interface and absorption within the glazing is:

$$\tau\left(\theta\right) = e^{-\left(KL/\cos\theta_r\right)}\left[1 - \frac{1}{2}\left(\frac{\sin^2\left(\theta_r - \theta\right)}{\sin^2\left(\theta_r + \theta\right)} + \frac{\tan^2\left(\theta_r - \theta\right)}{\tan^2\left(\theta_r + \theta\right)}\right)\right] \qquad (5.2.12\text{-}14)$$

where K is the glazing extinction coefficient and L is the glazing thickness. The product of K and L is a parameter for the model. To obtain the incidence angle modifier ($K_{\tau\alpha}$), Eqn. (5.2.12-14) needs be evaluated for incidence angles of 0° and θ. The ratio of these two transmittances yields the incidence angle modifier:

$$K_{\tau\alpha}\left(\theta\right) = \frac{\tau\left(\theta\right)}{\tau\left(0\right)} \qquad (5.2.12\text{-}15)$$

Separate incidence angle modifiers are needed for beam, diffuse, and ground-reflected radiation.

Air Mass Modifier

Air mass is the ratio of the mass of air that the beam radiation has to traverse at any given time and location to the mass of air that the beam radiation would traverse if the sun were directly overhead. Selective absorption by species in the atmosphere causes the spectral content of irradiance to change, altering the spectral distribution of the radiation incident on the PV panel. Following King et al. (1998), an empirical relation is used to account for air mass effects:

$$\frac{M}{M_{ref}} = \sum_0^4 a_i \left(AM \right)^i \qquad (5.2.12\text{-}16)$$

where

$$AM = \frac{1}{\cos\left(\theta_z\right) + 0.5057\left(96.080 - \theta_z\right)^{-1.634}} \qquad (5.3.12\text{-}17)$$

$$a_0=0.918093 \quad a_1=0.086257 \quad a_2=-0.024459 \quad a_3=0.002816 \quad a_4=-0.000126 \quad (5.2.12\text{-}18)$$

Module Operating Temperature (Thermal model)

Type 194 uses temperature data from the standard NOCT (Nominal Operating Cell Temperature) measurements to compute the module temperature T_c at each timestep. The NOCT temperature ($T_{c,NOCT}$) is the operating temperature of the module with a wind speed of 1 m/s, no electrical load, and a certain specified insolation and ambient temperature [Beckman and Duffie, 1991]. The values for insolation $G_{T,NOCT}$ and ambient temperature $T_{a,NOCT}$ are usually 800 W/m^2 and 20º C. Type 194 uses the NOCT data to determine the ratio of the module transmittance-reflectance product to the module loss coefficient:

$$\frac{\tau\alpha}{U_L} = \frac{\left(T_{c,NOCT} - T_{a,NOCT}\right)}{G_{T,NOCT}} \qquad \textbf{Eq 5.2.12-19}$$

Assuming that this ratio is constant, the module temperature at any timestep is:

$$T_c = T_a + \frac{\left(1 - \dfrac{\eta_{ref}}{\tau\alpha}\right)}{\left(\dfrac{G_T \tau\alpha}{U_L}\right)} \qquad \textbf{Eq 5.2.12-20}$$

η_c is the electrical efficiency of the module at reference conditions. $T_{c,NOCT}$, $T_{a,NOCT}$, and $G_{T,NOCT}$ are set in PARAMETERS 12, 13, and 14 respectively. $\tau\alpha$ may be either a constant or the a value calculated from an incidence angle correlation, as described here below.

Multi-Array Modules

The electrical calculations discussed for five-parameter PV model deal only with a single module. Type 194 may be used to simulate arrays with any number of modules. TRNSYS PARAMETERS 10 and 11 define the number of modules in series (NS) and modules in parallel (NP) for the entire

array. The total number of modules in the array is the product of NS and NP. When simulating a single module only, both NS and NP are set to 1. Note that the voltage supplied to Type 194 with INPUT 3 is the voltage for the entire array and not just for a single module. Module mismatch losses are not considered in this model.

Photovoltaic array with inverter

Cell output can be maximized by operating near or at the maximum power point. Maximum power trackers are devices that keep the impedance of the circit of the cells at levels corresponding to best operation and also convert the resulting power from the PV array so that its voltage is that required by the load. If AC power is needed, DC/AC inverters are required.

The effect of the inverter on the performance of the system can be characterized by an additional efficiency that reduces the power provided by the PV array. A data file is used for providing the efficienty of the inverter as function of array power and voltage. The data file follows the specifications of the subroutine DYNAMIC_DATA. The following is an example of a data file with efficiency values for 7 values of array power (in Watts) and 3 values of voltage.

```
0.000E+00  0.350E+03  0.700E+03  0.105E+04  0.175E+04  0.245E+04  0.350E+04
0.104E+03  0.135E+03  0.164E+03
0.797            !Efficiency at Power = 0.000E+00 and Voltage =  0.104E+03
0.780            !Efficiency at Power = 0.000E+00 and Voltage =  0.135E+03
0.748            !Efficiency at Power = 0.000E+00 and Voltage =  0.164E+03
0.797            !Efficiency at Power = 0.350E+03 and Voltage =  0.104E+03
0.780            !Efficiency at Power = 0.350E+03 and Voltage =  0.135E+03
0.748            !Efficiency at Power = 0.350E+03 and Voltage =  0.164E+03
0.862            !Efficiency at Power = 0.700E+03 and Voltage =  0.104E+03
0.843            !Efficiency at Power = 0.700E+03 and Voltage =  0.135E+03
0.827            !Efficiency at Power = 0.700E+03 and Voltage =  0.164E+03
0.885            !Efficiency at Power = 0.105E+04 and Voltage =  0.104E+03
0.867            !Efficiency at Power = 0.105E+04 and Voltage =  0.135E+03
0.860            !Efficiency at Power = 0.105E+04 and Voltage =  0.164E+03
0.929            !Efficiency at Power = 0.175E+04 and Voltage =  0.104E+03
0.920            !Efficiency at Power = 0.175E+04 and Voltage =  0.135E+03
0.916            !Efficiency at Power = 0.175E+04 and Voltage =  0.164E+03
0.922            !Efficiency at Power = 0.245E+04 and Voltage =  0.104E+03
0.921            !Efficiency at Power = 0.245E+04 and Voltage =  0.135E+03
0.919            !Efficiency at Power = 0.245E+04 and Voltage =  0.164E+03
0.918            !Efficiency at Power = 0.350E+04 and Voltage =  0.104E+03
0.919            !Efficiency at Power = 0.350E+04 and Voltage =  0.135E+03
0.915            !Efficiency at Power = 0.350E+04 and Voltage =  0.164E+03
```

5.2.12.3   References

DeSoto, W., Klein, S.A. and Beckman, W.A., "Improvement and Validation of a Model for PV Array Performance," accepted for publication in Solar Energy Journal, (in press 2005)

Duffie, John A. and William A. Beckman. *Solar Engineering of Thermal Processes*. New York: John Wiley & Sons, Inc., 1991.

King, D.L., Kratochvil, J.A., Boyson, W.E., Bower, W.I., 1998. Field Experience with a New Performance Characterization Procedure for Photovoltaic Arrays presented at the 2nd World Conference and Exhibition on Photovoltaic Solar energy Conversion, Vienna, Austria, July 6-10.

5.3 Heat Exchangers

This category includes several heat exchanger models.

Type 5 is a steady-state heat exchanger model that allows to simulate various flow configurations (counterflow, crossflow, parallel flow, shell and tube) . The overall UA value of heat exchangers is given as an Input.

Type 17 models a cascaded heat recovery system that includes several heat exchangers, each of which is simulated using the same hypotheses as in Type 5.

Type 91 models a constant effectiveness heat exchanger (The effectiveness is given as a parameter).

5.2.1   Type 5: Heat Exchanger

A zero capacitance sensible heat exchanger is modeled in the parallel, counter, various cross flow configurations and shell and tube modes. For all modes, given the hot and cold side inlet temperatures and flow rates, the effectiveness is calculated for a given fixed value of the overall heat transfer coefficient. The cross flow modes assume one of the following.

1.   That the hot (source) side fluid is unmixed while the cold (load) side is completely mixed

2.   That the cold (load) side fluid is unmixed while the hot (source) side is completely mixed

3.   That neither the cold nor the hot side fluids are mixed or

4.   That both the hot and cold sides are mixed.

The mathematical description that follows is covered in detail in Kays and London (1). The shell and tube model and the situation in which both fluids are unmixed are covered in DeWitt and Incropera (2). Type 91 models a constant effectiveness heat exchanger in which UA is calculated instead of being provided as an Input.

5.2.1.1   Nomenclature

C_c	capacity rate of fluid on cold side, $\dot{m}_c C_{pc}$
C_h	capacity rate of fluid on hot side, $\dot{m}_h C_{ph}$
C_{max}	maximum capacity rate
C_{min}	minimum capacity rate
C_{pc}	specific heat of cold side fluid
C_{ph}	specific heat of hot side fluid
ε	heat exchanger effectiveness
$\dot{m}_c$	fluid mass flow rate on cold side
$\dot{m}_h$	fluid mass flow rate on hot side
$\dot{Q}_T$	total heat transfer rate across heat exchanger
$\dot{Q}_{max}$	the maximum heat transfer rate across exchanger
T_{ci}	cold side inlet temperature
T_{co}	cold side outlet temperature
T_{hi}	hot side inlet temperature
T_{ho}	hot side outlet temperature
UA	overall heat transfer coefficient of exchanger
N	number of shell passes

5.2.1.2   Mathematical Description

Type 5 relies on an effectiveness minimum capacitance approach to modeling a heat exchanger. Under this assumption, the user is asked to provide the heat exchanger's UA and inlet conditions. The model then determines whether the cold (load) or the hot (source) side is the minimum capacitance side and calculates an effectiveness based upon the specified flow configuration and on UA. The heat exchanger outlet conditions are then computed, for all flow configurations using Eq. 5.3-19 and Eq. 5.3-20. The capacitance of each side of the heat exchanger is calculated according to the following four equations.

$$C_c = \dot{m}_c C_{pc} \qquad\qquad\qquad \textbf{Eq. 5.3-1}$$

$$C_h = \dot{m}_h C_{ph} \qquad\qquad\qquad \textbf{Eq. 5.3-2}$$

$$C_{max} = \text{maximum value of } C_h \text{ and } C_c \qquad\qquad\qquad \textbf{Eq. 5.3-3}$$

$$C_{min} = \text{minimum value of } C_h \text{ and } C_c \qquad\qquad\qquad \textbf{Eq. 5.3-4}$$

A schematic of the heat exchanger is shown in Figure 5.2.1–1 below.
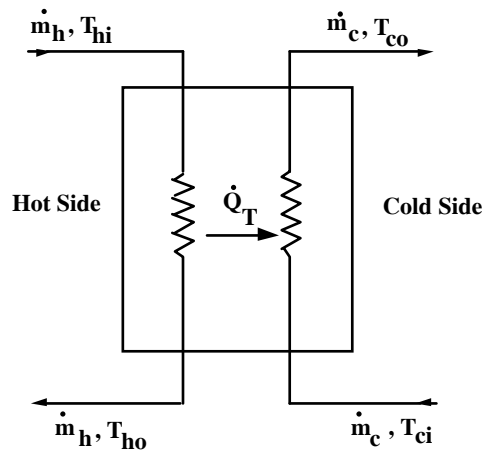
Figure 5.2.1–1: Heat Exchanger Schematic

The following indicate the expression used to calculate the heat exchanger effectiveness at each time step depending upon heat exchanger configuration.

MODE 1 - PARALLEL FLOW

$$\varepsilon = \frac{1 - \exp\left(-\frac{UA}{C_{min}}\left(1 + \frac{C_{min}}{C_{max}}\right)\right)}{1 + \frac{C_{min}}{C_{max}}}$$

Eq. 5.3-5

MODE 2 – COUNTER FLOW

$$\varepsilon = \frac{1 - \exp\left(-\frac{UA}{C_{min}}\left(1 - \frac{C_{min}}{C_{max}}\right)\right)}{1 - \left(\frac{C_{min}}{C_{max}}\right)\exp\left(-\frac{UA}{C_{min}}\left(1 - \frac{C_{min}}{C_{max}}\right)\right)}$$

Eq. 5.3-6

MODE 3 – CROSS FLOW (HOT (SOURCE) SIDE UNMIXED, COLD (LOAD) SIDE MIXED)

If $C_{max} = C_h$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{min}}\frac{C_{min}}{C_{max}}\right)$$

Eq. 5.3-7

$$\varepsilon = 1 - \exp\left(-\gamma\frac{C_{max}}{C_{min}}\right)$$

Eq. 5.3-8

If $C_{min} = C_h$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{min}}\right)$$

Eq. 5.3-9

$$\varepsilon = \frac{C_{max}}{C_{min}}\left(1 - \exp\left(-\gamma\frac{C_{min}}{C_{max}}\right)\right)$$

Eq. 5.3-10

MODE 4 – CROSS FLOW (COLD (LOAD) SIDE UNMIXED, HOT (SOURCE) SIDE MIXED)

If $C_{max} = C_c$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{min}}\right)$$

Eq. 5.3-11

$$\varepsilon = \frac{C_{max}}{C_{min}}\left(1 - \exp\left(-\gamma\frac{C_{min}}{C_{max}}\right)\right)$$

Eq. 5.3-12

If $C_{min} = C_c$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{min}} \frac{C_{min}}{C_{max}}\right)$$

Eq. 5.3-13

$$\varepsilon = 1 - \exp\left(-\gamma \frac{C_{max}}{C_{min}}\right)$$

Eq. 5.3-14

MODE 5 – CROSS FLOW: BOTH SIDES UNMIXED

$$\varepsilon = 1 - \exp\left[\left(\frac{C_{max}}{C_{min}}\right)\left(\frac{UA}{C_{min}}\right)^{0.22}\left\{\exp\left[-\frac{C_{min}}{C_{max}}\left(\frac{UA}{C_{min}}\right)^{0.78}\right]-1\right\}\right]$$

Eq. 5.3-15

MODE 6 – CROSS FLOW: BOTH SIDES MIXED

$$\varepsilon = \frac{\dfrac{UA}{C_{min}}}{\dfrac{\dfrac{UA}{C_{min}}}{1-e^{-\left(UA/C_{min}\right)}} + \dfrac{\left(C_{min}/C_{max}\right)\dfrac{UA}{C_{min}}}{1-e^{-\left(UA/C_{min}\right)\left(C_{min}/C_{max}\right)}} - 1}$$

Eq. 5.3-16

MODE 7 – SHELL AND TUBE

$$\varepsilon_1 = 2\left\{1+\frac{C_{min}}{C_{max}}+\left(1+\left(\frac{C_{min}}{C_{max}}\right)^2\right)^{0.5} * \frac{1+\exp\left[-\frac{UA}{C_{min}}\left(1+\left(\frac{C_{min}}{C_{max}}\right)^2\right)^{0.5}\right]}{1-\exp\left[-\frac{UA}{C_{min}}\left(1+\left(\frac{C_{min}}{C_{max}}\right)^2\right)^{0.5}\right]}\right\}^{-1}$$

Eq. 5.3-17

$$\varepsilon = \left[\left(\frac{1-\varepsilon_1\dfrac{C_{min}}{C_{max}}}{1-\varepsilon_1}\right)^N - 1\right]\left[\left(\frac{1-\varepsilon_1\dfrac{C_{min}}{C_{max}}}{1-\varepsilon_1}\right)^N - \frac{C_{min}}{C_{max}}\right]^{-1}$$

Eq. 5.3-18

ALL MODES

$$T_{ho} = T_{hi} - \varepsilon \left(\frac{C_{min}}{C_h}\right)(T_{hi} - T_{ci})$$

Eq. 5.3-19

$$\dot{Q}_T = \varepsilon\, C_{min}\,(T_{hi} - T_{ci})$$

Eq. 5.3-20

SPECIAL CASES

Mode 3: If

$$\left|\frac{C_{min}}{C_{max}} - 1.0\right| < 0.01$$

Eq. 5.3-21

then

$$\varepsilon = \frac{\dfrac{UA}{C_{min}}}{\dfrac{UA}{C_{min}} + 1.0}$$

Eq. 5.3-22

All Modes: If

$$\frac{C_{min}}{C_{max}} \leq 0.01$$

Eq. 5.3-23

then

$$\varepsilon = 1.0 - \exp\left(-\frac{UA}{C_{min}}\right)$$

Eq. 5.3-24

5.2.2   Type 17: Waste Heat Recovery

This component models a cascaded waste heat recovery system (WHR) as shown in Figure 5.2.2–1. Energy recovery may occur through up to 5 secondary heat exchangers and be delivered across a single primary heat exchanger. Optionally, some secondary heat exchangers may deliver, rather than recover energy. The analysis used for each heat exchanger is identical to that of the Type 5 component. The user is referred to the Type 5 documentation for description of the four possible heat-exchanger modes and the mathematical analysis.
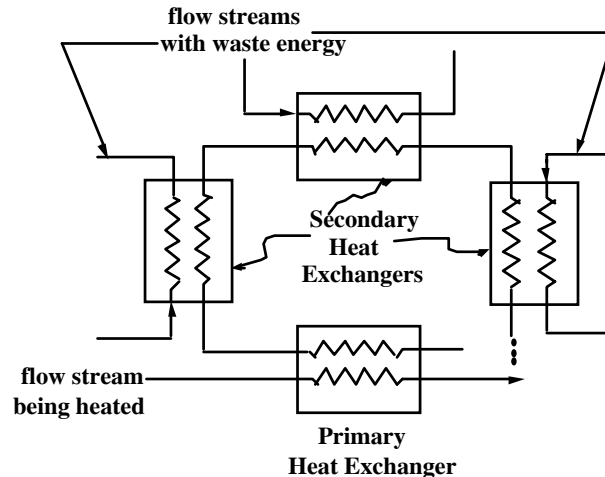
Figure 5.2.2–1: Cascaded Waste Heat Recovery System

5.2.2.1   Mathematical Description

The Type 17 iteratively solves the system of equations representing the heat exchangers. Convergence is assumed when the outlet temperature of the hot side of the primary heat exchanger, changes between successive iterations by less than a user-specified amount, TOL. If convergence is not attained within NSTICK iterations, any oscillating controlled pumps are turned off. There are three possible control strategies for the primary and secondary heat exchangers as follows.

- **NO CONTROL** - Energy is transferred into or out of the WHR loop whenever there is flow on both sides of the heat exchanger. ΔT_{min} is ignored in this case. External control is possible through use of a separate pump and controller.

- **ENERGY RECOVERY** - Energy is transferred into the WHR loop whenever the recovery stream inlet temperature is ΔT_{min} greater than the WHR side inlet temperature. Otherwise, the conditions of recovery stream outlet are set equal to those of the inlet and the heat transfer is zero. This is not an option for the primary heat exchanger.

- **ENERGY DELIVERY** - Energy is transferred from the WHR loop whenever the inlet to the WHR loop side of the heat exchanger is ΔT_{min} greater than the external stream inlet. Otherwise, the conditions of external stream outlet are set equal to those of the inlet and the heat transfer is zero.

At the end of the simulation, summaries of the percentages of time steps that NSTICK was exceeded and that convergence was not attained in NSTICK+5 iterations is printed.

5.2.3 Type 91: Constant Effectiveness Heat Exchanger

A zero capacitance sensible heat exchanger is modeled as a constant effectiveness device that is independent of the system configuration. The maximum possible heat transfer rate is calculated based on the minimum capacity rate fluid and the cold side and hot side fluid inlet temperatures. In this mode the effectiveness of the heat exchanger is Input as a parameter and the concept of an overall heat transfer coefficient for the heat exchanger is not used. The mathematical description that follows is covered in detail in Kays and London (1).

5.2.3.1 Nomenclature

C_c	capacity rate of fluid on cold side, $\dot{m}_c C_{pc}$
C_h	capacity rate of fluid on hot side, $\dot{m}_h C_{ph}$
C_{max}	maximum capacity rate
C_{min}	minimum capacity rate
C_{pc}	specific heat of cold side fluid
C_{ph}	specific heat of hot side fluid
ε	heat exchanger effectiveness
$\dot{m}_c$	fluid mass flow rate on cold side
$\dot{m}_h$	fluid mass flow rate on hot side
$\dot{Q}_T$	total heat transfer rate across heat exchanger
$\dot{Q}_{max}$	the maximum heat transfer rate across exchanger
T_{ci}	cold side inlet temperature
T_{co}	cold side outlet temperature
T_{hi}	hot side inlet temperature
T_{ho}	hot side outlet temperature
UA	overall heat transfer coefficient of exchanger

5.2.3.2 Mathematical Description

Type 91 relies on an effectiveness minimum capacitance approach to modeling a heat exchanger. Under this assumption, the user is asked to provide the heat exchanger's effectiveness and inlet conditions. The model then determines whether the cold (load) or the hot (source) side is the minimum capacitance side and calculates the heat transfer based on Eq. 5.3-31. The heat exchanger outlet conditions are then computed using Eq. 5.3-32 and Eq. 5.3-33. The capacitance of each side of the heat exchanger is calculated according to the following four equations.

$$C_c = \dot{m}_c C_{pc}$$

Eq. 5.3-25

$$C_h = \dot{m}_h C_{ph}$$

Eq. 5.3-26

$$C_{max} = \text{maximum value of } C_h \text{ and } C_c$$

Eq. 5.3-27

$$C_{min} = \text{minimum value of } C_h \text{ and } C_c$$

Eq. 5.3-28

A schematic of the heat exchanger is shown in Figure 5.2.3–1 below.
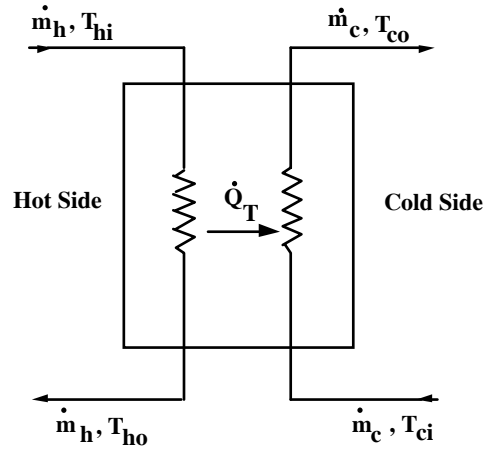
Figure 5.2.3–1: Heat Exchanger Schematic

The following expressions are used to determine the maximum possible amount of heat transfer at a given time step.

If $C_{min} = C_h$, $\dot{Q}_{max} = C_h (T_{hi} - T_{ci})$

Eq. 5.3-29

If $C_{min} = C_c$, $\dot{Q}_{max} = C_c (T_{hi} - T_{ci})$

Eq. 5.3-30

The actual heat transfer then depends upon the user specified effectiveness.

$$\dot{Q}_T = \varepsilon \, \dot{Q}_{max}$$

Eq. 5.3-31

Lastly, heat exchanger outlet conditions are calculated for the two flow streams.

$$T_{ho} = T_{hi} - \left(\frac{\dot{Q}_T}{C_h} \right)$$

Eq. 5.3-32

$$T_{co} = T_{ci} + \left(\frac{\dot{Q}_T}{C_c} \right)$$

Eq. 5.3-33

5.3 HVAC

The Types in this section model HVAC components and systems:

- Type 6 Auxiliary heater
- Type 20: Dual Source Heat Pump
- Type 32: Simplified Cooling Coil
- Type 42: Conditioning Equipment
- Type 43: Part Load Performance
- Type 51: Cooling Tower
- Type 52: Detailed Cooling Coil
- Type 53: Parallel Chillers
- Type 92: ON/OFF Auxiliary Cooling Device
- Type 107: Single Effect Hot Water Fired Absorption Chiller
- Type 121: Simple Furnace / Air Heater

5.3.1   Type 6: Auxiliary heater

An auxiliary heater is modeled to elevate the temperature of a flowstream using either internal control, external control or a combination of both. The heater is designed to add heat to the flowstream at a rate less than or equal to $\dot{Q}_{max}$, which is a user determined quantity, whenever the control function γ is equal to 1 and the outlet temperature is less than the setpoint T_{set}.

By specifying a constant value of γ equal to 1 and a sufficiently large value for $\dot{Q}_{max}$, Type 6 will perform like a domestic hot water auxiliary heater with internal control to maintain an outlet temperature of T_{set}.

By providing a control function of 0 or 1 and setting T_{set} to a very high value with a reasonably low value of $\dot{Q}_{max}$, Type 6 will perform like an externally controlled ON/OFF heating device.

Users should be aware that the maximum thermal energy transfer to the flowstream is not $\dot{Q}_{max}$ but $\eta_{htr}*\dot{Q}_{max}$.

5.3.1.1   Nomenclature

Cpf	[kJ/kg.K]	fluid specific heat
ṁl	[kg/hr]	inlet fluid mass flow rate
ṁo	[kg/hr]	outlet fluid mass flow rate
$\dot{Q}_{aux}$	[kJ/hr]	required heating rate including efficiency effects
$\dot{Q}_{fluid}$	[kJ/hr]	rate of heat addition to fluid stream
$\dot{Q}_{loss}$	[kJ/hr]	rate of thermal losses from heater to environment
$\dot{Q}_{max}$	[kJ/hr]	maximum heating rate of heater
Tenv	[C]	temperature of heater surroundings for loss calculations
Ti	[C]	fluid inlet temperature
To	[C]	fluid outlet temperature
Tset	[C]	set temperature of heater internal thermostat
UA	[kJ/hr]	overall loss coefficient between the heater and its surroundings during operation
γ	[-]	external control function which has values of 0 or 1
η_{htr}	[0..1]	efficiency of auxiliary heater

5.3.1.2   Mathematical Description

If $T_i \geq T_{set}$, $\dot{m}_i \leq 0$, or $\gamma = 0$ then

$T_O = T_i$, $\dot{m}_o = \dot{m}_i$, $\dot{Q}_{loss} = 0$, $\dot{Q}_{fluid} = 0$, and $\dot{Q}_{aux} = 0$

Otherwise, an energy balance on the steady-state heater reveals:

$$T_O = \frac{\dot{Q}_{max}\, \eta_{htr} + \dot{m}\, C_{pf}\, T_i + UA\, T_{env} - \dfrac{UA\, T_i}{2}}{\dot{m}\, C_{pf} + \dfrac{UA}{2}}$$

Eq. 5.3-1

$\dot{m}_o = \dot{m}_i$

$\dot{Q}_{aux} = \dot{Q}_{max}$

$\dot{Q}_{fluid} = \dot{m}_o\, C_{pf}\, (T_O - T_i)$

Eq. 5.3-2

$$\overline{T} = \frac{(T_O + T_{in})}{2}$$

Eq. 5.3-3

$\dot{Q}_{loss} = UA\, (\overline{T} - T_{env}) + (1 - \eta_{htr})\, \dot{Q}_{max}$

Eq. 5.3-4

Unless $T_o > T_{set}$, then

$T_o = T_{set}$,

$m_o = m_i$,

$\dot{Q}_{fluid} = \dot{m}_o\, C_{pf}\, (T_{set} - T_i)$

Eq. 5.3-5

$$\overline{T} = \frac{(T_{set} + T_{in})}{2}$$

Eq. 5.3-6

$$\dot{Q}_{aux} = \frac{\dot{m}\, C_{pf}\, (T_{set} - T_i) + UA\, (\overline{T} - T_{env})}{\eta_{htr}}$$

Eq. 5.3-7

where: $Q_{aux} = Q_{loss} + Q_{fluid}$

5.3.2 Type 20: Dual Source Heat Pump

This component models the performance of a heat pump having two evaporators; a liquid source to utilize heat from a solar system or other processes, and an ambient air source to be used when the outdoor temperature exceeds the liquid source temperature or if the liquid source temperature approaches its freezing point. The model also allows a direct heating mode in which the hot liquid source bypasses the heat pump and delivers energy across a heat exchanger whenever its temperature exceeds a user specified minimum, T_{dh}.

A schematic of the dual source heat pump considered by this component is shown in Figure 5.3.2–1. The entire system is controlled by a single control Input, γ_{htr}. If the value of this control function is 0, then no heating is required and the heat pump delivers no energy. If, on the other hand, γ_{htr} is 1, then an internal controller determines the heating mode. Direct liquid source heating occurs if the source temperature is greater than T_{dh}. Otherwise, heat pump heating occurs using either the liquid or ambient source, whichever has the higher temperature. If, however, either source temperature falls below user specified minimums, then the heat is not allowed to operate in that (or both) mode(s).

The performance of the heat pump is determined with user-supplied steady-state performance data as a function of the inlet fluid temperature to the evaporator only. No dependence upon condenser side conditions is considered. The Type 42 Conditioning Equipment is capable of modeling the performance of a single source heat pump as a function of more than one independent variable. The Type 20 also does not consider transients associated with frequent cycling. The effect of cycling on the efficiency of any piece of equipment can be considered through use of the Type 43 Part Load Performance component.

The heat pump performance data is read and interpolated using subroutine DATA (See Manual 08-Progammer's Guide). It should be provided in a file accessed through a Fortran logical unit. A set of data for each evaporator source is required. The data consists of between 2 and 10 evaporator inlet temperatures. For each temperature, corresponding values of heat pump capacity, energy absorbed by the evaporator, and electrical energy required must be provided. Performance data is read in free format. The first values in the data file must be the evaporator temperatures in increasing order. Next are values of capacity, energy absorbed, and electrical Input at the lowest evaporator temperature; followed by values at the next evaporator temperature, etc.
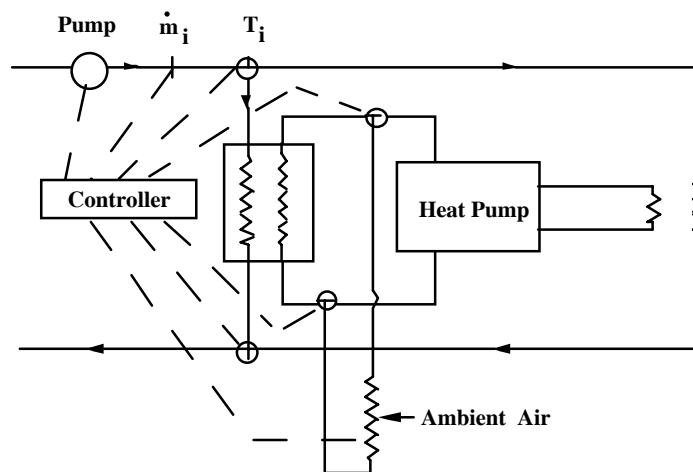
Figure 5.3.2–1: Heat Pump Model Schematic

5.3.2.1   Nomenclature

Cpf	[kJ/kg.K]	specific heat of fluid from liquid source
COP	[-]	coefficient of performance of heat pump
$\dot{m}_i$	[kg/hr]	mass flow rate of fluid from liquid source
$\dot{m}_o$	[kg/hr]	mass flow of fluid returning to liquid source
$\dot{Q}_{abs}$	[kJ/hr]	rate of energy absorbed by the heat pump evaporator
$\dot{Q}_{dn}$	[kJ/hr]	rate of energy delivery to room by direct liquid source heating
$\dot{Q}_{ei}$	[kJ/hr]	rate of electrical energy required by heat pump
$\dot{Q}_{hp}$	[kJ/hr]	rate of energy delivery by heat pump
Ta	[C]	ambient temperature
Tdh	[C]	minimum fluid source temperature necessary for direct liquid source heating
Ti	[C]	temperature of fluid from liquid source
Tmin,a	[C]	minimum ambient temperature necessary for ambient source heat pump operation
Tmin,l	[C]	minimum fluid temperature necessary for heat pump operation using liquid source
To	[C]	temperature of fluid returning to liquid source
TR	[C]	temperature of room air heated by heat pump or directly by the liquid source
Cmin	[kJ/hr.K]	effectiveness times minimum capacitance rate (mass flow rate times specific heat) of heat exchanger for direct liquid source heating
htr	[-]	control function for heat pump system operation (0 - off, 1 - on)

5.3.2.2   Mathematical Description

If γ_{htr} = 0 or ($T_i < T_{dh}$, $T_i < T_{min,l}$ and $T_a < T_{min,a}$) then

$$T_o = T_i$$

$$\dot{m}_o = 0$$

$$\dot{Q}_{hp} = \dot{Q}_{dh} = \dot{Q}_{abs} = \dot{Q}_{ei} = COP = 0$$

If γ_{htr} = 1, then

If $T_i > T_{dh}$

$$\dot{Q}_{dh} = \varepsilon C_{min} (T_i - T_R) \qquad\qquad \textbf{Eq. 5.3-8}$$

$$T_o = T_i - \dot{Q}_{dh}/\dot{m}_i C_{pf} \qquad\qquad \textbf{Eq. 5.3-9}$$

$$\dot{m}_o = \dot{m}_i$$

$$\dot{Q}_{hp} = \dot{Q}_{abs} = \dot{Q}_{ei} = COP = 0$$

If $T_i < T_{dh}$ and $T_i \geq T_{min,l}$ and ($T_i \geq T_a$ or $T_a < T_{min,a}$) then

$\dot{Q}_{hp}, \dot{Q}_{abs}, \dot{Q}_{ei}$ = liquid source performance at T

$COP = \dot{Q}_{hp}/\dot{Q}_{ei}$ **Eq. 5.3-10**

$T_o = T_i - \dot{Q}_{abs}/\dot{m}_i C_{pf}$ **Eq. 5.3-11**

$\dot{m}_o = \dot{m}_i$

$\dot{Q}_{dh} = 0$

If $T_i < T_{dh}$ and $T_a \geq T_{min,a}$ and ($T_a > T_i$ or $T_i < T_{min,l}$) then

$\dot{Q}_{hp}, \dot{Q}_{abs}, \dot{Q}_{ei}$ = ambient source performance at T_a

$COP = \dot{Q}_{hp}/\dot{Q}_{ei}$

$T_o = T_i$

$\dot{m}_o = 0$

$\dot{Q}_{dh} = 0$

5.3.3 Type 32: Simplified Cooling Coil

This component models the performance of a chilled water cooling coil. It may be used with a component that calculates a total cooling capacity, such as the Type 42 Conditioning Equipment, and a component which models a space to be cooled, such as the Type 19 Zone or Type 56 Building. Its purpose is to separate the cooling Input into sensible (temperature) and latent (humidity) effects. The analysis is based upon empirical relationships taken from an ASHRAE publication (1). Note that Type 52 is a more sophisticated cooling coil model.

5.3.3.1 Nomenclature

A_f	Face area of coil
BRCW	Base rating of coil
$C_{p,a}$	Specific heat of air
d_i	Inside diameter of tubes
$\dot{H}_{a,i}$	Enthalpy of inlet air stream to coil
$\dot{H}_{a,o}$	Enthalpy of outlet air
LMTD	Log mean temperature difference between air and water flow streams
$\dot{m}_a$	Mass flow rate of air stream
$\dot{m}_w$	Mass flow rate of water
N_{coil}	Number of parallel water flow circuits
N_{row}	Number of rows deep of coil tubes
$\dot{Q}_L$	Latent energy transfer rate
$\dot{Q}_S$	Sensible energy transfer rate
$\dot{Q}_T$	Total energy transfer rate
$T_{db,i}$	Dry bulb temperature of entering air stream
$T_{db,o}$	Dry bulb temperature of leaving air stream
$T_{dp,i}$	Dew point temperature of leaving air stream
$T_{w,i}$	Entering chilled water temperature
$T_{w,o}$	Leaving chilled water temperature
$T_{wb,i}$	Wet bulb temperature of entering air stream
$T_{wb,o}$	Wet bulb temperature of leaving air stream
V_a	Velocity of air across coil
V_w	Velocity of chilled water in coil tubes
WSF	Wetted surface factor
ρ_a	Air density
ρ_w	Water density

5.3.3.2 Mathematical Description

The total heat transfer rate across a chilled water coil, cooling a moist air stream, is the difference in enthalpy across either flow stream or

$$\dot{Q}_T = \dot{m}_w C_{pw} (T_{w,o} - T_{w,i})$$

<div style="text-align: right;">**Eq. 5.3-12**</div>

$$\dot{Q}_T = \dot{H}_{a,i} - \dot{H}_{a,o}$$

Eq. 5.3-13

A third empirical relationship for the total heat transfer taken from Reference 1 is given as:

$$\dot{Q}_T = N_{row} * A_f * BRCW * WSF * LMTD$$

Eq. 5.3-14

The base rating, BRCW, is the heat transfer per unit face area per log mean temperature difference for an entering water temperature equal to the dew point temperature of the entering air stream. Empirical relationships for BRCW and the wetted surface factor, WSF, also taken from Reference 1 are

$$\frac{1}{BRCW} = C_1 + \frac{C_2}{V_a} + \frac{C_3}{V_w} + \frac{C_4}{V_w^2} + \frac{C_s}{V_a^3} + \frac{C_6}{V_w^2 V_a^4}$$

Eq. 5.3-15

$$WSF = k_1 + k_2 \Delta T_1 + k_3 \Delta T_1 \Delta T_2 + k_4 \Delta T_1^2 + k_5 \Delta T_1 \Delta T_2^2 + k_6 \Delta T_1^2 \Delta T_2$$
$$+ k_7 \Delta T_1 \Delta T_2^3 + k_8 \Delta T_1^2 \Delta T_2^3 + k_9 \Delta T_1^3 \Delta T_2^3$$

Eq. 5.3-16

where C_1 - C_6 and k_1 - k_9 are empirical constants and

$$\Delta T_1 = T_{dp,i} - T_{w,i}$$

Eq. 5.3-17

$$\Delta T_2 = T_{db,i} - T_{w,i}$$

Eq. 5.3-18

Eq. 5.3-15 was developed for face air velocities in the range of 200 to 800 ft/min and water velocities from 1 to 8 ft/sec. Eq. 5.3-16 was fit for ΔT_1 from 0°F to 30°F and ΔT_2 from 10°F to 60°F. If any of these quantities fall outside the range for which the empirical constants were generated, then the end of range values is used.

The velocities of the air and water streams are

$$V_a = \frac{\dot{m}_a}{\rho_a A_f}$$

Eq. 5.3-19

$$V_w = \frac{4 \dot{m}_w}{\rho_w \pi d_i^2 N_{COIL}}$$

Eq. 5.3-20

Eq. 5.3-12 through Eq. 5.3-14 are solved using an iterative procedure to determine the heat transfer and outlet water and air conditions. Psychrometric curve fits are used for relating different properties of the air stream at both inlet and outlet conditions. Given the outlet conditions, the sensible and latent heat transfers are

$$\dot{Q}_s = m_a C_{p,a} \left(T_{db,o} - T_{db,i} \right)$$

Eq. 5.3-21

$$\dot{Q}_L = \dot{Q}_T - \dot{Q}_s$$

Eq. 5.3-22

5.3.3.3   References

1. "Procedures For Simulating the Performance of Components and Systems for Energy Calculations", Third Edition, ASHRAE, 1975.

5.3.4 Type 42: Conditioning Equipment

This component models any piece of equipment whose performance can be characterized in terms of between 1 and 3 independent variables and between 1 and 5 dependent performance variables. Examples include: 1) an ambient source heat pump whose heating capacity and COP depend only on the outdoor air temperature, 2) an air conditioner whose cooling capacity and COP depend upon the ambient temperature and humidity, 3) a chemical heat pump whose performance is characterized in terms of generator, evaporator, and condenser conditions. Equipment performance is determined from user-supplied steady-state data. Reduced performance associated with frequent cycling or other means of controlling capacity is not considered. These effects can be accounted for through the use of the Type 43 Part Load Performance component.

5.3.4.1 Mathematical Description

The equipment is controlled by a single control Input, γ. The values of the dependent variables output by this component are just the product of each performance variable evaluated at the current conditions and the control function. If γ is 0, then all outputs are 0. If γ is 1, then the outputs are the interpolated values from the user supplied data.

The equipment performance data is read and interpolated using subroutine DATA. It should be provided in a file accessed through a Fortran logical unit, LU, as outlined in Section 8.6.5.4 Manual 08 – Programmer's Guide. Data values for each dependent performance variable are required for each combination of independent variable values specified. Examples using the TYPE 42 for one, two, and three independent variables follow:

Residential Heat Pump

The performance of an ambient source heat pump is primarily a function of the outdoor air temperature. Suppose one wished to use Type 42 to determine heating capacity, energy absorbed by the evaporator, and COP as a function of ambient temperature. In this case, there is a single independent variable (ambient temperature) and three dependent variables (capacity, absorbed energy, and COP). The first N_{X1} numbers in the data file must be values of ambient temperature in increasing order. Next are the values of capacity, energy absorbed, and COP at the lowest ambient temperature, followed by their values at the next air temperature, and so on. The current ambient temperature must be provided as the second Input. If the control function γ is 1, then the first three outputs will be values of capacity, energy absorbed, and COP at the current ambient temperature.

Air Conditioner

This example describes the use of the Type 42 to determine cooling capacity and COP of an air conditioner in terms of ambient temperature and relative humidity. Both the numbers of independent and dependent variables are two. Consider ambient temperature to be the primary independent variable. It is necessary to supply capacity and COP versus ambient temperature data for different values of relative humidity. The first N_{X2} numbers in the data file are the increasing values of relative humidity for which capacity and COP versus temperature data is provided. The next N_{X1} values are increasing ambient temperatures at which capacity and COP data are evaluated. Values of capacity and COP at the corresponding temperatures at the lowest

value of relative humidity are next, followed by capacity and COP values at these same temperatures, at the next relative humidity and so on. The second and third Inputs to this component should be the current values of the ambient temperature and relative humidity. The first two outputs are the values of capacity and COP at the current conditions times the control function, γ.

Chemical (Absorption) Heat Pump

The steady-state capacity and COP of an absorption heat pump may be characterized in terms of the energy Input rate to the generator, the evaporator fluid inlet temperature, and the condenser fluid inlet temperature. In this case, there are three independent and two dependent variables. Consider the generator energy as the primary independent variable and the evaporator and condenser inlet temperatures as the secondary and tertiary independent variables, respectively. It is necessary to provide N_{X3} . N_{X2} sets of capacity and COP data versus generator Input energy. The first N_{X3} numbers in the data file are increasing values of condenser inlet temperature. These are followed by N_{X2} values of increasing evaporator temperature and N_{X1} values of increasing generator Input energy. Values of capacity and COP for each value of generator Input at the lowest evaporator and condenser temperatures are next.

A set of these performance numbers is required for each evaporator temperature, still at the lowest condenser temperature. This sequence of data entry is repeated for each value of condenser temperature. The current energy Input to the generator, evaporator inlet temperature, and condenser inlet temperature must supplied as the second, third, and fourth Inputs to this component. The first two outputs are the products of the control function, γ, and the capacity and COP.

5.3.5   Type 43: Part Load Performance

This component determines purchased energy requirements and average operating efficiency (or COP) for heating or cooling equipment that is operating at less than full capacity. This condition generally results from the capacity of a machine being modulated in some manner to match the energy requirement or "load" of some process. The full-load capacity and efficiency, along with the load (or part-load capacity) are required as Inputs to this component. Energy loads for buildings may be calculated as outlined in the Building Loads and Structures Section using "energy rate" control. The user must also provide a relationship between the part-load factor (PLF) and the reciprocal of the duty cycle.

5.3.5.1   Nomenclature

Duty Cycle	ratio of part-load to full-load capacities
PLF	part-load factor; ratio of part-load to full-load efficiencies
$\dot{Q}_{eq}$	actual capacity; minimum of $\dot{Q}_{load}$ and $\dot{Q}_{max}$
$\dot{Q}_{load}$	energy rate required to meet the load (part-load capacity)
$\dot{Q}_{max}$	full-load capacity
$\dot{Q}_{pur}$	purchased energy required to operate equipment
max	full-load efficiency
op	part-load efficiency

5.3.5.2   Mathematical Description

The average operating efficiency of any equipment operating at part-load is given in terms of the full-load efficiency and part-load factor as

$$\eta_{op} = PLF \cdot \eta_{max}$$

Eq. 5.3-23

The part-load factor, PLF, is conveniently represented as a unique function of the reciprocal of the duty cycle as illustrated in Figure 5.3.5–1. The duty cycle is defined as the ratio of the load (or part-load capacity) to the full-load capacity.

$$\text{Duty Cycle} = \frac{\dot{Q}_{load}}{\dot{Q}_{max}}$$

Eq. 5.3-24
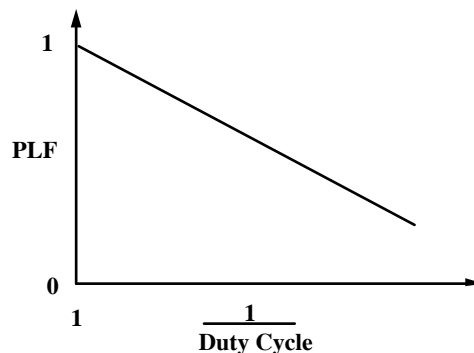
Figure 5.3.5–1: Part-Load Factor Definition

The user has the option of entering the slope of a linear relationship between PLF and 1/Duty Cycle. Otherwise, PLF vs. l/Duty Cycle data may be supplied in a file accessed by subroutine DATA through logical unit, LU (see Section 8.6.5.4 Manual 08 – Programmer's Guide). In this case, the first N_{data} numbers in the file are values of l/Duty Cycle in increasing order. These are followed by the corresponding PLF data points.

The actual delivery or removal energy rate of the heating or cooling equipment is

$$\dot{Q}_{eq} = \min (\dot{Q}_{max}, \dot{Q}_{load})$$
Eq. 5.3-25

The purchased energy is then

$$\dot{Q}_{pur} = \frac{\dot{Q}_{eq}}{\eta_{op}}$$
Eq. 5.3-26

5.3.6   Type 51: Cooling Tower

In a cooling tower, a hot water stream is in direct contact with an air stream and cooled as a result of sensible heat transfer due to temperature differences with the air and mass transfer resulting from evaporation to the air. The air and water streams may be configured in either counterflow or crossflow arrangements. Figure 5.3.6–1 shows a schematic of a counterflow forced-draft cooling tower. Ambient air is drawn upward through the falling water. Most towers contain a fill material that increases the water surface area in contact with the air. A cooling tower is usually composed of several tower cells that are in parallel and share a common sump. Water loss from the tower cells is replaced with make-up water to the sump.
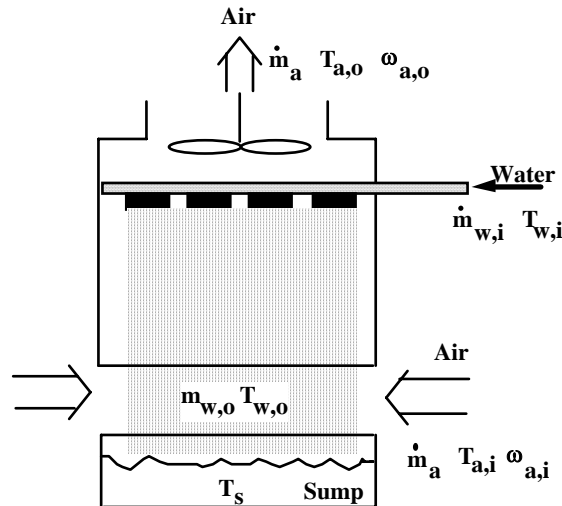
Figure 5.3.6–1: Schematic Of A Single Cell Counterflow Cooling Tower

This component models the performance of a multiple-cell counterflow or crossflow cooling tower and sump. There are two primary modes for this model. In the first mode, the user enters the coefficients of the mass transfer correlation, c and n (see mathematical description). Although this data is difficult to obtain, the ASHRAE Equipment Guide (1) and Simpson and Sherwood (2) give some typical data. In the second mode, the user enters overall performance data for the cooling tower and the model determines the parameters c and n that provide a best fit to the data in a least-squares sense. Values for c and n are output and can be used in subsequent simulations instead of the program recalculating them.

In mode 2, the user specifies parameters for the Fortran logical unit associated with a data file and the number of data points to be supplied. Each <u>line</u> of Input in the data file has the six items summarized in Table 5.3.6–1.

Table 5.3.6–1: Tower Performance Data Input

Data Item	Variable	Description	Units
1	$\dot{V}_a$	air volumetric flow rate	m^3/hr
2	$T_{a,i}$	air dry bulb temperature	°C
3	T_{wb}	air wet bulb temperature	°C
4	$\dot{m}_{w,i}$	water mass flow rate	kg/hr

5	$T_{w,i}$	water inlet temperature	°C
6	$T_{w,o}$	water outlet temperature	°C

A minimum of 2 and a maximum of 50 data points are required. The correlation used in this program is in terms of the ratio of the mass flow rate of water to the mass flow rate of air. The data must contain at least two different flow rate ratios in order for the program to correlate the data. For best results, the performance data should cover a range of conditions typical of the expected operation of the tower.

The example data file shown below was created from the data presented in Simpson and Sherwood (2) for the M-1 tower in English units:

```
line 1>    130600    86.0    75    6087     108.4    85.1
line 2>    71370     104.4   80    6087     120.0    96.1
line 3>    130700    85.9    75    8130     103.7    85.9
line 4>    71345     103.4   80    8130     115.8    98.0
line 5>    130600    85.6    75    10166    100.1    86.6
line 6>    71244     102.6   80    10166    114.5    100.7
```

5.3.6.1   *Nomenclature*

A_V	surface area of water droplets per tower cell exchange volume
C_{pw}	constant pressure specific heat of water
C_s	average derivative of saturation air enthalpy with respect to temperature
h_a	enthalpy of moist air per mass of dry air
h_D	mass transfer coefficient
h_s	enthalpy of saturated air
$\dot{m}_a$	mass flow rate of dry air
$\dot{m}_w$	mass flow rate of water
N_{cell}	number of tower cells operating
Ntu	mass transfer number of transfer units
$\dot{Q}_{cell}$	overall tower cell heat transfer rate
T_a	air temperature
T_{main}	temperature of water make-up to sump
T_s	fully-mixed sump temperature
T_w	water temperature
T_{wb}	ambient air wet bulb temperature
T_{ref}	water reference temperature (0 ° C)
V_{cell}	total tower cell exchange volume
V_s	total volume of water in sump
ω_a	air humidity ratio
ω_s	humidity of saturated air
ε_a	air-side heat transfer effectiveness
ρ_w	water density
SUBSCRIPTS:	
a	Air stream conditions
e	Effective
i	Inlet conditions
o	Outlet conditions
w	Water stream conditions
exit	Combined exit air conditions

5.3.6.2 Mathematical Description

Tower Cell Heat Rejection

Figure 5.3.6–2 shows a hypothetical process on a psychometric chart for the air states through a cooling tower. The air enters at a known state, characterized by a temperature, $T_{a,i}$, and humidity ratio, $\omega_{a,i}$ and exits at $T_{a,o}$ and $\omega_{a,o}$. The limiting exit state for the air would be if the air were saturated at a temperature equal to that of the incoming water stream. This corresponds to the maximum possible enthalpy of the exit air. Lines of constant enthalpy are shown for the air inlet and outlet and the saturated state corresponding to the water inlet. In terms of these enthalpies, the air-side heat transfer effectiveness is defined as the ratio of the air enthalpy difference to the maximum possible air enthalpy difference. For a known effectiveness, the heat rejection for an individual tower cell is then

$$\dot{Q}_{cell} = \varepsilon_a \dot{m}_a \left(h_{a,w,i} - h_{a,i} \right) \qquad \text{Eq. 5.3-27}$$

Using the assumption that the Lewis number equals one, Braun (3) has shown that the air effectiveness can be determined using the relationships for sensible heat exchangers with modified definitions for the number of transfer units and the capacitance rate ratios. For a counterflow cooling tower,

$$\varepsilon_a = \frac{1 - \exp\left(-Ntu\left(1 - m^*\right)\right)}{1 - m^*\exp\left(-Ntu\left(1 - m^*\right)\right)} \qquad \text{Eq. 5.3-28}$$
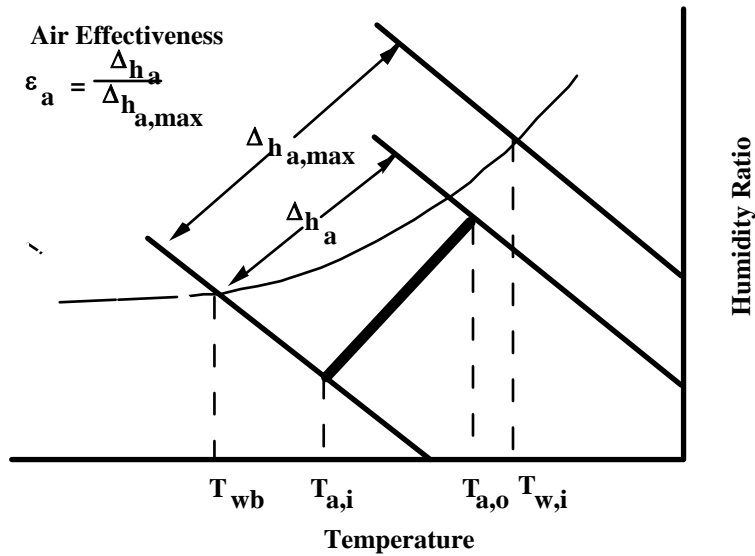
Figure 5.3.6–2: Psychometric Chart For The Air States Through A Cooling Tower

and for the cross-flow cooling tower,

$$\varepsilon_a = \frac{1}{m^*} \left(1 - \exp\left(-m^*\left(1 - \exp\left(-Ntu\right)\right)\right) \right) \qquad \text{Eq. 5.3-29}$$

where,

$$Ntu = \frac{h_D A_v V_{cell}}{\dot{m}_a}$$

Eq. 5.3-30

$$m* = \frac{\dot{m}_a C_s}{\dot{m}_{w,i} C_{pw}}$$

Eq. 5.3-31

The saturation specific heat, C_s, is defined as the average slope of the saturation enthalpy with respect to temperature curve. It is determined with the water inlet and outlet conditions and psychometric data using

$$C_s = \frac{h_{s,w,i} - h_{s,w,o}}{T_{w,i} - T_{w,o}}$$

Eq. 5.3-32

Tower Cell Performance Data

In order to determine tower effectiveness, it is necessary to have a relationship for the number of transfer units. General correlations for heat and mass transfer in cooling towers in terms of the physical tower characteristics are not readily available. As presented in the ASHRAE Equipment Guide (1), mass transfer data is generally correlated in the form

$$\frac{h_D A_v V_{cell}}{\dot{m}_w} = c \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^n$$

Eq. 5.3-33

Multiplying both sides of the above equation by $\dot{m}_w/\dot{m}_a$ and utilizing the definition for Ntu gives

$$Ntu = c \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{1+n}$$

Eq. 5.3-34

The exponent n is typically between -0.35 and -1.1, while c may be in the range of 0.5 to 5. Simpson and Sherwood (2) give data for a number of different tower designs. It is usually necessary to correlate specific data in order to determine the parameters for a particular tower. This component correlates performance data when in mode 2.

Tower Cell Exit Conditions

From an overall energy balance, the outlet temperature from a tower cell that is an inlet to the sump is determined as

$$T_{w,o} = \frac{\dot{m}_{w,i} C_{pw} (T_{w,i} - T_{ref}) - \dot{Q}_{cell}}{\dot{m}_{w,o} C_{pw}} + T_{ref}$$

Eq. 5.3-35

Most analyses neglect the water loss and assume that $m_{w,o} = m_{w,i}$. Generally, the water loss rate is on the order of 1% to 4% of the entering water flow rate. Neglecting this loss can result in about a 1 degree Celsius error in the exit water temperature. It is also necessary to know the water loss for analyzing the performance of the cooling tower sump, in order to incorporate the effects of water makeup. This component model includes the effect of the water loss.

From an overall mass balance, the exit water flow rate is

$$\dot{m}_{w,o} = \dot{m}_{w,i} - \dot{m}_a (\omega_{a,o} - \omega_{a,i})$$

Eq. 5.3-36

The exit humidity ratio is determined from an analytic solution to an equation for the mass transfer assuming an effective water surface condition and a Lewis Number of unity (3).

$$\omega_{a,o} = \omega_{s,w,e} + (\omega_{a,i} - \omega_{s,w,e}) \exp (-Ntu)$$

Eq. 5.3-37

The effective saturation humidity ratio, $\omega_{s,w,e}$, is found with psychometric data using an effective saturation enthalpy computed from the solution to the heat transfer equation.

$$h_{s,w,e} = h_{a,i} + \frac{h_{a,o} - h_{a,i}}{1 - \exp (-Ntu)}$$

Eq. 5.3-38

where,

$$h_{a,o} = h_{a,i} + \varepsilon_a (h_{s,w,i} - h_{a,i})$$

Eq. 5.3-39

To determine the air conditions exiting the tower, the exit air from each of the cells are combined to find "bulk" air conditions. The total exiting air flow rate is the sum of the flow rates exiting the cells,

$$\dot{m}_{a,exit} = \sum_{k=1}^{N_{cell}} \dot{m}_{a,k}$$

Eq. 5.3-40

The exiting enthalpy is found by summing the energy flow rates exiting the cells and dividing by the total air flow rate,

$$h_{a,exit} = \frac{\sum_{k=1}^{N_{cell}} (\dot{m}_a h_{a,0})_k}{\dot{m}_{a,exit}}$$

Eq. 5.3-41

From a mass balance on the moist air, an overall exit air humidity ratio can be calculated,

$$\omega_{a,exit} = \frac{\sum_{k=1}^{N_{cell}} (\dot{m}_{w,i} - \dot{m}_{w,o})_k}{\dot{m}_{a,exit}} + \omega_{a,i}$$

Eq. 5.3-42

Using $h_{a,exit}$ and $\omega_{a,exit}$, psychometrics data is used to find the bulk dry bulb temperature, $T_{a,exit}$, and the bulk wet bulb temperature, $T_{a,exit}$.

<u>Natural Convection Mode</u>

Under certain conditions cooling towers are operated with the fans off, using natural convection to move the air through the towers. This component allows a constant convective air flow rate to be specified as a parameter. The natural convection mode of the model is used when -1 is Input for the fan speed control signal.

<u>Sump and Fan Power Analyses</u>

Water enters the sump from each of the operating tower cells and from a water make-up source. The level of the sump is assumed to be constant, so that the flow of water make-up is equal to the total water loss from the cells. The water volume of the sump is further assumed to be fully-mixed, so that an energy balance is expressed as,

$$\rho_w \frac{dT_s}{dt} = \left[\sum_{k=1}^{N_{cell}} \left(\dot{m}_{w,0} \left(T_{w,o} - T_s \right) \right)_k \right] + \left[\left(\dot{m}_{w,i} - \sum_{k=1}^{N_{cell}} \left(\dot{m}_{w,o} \right)_k \right) - \left(T_{main} - T_s \right) \right]$$

Eq. 5.3-43

If the user specifies a sump volume less than or equal to zero, the left-hand side of the energy balance equation is set to zero and the steady-state sump temperature is computed.

The cooling tower fans are assumed to obey the fan laws. Given the power requirement at maximum fan speed, the power consumption for a cooling tower consisting of N_{cell} tower cells is calculated as

$$P_{tower} = \sum_{k=1}^{N_{cell}} \gamma_k^3 \, P_{max,k}$$

Eq. 5.3-44

where γ_k and $P_{max,k}$ are the relative fan speed and maximum power for the kth tower cell.

5.3.6.3   References

1. <u>ASHRAE Equipment Guide</u>, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, 1983.

2. Simpson, W.M. and Sherwood, T.K.,"Performance of Small Mechanical Draft Cooling Towers," <u>Refrigerating Engineering</u>, December, 1946.

3. Braun, J.E., "Methodologies for the Design and Control of Chilled Water Systems," Ph. D. Thesis, University of Wisconsin - Madison, 1988

5.3.7   Type 52: Detailed Cooling Coil

This component models the performance of a dehumidifying cooling coil, shown in Figure 5.3.7–1, using the effectiveness model outlined by Braun (1). The user must specify the geometry of the cooling coil and air duct. Either annular fins or continuous flat plate fins may be specified. The model does not account for ice formation on the coils during icing conditions.

The user may choose either a simple or detailed level of analysis. The level of detail determines the method used in modeling a coil operating under partially wet and dry conditions. In the detailed analysis a separate analysis is used for each of the dry and wet portions of the coil. In the simple level of analysis, the partially dry and wet coil is assumed to be either all dry or all wet. This is explained further in the mathematical description. The simple analysis provides a faster calculation of coil performance with normally only a small decrease in accuracy.

5.3.7.1   Nomenclature

C_{pm}	constant pressure specific heat of moist air
C_{pw}	constant pressure specific heat of liquid water
C_s	average slope of saturation air enthalpy versus temperature
C^*	ratio of air to water capacitance rate for dry analysis ($\dot{m}_a C_{pm}/\dot{m}_w C_{pw}$)
h_a	enthalpy of moist air per mass of dry air
h_s	enthalpy of saturated air per mass of dry air
$\dot{m}_a$	mass flow rate of dry air
$\dot{m}_w$	mass flow rate of water
m^*	ratio of air to water effective capacitance rate for wet analysis ($\dot{m}_a C_s/\dot{m}_w C_{pw}$)
N_{tu}	overall number of transfer units
$\dot{Q}$	overall heat transfer rate
T_a	air temperature
T_{dp}	air dewpoint temperature
T_s	surface temperature
T_w	water temperature
UA	overall heat conductance
ω_a	air humidity ratio
ω_s	humidity of saturated air
SUBSCRIPTS	
a	air stream conditions
dry	dry surface
e	effective
i	inlet or inside conditions
o	outlet or outside conditions
s	surface conditions
w	water stream conditions
wet	wet surface
x	point on coil where condensation begins

5.3.7.2   Mathematical Description

The limiting exit state for air that is cooled and dehumidified through a coiling coil would be if the air were saturated at a temperature equal to that of the incoming water stream. This corresponds to the minimum possible enthalpy of the exit air. The air-side heat transfer effectiveness is defined as the ratio of the air enthalpy difference to the maximum possible air enthalpy difference if the exit air were at the minimum possible enthalpy. Assuming that the Lewis number equals one, Braun (1) has shown that the air effectiveness can be determined using the relationships for

sensible heat exchangers with modified definitions for the number of transfer units and the capacitance rate ratios. This component models the performance of cooling coils utilizing this effectiveness model for counterflow geometries. The performance of multi-pass crossflow heat exchangers approach that of counterflow devices when the number of rows is greater than about four.

Fin efficiencies are required in order to calculate heat transfer coefficients between the air stream and coil. Threlkeld (2) notes that the performance of rectangular-plate fins of uniform thickness can be approximated by defining equivalent annular fins. Efficiencies are calculated for annular fins of uniform thickness ignoring end effects (3). Polynomial approximations are used to evaluate the Bessel functions used in calculating the efficiencies.
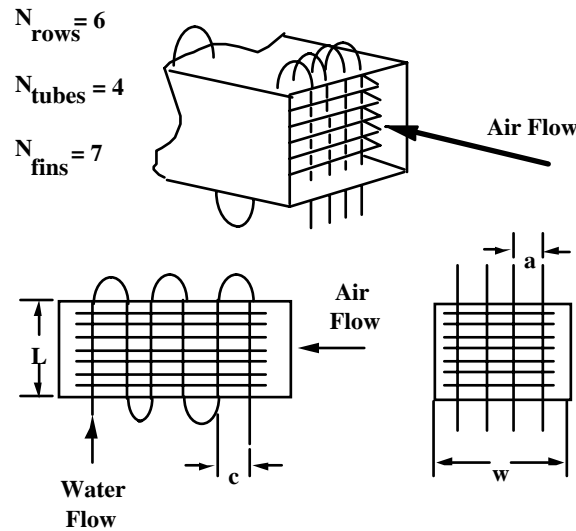
Figure 5.3.7–1: Schematic And Cross-Sectional Views Of A Cooling Coil.

Dry Coil Effectiveness

If the coil surface temperature at the air outlet is greater than the dewpoint of the incoming air, then the coil is completely dry throughout and standard heat exchanger effectiveness relationships apply.

In terms of the air-side heat transfer effectiveness, the dry coil heat transfer is

$$\dot{Q}_{dry} = \varepsilon_{dry,a}\dot{m}_a C_{pm}(T_{a,i} - T_{w,i})$$
Eq. 5.3-45

where

$$\varepsilon_{dry} = \frac{1 - \exp(-Ntu_{dry}(1 - C^*))}{1 - C^*\exp(-Ntu_{dry}(1 - C^*))}$$
Eq. 5.3-46

$$C^* = \frac{\dot{m}_a C_{pm}}{\dot{m}_w C_{pw}}$$
Eq. 5.3-47

$$Ntu_{dry} = \frac{UA_{dry}}{\dot{m}_a C_{pm}}$$

Eq. 5.3-48

The overall heat transfer conductance for dry heat exchangers is computed in terms of the heat transfer coefficients and fin efficiency as outlined in Threlkeld (2). For air flow over finned coil surfaces, correlations developed by Elmahdy (4) are utilized for determining the air-side heat transfer coefficient. The water-side heat transfer coefficient is determined using standard turbulent flow relations.

The exit air humidity ratio is equal to the inlet value, while the exit air and water temperatures are determined from energy balances on the flow streams as

$$T_{a,o} = T_{a,i} - \varepsilon_{dry,a}(T_{a,i} - T_{w,i})$$

Eq. 5.3-49

$$T_{w,o} = T_{w,i} - C^*(T_{a,i} - T_{a,o})$$

Eq. 5.3-50

The coil surface temperature at the air outlet is determined by equating the rate equation for heat transfer between the water and air streams with that between the water and the outside surface.

$$T_{s,o} = T_{w,i} + C^*\left(\frac{UA_{dry}}{UA_I}\right)(T_{a,o} - T_{w,i})$$

Eq. 5.3-51

If the surface temperature evaluated with the above equation is less than the inlet air dewpoint, then at least a portion of the coil is wet and the analysis in the following section must be applied.

<u>Wet Coil Effectiveness</u>

If the coil surface temperature at the air inlet is less than the dewpoint of the incoming air, then the coil is completely wet and dehumidification occurs throughout the coil.

For a completely wet coil, the heat transfer is

$$\dot{Q}_{wet} = \varepsilon_{wet,a}\, \dot{m}_a\, (h_{a,i} - h_{s,w,i})$$

Eq. 5.3-52

where

$$\varepsilon_{wet,a} = \frac{1 - \exp\left(-Ntu_{wet}(1 - m^*)\right)}{1 - m^* \exp\left(-Ntu_{wet}(1 - m^*)\right)}$$

Eq. 5.3-53

$$m^* = \frac{\dot{m}_a C_s}{\dot{m}_{w,i} C_{pw}}$$

Eq. 5.3-54

$$Ntu_{wet} = \frac{UA_{wet}}{\dot{m}_a}$$ **Eq. 5.3-55**

UA's are normally given in terms of a temperature difference, but in this case UA_{wet} is the heat conductance in terms of an enthalpy difference. Threlkeld (2) gives the relation for the overall wet surface enthalpy conductance for finned surfaces that is utilized in this model.

The saturation specific heat, C_s, is defined as the average slope of the saturation enthalpy curve with respect to temperature. It is determined with the water inlet and outlet conditions and psychometric data as:

$$C_s = \frac{h_{s,w,o} - h_{s,w,i}}{T_{w,o} - T_{w,i}}$$ **Eq. 5.3-56**

Analogous to the dry analysis, the exit air enthalpy and water temperature are

$$h_{a,o} = h_{a,i} + \varepsilon_{wet}(h_{a,i} - h_{s,w,i})$$ **Eq. 5.3-57**

$$T_{w,o} = T_{w,i} - \frac{\dot{m}_a}{\dot{m}_w C_{pw}}(h_{a,i} - h_{a,o})$$ **Eq. 5.3-58**

The average saturation specific heat, C_s, depends on the outlet water temperature and therefore an iterative method is required to find the outlet water temperature.

The exit air temperature is determined as described in the ASHRAE Equipment Guide (5).

$$T_{a,o} = T_{s,e} + (T_{a,i} - T_{s,e}) \exp\frac{-UA_o}{\dot{m}_a C_{pm}}$$ **Eq. 5.3-59**

where, the effective surface temperature is determined from its corresponding saturation enthalpy:

$$h_{s,s,e} = h_{a,i} + \frac{h_{a,o} - h_{a,i}}{1 - \exp\left(\frac{-UA_o}{\dot{m}_a C_{pm}}\right)}$$ **Eq. 5.3-60**

From the rate equations, the surface temperature at the air inlet is computed as

$$T_{s,i} = T_{w,o} + \frac{\dot{m}_a}{\dot{m}_w C_{pw}}\left(\frac{UA_{wet}}{UA_i}\right)(h_{a,i} - h_{s,w,o})$$ **Eq. 5.3-61**

If the surface temperature evaluated with the above equation is greater than the inlet air dewpoint, then a portion of the coil beginning at the air inlet is dry, while the remainder is wet.

Combined Wet and Dry Analysis

Depending upon the entering conditions and flow rates, only part of the coil may be wet. A detailed analysis involves determining the point in the coil at which the surface temperature equals the dewpoint of the entering air. A simpler approach is to assume that the coil is either completely wet or dry. The user specifies whether the simple or detailed analysis is to be used. The simpler approach requires less computational effort and should be used if its accuracy is acceptable.

<u>Simple Analysis</u>

The simple approach assumes that the coil is either completely wet of dry. Either assumed condition will tend to under predict the actual heat transfer. With the completely dry assumption, the latent heat transfer is neglected and the predicted heat transfer is low. With the assumption of a completely wet coil, the model predicts that the air is humidified during the portion of the coil in which the dewpoint of the air is less than the surface temperature. The latent heat transfer to the air associated with this "artificial" mass transfer reduces the overall calculated cooling capacity as compared with the actual situation. Since both the completely dry and wet analyses under predict the heat transfer, a simple approach is to utilize the results of the analysis that gives the largest heat transfer. The error associated with this method is generally less than 5 percent.

The steps for determining the heat transfer and outlet conditions using the simple analysis are summarized as follows:

Determine the coil heat transfer assuming that the coil is completely dry.

If the surface temperature at the air outlet determined with the dry analysis is less than the dewpoint of the entering air, then assume that the coil is completely wet and determine the heat transfer.

If the surface temperature at the air inlet determined with the wet analysis is greater the entering dewpoint temperature, then a portion of the coil is dry. The results of steps 1 or 2 that yield the largest heat transfer are utilized.

<u>Detailed Analysis</u>

Water will begin to condense on the surface of a cooling coil at the point where the surface temperature equals the dewpoint of the entering air. In order to calculate the heat transfer through the cooling coil, the relative areas associated with the wet and dry portions of the coil must be determined. Braun (1) presents the following method for calculating the heat transfer in a partially wet coil. The fraction of the coil surface area that is dry is

$$f_{dry} = \frac{-1}{K}\ln\left[\frac{(T_{dp} - T_{w,o}) + C^*(T_{a,i} - T_{dp})}{\left(1 - \frac{K}{Ntu_o}\right)(T_{a,i} - T_{w,o})}\right]$$

Eq. 5.3-62

where,

$$K = Ntu_{dry}\,(1 - C^*)$$

Eq. 5.3-63

The effectiveness for the wet and dry portions of the coil are

$$\varepsilon_{wet,a} = \frac{1 - \exp(-(1 - f_{dry})\,Ntu_{wet}\,(1 - m^*))}{1 - m^*\exp(-(1 - f_{dry})\,Ntu_{wet}\,(1 - m^*))}$$

Eq. 5.3-64

$$\varepsilon_{dry,a} = \frac{1 - \exp\left(-f_{dry}\,Ntu_{dry}\left(1 - C^*\right)\right)}{1 - C^*\exp\left(-f_{dry}\,Ntu_{dry}\left(1 - C^*\right)\right)}$$

Eq. 5.3-65

The water temperature at the point where condensation begins is

$$T_{w,x} = \frac{T_{w,i} + \dfrac{C^*\varepsilon_{wet,a}\left(h_{a,i} - h_{s,w,i}\right)}{C_{pm}} - C^*\varepsilon_{wet,a}\varepsilon_{dry,a}T_{a,i}}{\left(1 - C^*\varepsilon_{wet,a}\varepsilon_{dry,a}\right)}$$

Eq. 5.3-66

and the exit water temperature is

$$T_{w,o} = C^*\varepsilon_{dry,a}T_{a,i} + \left(1 - C^*\varepsilon_{dry,a}\right)T_{w,x}$$

Eq. 5.3-67

Since the fraction of the coil that is dry is dependent on the exit water temperature, an iterative method is required to find the exit water temperature.

The outlet air state from the coil is determined from

$$T_{a,o} = T_{s,e} + \left(T_{a,x} - T_{s,e}\right)\exp\left(-\left(1 - f_{dry}\right)Ntu_o\right)$$

Eq. 5.3-68

where $T_{s,e}$ is the effective surface temperature in the wet coil section and is determined from the saturation condition associated with

$$h_{s,s,e} = h_{a,x} + \frac{h_{a,o} - h_{a,x}}{1 - \exp\left(-\left(1 - f_{dry}\right)Ntu_o\right)}$$

Eq. 5.3-69

The air temperature and enthalpy at the point where condensation occurs are

$$T_{a,x} = T_{a,i} - \varepsilon_{dry,a}\left(T_{a,i} - T_{w,x}\right)$$

Eq. 5.3-70

$$h_{a,x} = h_{a,i} - \varepsilon_{dry,a}C_{pm}\left(T_{a,i} - T_{w,x}\right)$$

Eq. 5.3-71

<u>Coil Performance</u>

Three heat transfer rates are calculated from energy balances on the water and air streams. The total energy transferred across the coil is

$$\dot{Q}_{coil} = \dot{m}_w C_{pw}\left(T_{w,o} - T_{w,i}\right)$$

Eq. 5.3-72

The heat transfer attributed to condensing the moisture in the air is calculated as

$$\dot{Q}_{lat} = \dot{m}_a\left(\omega_{a,i} - \omega_{a,o}\right)h_{fg}$$

Eq. 5.3-73

where h_{fg} is the heat of vaporization for water and assumed constant at the value for standard conditions (2452 kJ/kg). The heat transfer attributed to sensible heat transfer is simply

$$\dot{Q}_{sens} = \dot{Q}_{coil} - \dot{Q}_{lat}$$

<div align="right">**Eq. 5.3-74**</div>

5.3.7.3   References

1. Braun, J.E., "Methodologies for the Design and Control of Chilled Water Systems," Ph. D. Thesis, University of Wisconsin - Madison, 1988.

2. Threlkeld J.L., Thermal Environmental Engineering, Prentice-Hall,New York, Second Edition, 1970.

3. Chapman, A.J., Heat Transfer, Macmillan Publishing Company, New York, N.Y., Fourth Edition, 1984.

4. Elmahdy, A.H. and Biggs, R.C., "Finned Tube Heat Exchanger: Correlation of Dry Surface Heat Transfer Data," ASHRAE Transactions, Vol. 85, Part 2, pp. 262-273, 1979.

5. ASHRAE Equipment Guide, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, 1983.

5.3.8   Type 53: Parallel Chillers

This component models the thermal performance and power requirements of identical motor driven chillers that are oriented in parallel as illustrated in Figure 5.3.8–1.   Each of the operating chillers is assumed to be controlled to maintain a specified chilled water supply temperature through modulation of the compressor capacity (either vane control or variable speed).   The Inputs to the component are the temperatures and total flow rates of the evaporator and condenser water, the desired chilled water set point, and the total number of chillers operating. The flow rates are divided equally between each of the operating chillers so as to give identical loading and heat rejection for each chiller.

The model relies on an empirical curve-fit to performance data. The user must create an external file containing performance data for a single chiller. The component parameter list specifies the Fortran logical unit associated with the data file and the number of operating points in the file. Each line of Input in the data file has three items, as summarized in Table 5.3.8–1, which describe the operating point.

Table 5.3.8–1: Chiller Performance Data Input

Data Item	Variable	Description
1	X	ratio of chiller load to a specified design load
2	Y	ratio of the temperature difference between the condenser water outlet and the evaporator water outlet relative to a specified design temperature difference
3	Z	ratio of the measured power relative to the power at the specified design conditions

Note: These ratios are explained further in the mathematical description section.
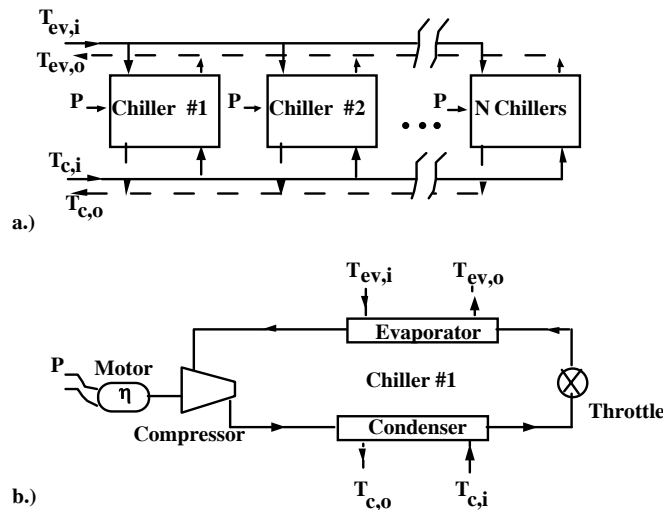
Figure 5.3.8–1: a) Parallel Chillers. b) Single Chiller

The design load, design temperature difference, and the associated design power requirement with which the performance data is normalized are specified as parameters for this component. Typically, they correspond to a condition of maximum chiller power consumption, but any operating point may be used as the design point.

A minimum of 6 data points is required and a maximum of 100 points is allowed. The user should attempt to provide data points that cover the expected operating range of the chiller.

5.3.8.1 Nomenclature

$C_{p,ev}$	specific heat of evaporator water
$C_{p,c}$	specific heat of condenser water
$\dot{m}_{ev}$	evaporator water mass flow rate
$\dot{m}_c$	condenser water mass flow rate
η_m	overall motor (+ gearbox) efficiency
N_{ch}	number of operating chillers (N_{ch} is less than or equal to the total number of chillers in parallel.)
P_{tot}	total power consumption for N_{ch} h chillers
P_{des}	power consumption at specified design conditions for an individual chiller
$\dot{Q}_{des}$	chilled water load at specified design conditions for an individual chiller
$\dot{Q}_{cond}$	total heat rejection through the condensers for N_{ch} h chillers
$\dot{Q}_{load}$	total chilled water load for N_{ch} chillers
$T_{chw,s}$	chilled water set temperature
$T_{ev,i}$	evaporator water inlet temperature
$T_{ev,o}$	evaporator water outlet temperature
$T_{c,I}$	condenser water inlet temperature
$T_{c,o}$	condenser water outlet temperature
ΔT_{des}	temperature difference between the condenser water outlet and the evaporator water outlet at the specified design conditions

5.3.8.2 Mathematical Description

The ratios required for the chiller performance Input file data are:

$$X = \frac{\dot{Q}_{load}}{N_{ch}\dot{Q}_{des}}$$

Eq. 5.3-75

$$Y = \frac{T_{c,o} - T_{ev,o}}{\Delta T_{des}}$$

Eq. 5.3-76

$$Z = \frac{P_{tot}}{N_{ch}P_{des}}$$

Eq. 5.3-77

Braun (1) has shown that the dimensionless power consumption of either variable-speed or fixed-speed, vane controlled chillers may be correlated with the following empirical form:

$$Z = a_0 + a_1X + a_2X^2 + a_3Y + a_4Y^2 + a_5XY$$

Eq. 5.3-78

The empirical coefficients of the above equation (a_0 - a_5) are determined with linear least-squares curve-fitting applied to measured or modeled performance data. The overall chiller

power consumption for N_{ch} chillers operating in parallel with equal evaporator and condenser water flow rates is

$$P_{tot} = N_{ch}P_{des} (a_0 + a_1X + a_2X^2 + a_3Y + a_4Y^2 + a_5XY) \qquad \text{Eq. 5.3-79}$$

In order to estimate the chiller power consumption with the above relation, it is necessary to know the load and leaving water temperatures. The chiller is controlled to give a specified chilled water supply temperature to the load. The chilled water load is computed from the chilled water set point and entering conditions as:

$$\dot{Q}_{load} = \dot{m}_{ev}C_{p,ev} (T_{ev,i} - T_{chw,s}) \qquad \text{Eq. 5.3-80}$$

If the computed load is greater than a maximum or less than a minimum chiller capacity specified as parameters, then the load is restricted to one of these limits and a new chilled water supply temperature that gives this load is determined.

The next step is to find the leaving condenser water temperature, which depends upon the entering conditions, load, and power consumption. The heat rejection from the condensers can be found from an overall energy balance on the chiller:

$$\dot{Q}_{cond} = \dot{Q}_{load} + \eta_m P_{tot} \qquad \text{Eq. 5.3-81}$$

The heat rejection from the condensers can also be written in terms of the condenser fluid conditions:

$$\dot{Q}_{cond} = \dot{m}_c C_{p,c} (T_{c,o} - T_{c,i}) = \dot{m}_c C_{p,c} [Y\Delta T_{des} - (T_{c,i} - T_{ev,o})] \qquad \text{Eq. 5.3-82}$$

Substitutions for the heat rejection and the total chiller power in the energy balance leads to an implicit relationship for the dimensionless leaving water temperature.

$$\dot{m}_c C_{p,c} [Y\Delta T_{des} - (T_{c,i} - T_{ev,o})] = \dot{Q}_{load} + \eta_m N_{ch}P_{des} (a_0 + a_1X + a_2X^2 + a_3Y + a_4Y^2 + a_5XY) \qquad \text{Eq. 5.3-83}$$

The above equation is quadratic in Y and may be solved explicitly.

A coefficient of performance (COP) can be defined as:

$$COP = \frac{\dot{Q}_{load}}{P_{tot}} \qquad \text{Eq. 5.3-84}$$

5.3.8.3   References

1. Braun, J.E., "Performance and Control Characteristics of Large Central Cooling System," <u>ASHRAE Transactions</u>, Vol. 93, Part 1, 1987.

5.3.9   Type 92: ON/OFF Auxiliary Cooling Device

The auxiliary cooling device is the compliment to the Type 6 Auxiliary Heater (see section 5.3.1). Instead of adding heat to a flow stream, the auxiliary cooling device removes heat. Like Type 6, the cooler is designed to remove heat from the flow stream at a user determined rate, $\dot{Q}_{max}$, whenever the external control Input, γ is equal to 1 and the cooling unit outlet temperature is greater than a user specified minimum, T_{set}.

5.3.9.1   Nomenclature

Cpf	[kJ/kg.K]	fluid specific heat
$\dot{m}$l	[kg/hr]	inlet fluid mass flow rate
$\dot{m}$o	[kg/hr]	outlet fluid mass flow rate
$\dot{Q}_{aux}$	[kJ/hr]	required heating rate including efficiency effects
$\dot{Q}_{fluid}$	[kJ/hr]	rate of heat addition to fluid stream
$\dot{Q}_{loss}$	[kJ/hr]	rate of thermal losses from heater to environment
$\dot{Q}_{max}$	[kJ/hr]	maximum heating rate of heater
Tenv	[C]	temperature of heater surroundings for loss calculations
Ti	[C]	fluid inlet temperature
To	[C]	fluid outlet temperature
Tset	[C]	set temperature of heater internal thermostat
UA	[kJ/hr]	overall loss coefficient between the heater and its surroundings during operation
	[-]	external control function which has values of 0 or 1
η_{htr}	[0..1]	efficiency of auxiliary heater

5.3.9.2   Mathematical Description

If $T_i \leq T_{set}$, $\dot{m}_i \leq 0$, or $\gamma = 0$ then

$$T_o = T_i,\ \dot{m}_o = \dot{m}_i,\ \dot{Q}_{loss} = 0,\ \dot{Q}_{fluid} = 0,\ \text{and } \dot{Q}_{aux} = 0$$

Otherwise, an energy balance on the steady-state cooling device reveals:

$$T_o = \frac{\dot{Q}_{max}\,\eta_{htr} + \dot{m}\,C_{pf}\,T_i + UA\,T_{env} - \dfrac{UA\,T_i}{2}}{\dot{m}\,C_{pf} + \dfrac{UA}{2}}$$

Eq. 5.3-85

$$\dot{m}_o = \dot{m}_i$$

$$\dot{Q}_{aux} = \dot{Q}_{max}$$

$$\dot{Q}_{fluid} = \dot{m}_o\,C_{pf}\,(T_i - T_o)$$

Eq. 5.3-86

$$\overline{T} = \frac{(T_o + T_{in})}{2}$$

Eq. 5.3-87

$$\dot{Q}_{loss} = UA\,(\overline{T} - T_{env}) + (1 - \eta_{htr})\,\dot{Q}_{max}$$

Eq. 5.3-88

Unless $T_o < T_{set}$, then

$T_o = T_{set}$,

$\dot{m}_o = \dot{m}_i$,

$$\dot{Q}_{fluid} = \dot{m}_o\,C_{pf}\,(T_{set} - T_i)$$

Eq. 5.3-89

$$\overline{T} = \frac{(T_{set} + T_{in})}{2}$$

Eq. 5.3-90

$$\dot{Q}_{loss} = UA\,(\overline{T} - T_{env}) + (1 - \eta_{htr})\,\dot{Q}_{max}$$

Eq. 5.3-91

$$\dot{Q}_{aux} = \frac{\dot{m}\,C_{pf}\,(T_{set} - T_i) + UA\,(\overline{T} - T_{env})}{\eta_{htr}}$$

Eq. 5.3-92

where: $\dot{Q}_{aux} = \dot{Q}_{loss} + \dot{Q}_{fluid}$

5.3.10　Type 107: Single Effect Hot Water Fired Absorption Chiller

Type107 uses a normalized catalog data lookup approach to model a single-effect hot-water fired absorption chiller. "Hot Water-Fired" indicates that the energy supplied to the machine's generator comes from a hot water stream. Because the data files are normalized, the user may model any size chiller using a given set of data files. Example files are provided.

5.3.10.1　Nomenclature

Capacity	[kJ/hr]	Mass flow rate of air entering the "fresh air" side of the device.
$f_{FullLoadCapacity}$	[0..1]	Fraction of the device's full load capacity during operation under current conditions.
$f_{NominalCapacity}$	[0..1]	Fraction of the device's nominal capacity during operation under current conditions.
$Capacity_{rated}$	[kJ/hr]	Rated cooling capacity of the device
$\dot{Q}_{remove}$	[kJ/hr]	Amount of energy that must be removed from the chilled water stream in order to reach the set point temperature
$T_{chw,set}$	[ºC]	"Chilled water" stream set point.
f_{design}	[0..1]	Fraction of design capacity at which the machine is currently operating.
COP_{rated}	[-]	Machine's rated Coefficient of Performance.
$f_{DesignEnergyInput}$	[0..1]	Fraction of design energy Input currently required by the machine.
$T_{hw,out}$	[ºC]	Temperature of fluid exiting the "hot water" stream
$T_{hw,in}$	[ºC]	Temperature of fluid entering the "hot water" stream
$\dot{Q}_{hw}$	[kJ/hr]	Energy removed from the "hot water" stream
$\dot{m}_{hw}$	[kg/hr]	Mass flow rate of the "hot water" stream fluid
Cp_{hw}	[kJ/kg.K]	Specific heat of the "hot water" stream fluid.
$T_{chw,out}$	[ºC]	Temperature of fluid exiting the "chilled water" stream
$T_{chw,in}$	[ºC]	Temperature of fluid entering the "chilled water" stream
$\dot{Q}_{chw}$	[kJ/hr]	Energy removed from the "chilled water" stream
$\dot{m}_{chw}$	[kg/hr]	Mass flow rate of the "chilled water" stream fluid
Cp_{chw}	[kJ/kg.K]	Specific heat of the "chilled water" stream fluid.
$T_{cw,out}$	[ºC]	Temperature of fluid exiting the "cooling water" stream
$T_{cw,out}$	[ºC]	Temperature of fluid entering the "cooling water" stream
$\dot{Q}_{cw}$	[kJ/hr]	Energy added to the "cooling water" stream
$\dot{m}_{cw}$	[kg/hr]	Mass flow rate of the "cooling water" stream fluid
Cp_{cw}	[kJ/kg.K]	Specific heat of the "cooling water" stream fluid.
$\dot{Q}_{aux}$	[kJ/hr]	Energy draw of parasitics (solutions pumps, controls, etc.)
COP	[-]	Coefficient of Performance for the device.

5.3.10.2 Mathematical Description

In a "conventional" refrigeration cycle, refrigerant returns as low pressure vapor (ideally near the saturated vapor point) from the evaporator. This vapor then passes through an electrically driven compressor in which it is turned into a higher pressure gas before being passed to the condenser. Both the work of pressurizing the vapor and the work of pumping the refrigerant around the loop is done by the an electrically driven compressor. In a "single effect" absorption machine, the refrigerant vapor (typically water) returning from the evaporator is absorbed in a medium (often aqueous ammonia or lithium bromide) and is cooled to a liquid state, rejecting its heat to a cooling fluid stream. This liquid is then pumped into a device called a generator, where heat is added from a hot water stream to desorb the refrigerant from its solution. Once the refrigerant is revaporized, it enters the condenser and follows a standard refrigerant cycle (condenser, expansion valve, evaporator). A single effect absorption cycle is shown schematically in Figure 5.3.10–1.
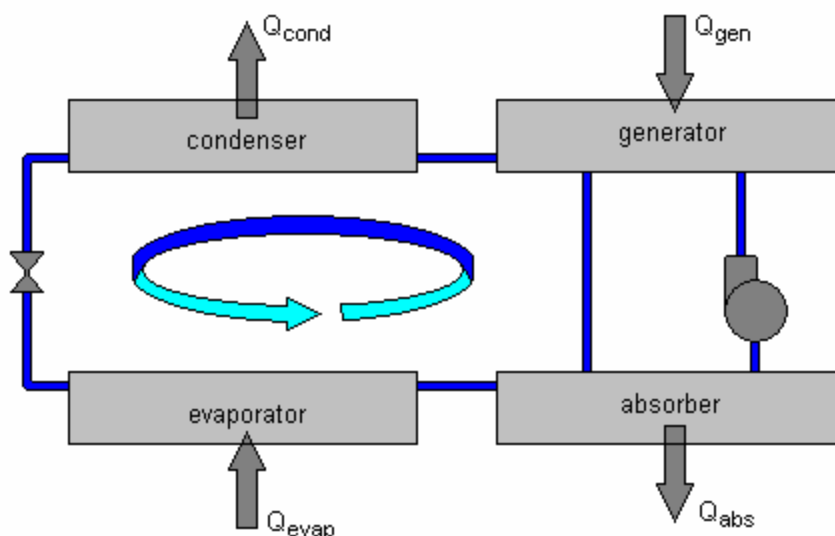
Figure 5.3.10–1: Single-Effect Absorption Chiller Device Schematic

The benefit of an absorption refrigerant cycles is that the energy required to pump the liquid refrigerant from a low pressure in the absorber to a higher pressure in the generator is comparatively small and the remainder of the work (liquefying and vaporizing the refrigerant) can be accomplished with heat instead of electricity. This fact makes absorption chillers especially valuable in cogeneration systems where waste heat from steam and other processes is abundant.

Type107 uses a catalog data lookup approach to predict the performance of a single effect, hot water fired absorption chiller. In this design, the heat required to desorb the refrigerant is provided by a stream of hot water. The energy of the refrigerant absorption process is rejected to a cooling water stream and the machine is designed to chill a third fluid stream to a user designated set point temperature. Because of the catalog data lookup approach, Type107 is not applicable over every range of inlet conditions. As with other components that rely on catalog data, the performance of the machine can be predicted and interpolated within the range of available data but cannot be extrapolated beyond the range. One beneficial feature to this model is that the data, taken directly from manufacturer's catalogs available online is normalized so that once a data file has been created, it may be used to model absorption machines other than the specific

size for which the data was intended. In creating example data files for distribution with this component, the developers noted that there was very little variability between data files once they were normalized. Using normalized data and the model's first two parameters (design coefficient of performance and design capacity) the user can adjust the size of the machine being modeled to whatever is appropriate to the system being simulated.

Type107 requires a single data file, which is to be specified in the standard TRNSYS data format for the DynamicData subroutine. The data file is discussed in section 5.3.10.3.

The file contains values of normalized fraction of full load capacity and fraction of design energy Input for various values of fraction of design load (-) chilled water set point temperature (ºC) entering cooling water temperature (ºC) and entering hot water temperature (ºC).

Upon determining that the absorption chiller is ON based on the value of the control signal, Type107 first determines the fraction of design load at which it must operate first by calculating the amount of energy that must be removed from the chilled water stream in order to bring it from its entering temperature to the set point temperature:

$$\dot{Q}_{remove} = \dot{m}_{chw} Cp_{chw} \left(T_{chw,in} - T_{chw,set} \right)$$

Eq. 5.3-93

The required energy removal is then divided by the machine's capacity (parameter 1) to determine the fraction of design load at which the machine is required to operate.

$$f_{DesignLoad} = \frac{\dot{Q}_{remove}}{Capacity_{Rated}}$$

Eq. 5.3-94

Type107 then calls the TRNSYS Dynamic Data subroutine with the user specified hot water inlet temperature, cooling water inlet temperature, chilled water set point temperature, and fraction of design load. Dynamic Data reads the user specified data file and returns values of the fraction of the machine's rated capacity that is available given the hot water entering temperature. This reduced capacity is called the nominal capacity as opposed to the rated capacity. The capacity of the machine at any given time, therefore is given by Eq. 5.3-95.

$$Capacity = f_{FullLoadCapacity} * f_{NominalCapacity} Capacity_{Rated}$$

Eq. 5.3-95

Dynamic Data also returns the machine's fraction of design energy Input for the current conditions. When operating at rated capacity, the design energy Input must be provided to the chiller in order for it to operate. When the chiller is running at part load, only a fraction of the design energy Input is required. With this value returned by Dynamic Data, the energy delivered to the chiller by the hot water stream can be calculated using Eq. 5.3-96.

$$\dot{Q}_{hw} = \frac{Capacity_{Rated}}{COP_{Rated}} f_{DesignEnergyInput}$$

Eq. 5.3-96

The hot water stream outlet temperature is then

$$T_{hw,out} = T_{hw,in} - \frac{\dot{Q}_{hw}}{\dot{m}_{hw} Cp_{hw}}$$

Eq. 5.3-97

The chilled water outlet temperature, which should be the set point temperature but may be greater if the machine is capacity limited, is then calculated as:

$$T_{chw,out} = T_{chw,in} - \frac{MIN\left(\dot{Q}_{remove}, Capacity\right)}{\dot{m}_{chw} Cp_{chw}}$$

Eq. 5.3-98

In order for energy to balance in the device, the energy rejection to the cooling water stream is given by Eq. 5.3-99.

$$\dot{Q}_{cw} = \dot{Q}_{chw} + \dot{Q}_{hw} + \dot{Q}_{aux}$$

Eq. 5.3-99

The term Q_{aux} accounts for the energy consumed by the various parasitics in the system such as solution pumps, fluid stream pumps, controls. The auxiliary energy requirement of the device is specified among the model's parameters. Type107 assumes that the entire auxiliary energy requirement is used whenever the device is in operation, regardless of whether or not it is operating at full capacity.

Lastly, the temperature of the exiting cooling water stream can be calculated using Eq. 5.3-100.

$$T_{cw,out} = T_{cw,in} + \frac{\dot{Q}_{cw}}{\dot{m}_{cw} Cp_{cw}}$$

Eq. 5.3-100

The device COP is defined as shown in Eq. 5.3-101.

$$COP = \frac{\dot{Q}_{chw}}{\dot{Q}_{aux} + \dot{Q}_{hw}}$$

Eq. 5.3-101

5.3.10.3   External data file

Type 107 reads the cooling machine performance data from a data file. An example is provided in "Examples\Data Files". The data file format is as follows:

```
<Fraction of design load 1>  <Fract. Of design load 2>  etc.   NF values [0;1]
<Chilled water setpoint 1>  <Chilled water setpoint 2>  etc.   NS values [°C]
<Entering Chilled Water Temperature 1>  < ECWT 2>  etc.        NE values [°C]
<Inlet Hot Water Temperature 1>  <IHWT 2>  etc.               NI values [°C]
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,1,1}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,1,2}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,1,3}
... (loop on IHWT values for Frac. Of design load 1, CWSet 1, ECWT 1)
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,1,NI}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,2,1}
... (loop on IHWT values for Frac. Of design load 1, CWSet 1, ECWT 2)
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,2,NI}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,3,1}
... (loop on IHWT values for Frac. Of design load 1, CWSet 1, ECWT 3)
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,3,NI}
... (loop on ECWT values for Frac. Of design load 1, CWSet 1 – all IHWT val.)
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,1,NE,NI}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,2,1,1}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,2,1,2}
... (loop on CWSet values for Frac. Of design load 1 – all ECWT and IHWT val.)
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {1,NS,NE,NI}
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {2,1,1,1}
```

```
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {2,1,1,2}
... (loop on Frac. Of design load values – all CWSet, ECWT and IHWT val.)
<Fraction of rated capacity> <Fract. Of Design Energy Input>  for {NF,NS,NE,NI}
```

Where {i,j,k,l} means that the fraction of rated capacity and the fraction of design energy Input are given for:

- i[th] value of the Fraction of design load
- j[th] value of the Chilled water setpoint
- k[th] value of the Entering chilled water temperature
- l[th] value of the Inlet hot water temperature

The principle of the data file is that the first 4 lines give the values of the 4 independent variables that will be used in the performance map. Then the 2 dependent variables are given for all combinations of the independent variables. The values of the last independent variables are first cycled through, then the 3rd independent variable, etc.

EXAMPLE

```
0.0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0  !Fraction of Design Load
5.56 6.11 6.67 7.22 7.78 8.89 10.0  !Chilled Water Setpoint (C)
26.7 29.4 32.2  !Entering Cooling Water Temperature (C)
108.9  111.7  113.9  115.0  116.1 !Inlet Hot Water Temperature (C)
0.9878 0.0000 !Capacity and Design Energy Input Fract. at 0.0 5.56 26.7 108.9
1.0367 0.0000 !Capacity and Design Energy Input Fract. at 0.0 5.56 26.7 111.7

... etc.  (see the example file in "Examples\Data Files" for more details)

1.0469 0.9800 !Capacity and Design Energy Input Fract. at 1.0 10.0 32.2 116.1
```

5.3.11   Type 121: Simple Furnace / Air Heater

Much like Type6 does for fluids, Type 121 represents an air heating device that can be controlled either externally, or set to automatically try and attain a set point temperature. The furnace is bound by a heating capacity and an efficiency. Thermal losses from the furnace are based on the average air temperature. The outlet state of the air is determined by an enthalpy based energy balance that takes pressure effects into account.

5.3.11.1   Nomenclature

$h_{air,in}$ [kJ/kg.K]   Enthalpy of air entering the furnace.

$h_{air,out}$ [kJ/kg.K]   Enthalpy of air exiting the furnace.

$\dot{m}_{air}$ [kg/hr]   Mass flow rate of air (entering mass flow rate = exiting mass flow rate)

$\dot{q}_{max}$ [kJ/hr]   Capacity of the furnace

$\dot{q}_{\eta}$ [kJ/hr]   Maximum heating rate of the furnace (accounting for efficiency effects)

UA [kJ/K]   Overall thermal loss coefficient for the furnace.

$\overline{T}$ [C]   Average temperature of air in the furnace.

T_{env} [C]   Temperature of the air surrounding the furnace (for loss calculations)

5.3.11.2   Mathematical Description

The operation of Type 121 is governed by the energy balance shown in Figure 5.3.11–1.
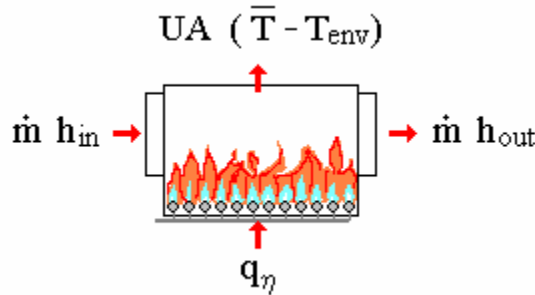
Figure 5.3.11–1: Furnace Energy Balance

Where h_{in} and h_{out} refer to the enthalpy of air entering and exiting the furnace, respectively. Thermal loss calculations are made based on the average temperature of air in the furnace and q_{η} is the capacity of the furnace multiplied by its overall efficiency. In other words, q_{η} is the amount of energy actually transferred from the fuel to the air in the furnace. The energy balance is written as shown in Eq. 5.3-102 so as to solve for the enthalpy of air exiting the furnace.

$$h_{air,out} = h_{air,in} + \frac{q_{\eta}}{\dot{m}} - \frac{UA}{\dot{m}}\left(\overline{T} - T_{env}\right)$$ **Eq. 5.3-102**

Because the outlet temperature of the air is not initially known, Type 121 uses an iterative process to arrive at the exiting air condition. The enthalpy of entering air is calculated and returned by the TRNSYS PSYCHROMETRICS routine whereupon the Eq. 5.3-102 energy balance is solved first guessing that the inlet and outlet air temperatures are equal. The resulting outlet enthalpy is passed back to the PSYCHROMETRICS routine, which in turn returns a new outlet air temperature. The new outlet air temperature is used to modify the energy balance, affecting both the thermal loss term and the energy exiting through the air stream. Iteration continues until the temperature of outlet air returned from PSYCHROMETRICS changes less than 0.01 ºC. This default tolerance may be modified in the Type 121 source code if desired.

Type 121 also accounts for air pressure drop across the furnace. The pressure drop is applied to the air outlet conditions whether or not the furnace is in operation and whether or not air is flowing. The assumption that pressure drop occurs without regard to flow is made so that TRNSYS is better able to converge upon a solution when a system starts up. Users wishing to ignore pressure effects should simply set the pressure drop parameter to zero.

5.4   Hydrogen Systems

Acknowledgements

The Hydrogen Systems components in this section are part of the HYDROGEMS library developed by Øystein Ulleberg and Ronny Glöckner at the Institute for Energy Technology (IFE), Norway. Those components have been integrated into the standard TRNSYS library for version 16.

Available components

At the core of the Hydrogen Energy Systems library are two different fuel cell models, Type 170 and Type 173. Type 170 models a Proton Exchange Membrane Fuel Cell (PEMFC) and Type 173 models an Alkaline Fuel Cell (AFC). Both models include detailed electrical, thermodynamic and thermal models and can operate from Hydrogen and Air or Hydrogen and (pure) Oxygen.

Hydrogen storage is modeled by Type 164 (compressed gas tank). The model calculates the gas pressure using the ideal gas law or the van der Waals equation of state for real gases.

Electricity generation from Hydrogen in an Advanced Alkaline Water Electrolyzer is modeled in Type 160. The model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships. A dynamic thermal model is also included.

The library also includes dedicated high level controllers (Type 100, electrolyzer controller, and Type 105, Master level controller) and accessories (Type 167, multistage compressor).

Detailed mathematical reference

In addition to this manual, the Hydrogen Systems components mathematical description is provided as an EES-based executable program which is included with TRNSYS 16. The program (HydrogenSystemsDocumentation.exe) is located in "%TRNSYS16%\Documentation" (where %TRNSYS16% is the TRNSYS 16 installation directory).

5.4.1 Type 100: Electrolyzer controller

Type 100 implements a set of control functions for an electrolyzer of an integrated mini-grid connected system (e.g. RE source, electrolyzer, H_2 storage, fuel cell). The electrolyzer can operate in two power modes (constant or variable power).

5.4.1.1 Nomenclature

P_{excess}	[W]	Excess power from the RE sources to the mini-grid
SOC	[-]	State Of Charge of the energy storage
$P_{ely,set}$	[W]	Electrolyzer setpoint power
P_{idle}	[W]	Electrolyzer idling (minimum) power
EL_{low}	[-]	State Of Charge for which the Electrolyzer is switched ON
EL_{up}	[-]	State Of Charge for which the Electrolyzer is switched OFF

5.4.1.2 Mathematical description

The controller actually set a power setpoint for a power device that is linking the electrolyzer. The power setpoint is adjusted to maintain the state of charge of a storage device (e.g. compressed gas tank) within the target range.

CONTROL STRATEGY

If the electrolyzer is currently OFF (Idling):

- If SOC < EL_{low}, switch ON and operate with $P_{ely,set} = P_{excess}$
- Else, remain OFF (Idling)

If the electrolyzer is currently ON:

- If SOC > EL_{up}, switch OFF (Idling)
- Else, keep operating at $P_{ely,set} = P_{excess}$

IDLING POWER

The electrolyzer is assumed to have a minimum idling power. When switched "OFF", $P_{ely,set}$ is not set to zero but to P_{idle}.

CONTROLLER MODES

The controller has two modes: Constant power and Variable power.

In Variable Power mode (MODE = 1):

- If the electrolyzer is ON: $P_{ely,set} = Max (P_{excess} , P_{idle})$
- If the electrolyzer is OFF: $P_{ely,set} = P_{idle}$

In Constant Power mode (MODE = 2):

- If the electrolyzer is ON: $P_{ely,set} = P_{excess}$ (always)
- If the electrolyzer is OFF: $P_{ely,set} = P_{idle}$

This means that in Constant Power mode, Type 100 will allow the electrolyzer to operate at a power below the set limit for idling. To ensure correct operation of Type 160 (electrolyzer), it is necessary to implement a correction mechanism in the system.

5.4.1.3   Special considerations

It is important to realize that the action from the controller is to calculate a power setpoint for a power conditioning device (Type 175) which is connected to the electrolyzer (Type 160). The controller also has a "switch" output for numerical reasons, but that output should not be connected to the electrolyzer. Please study the examples of Hydrogen System control to make sure you understand the operation of Type 100.

5.4.2   Type 105: Master level controller for SAPS

Type 105 is a master level controller for a stand-alone power system that consists of wind turbines (or another source of renewable power), an electrolyzer, a fuel cell, a Hydrogen storage device and Diesel Engine Generator Sets (or another auxiliary power source that consists of multiple units).

In the following, WECS is used to refer to the wind turbine(s) and DEGS is used to refer to Diesel Engine Generator Sets. The reader should keep in mind that both systems can be replaced with other components that have similar properties as far as the controller is concerned.

5.4.2.1   Nomenclature

P_{WECS}	[W]	Power generated by the WECS
$P_{DEGS,max}$	[W]	Rated Power generated by one DEGS
$P_{DEGS,set}$	[W]	Power setpoint for each DEGS
N_{DEGS}	[-]	Number of DEGS operating at fixed power
$N_{DEGS,min}$	[-]	Minimum number of DEGS operating at any time
$N_{DEGS,max}$	[-]	Maximum number of DEGS operating at any time
$P_{FC,min}$	[W]	Minimum (idling) Power of the Fuel Cell
$P_{FC,max}$	[W]	Rated Power of the Fuel Cell
$P_{FC,set}$	[W]	Power setpoint for the Fuel Cell
$P_{Ely,min}$	[W]	Minimum (idling) Power of the Electrolyzer
$P_{Ely,max}$	[W]	Rated Power of the Electrolyzer
$P_{Ely,set}$	[W]	Power setpoint for the Electrolyzer
P_{Load}	[W]	Power to the load
P_{dump}	[W]	Dumped Power
P_{busbar}	[W]	Power balance on the mini-grid bus bar
SOC	[-]	State Of Charge of the energy storage
EL_{low}	[-]	State Of Charge for which the Electrolyzer is switched ON
EL_{up}	[-]	State Of Charge for which the Electrolyzer is switched OFF
FClow	[-]	State Of Charge for which the Fuel Cell is switched OFF
FCup	[-]	State Of Charge for which the Fuel Cell is switched ON

5.4.2.2   Mathematical description

The controller makes decisions based on the mini-grid bus bar power balance, assuming that the minimum number of DEGS is operating and that the Fuel Cell and Electrolyzer are idling:

$$P_{busbar} \; = \; P_{WECS} + N_{DEGS,min} \, P_{DEGS,max} + \; P_{FC,min} \, \text{-} \; P_{Load} - P_{Ely,min} \qquad \textbf{Eq 5.4.2-1}$$

EXCESS POWER ($P_{BUSBAR} > 0$ IN EQ 5.4.2-1)

1. Electrolyzer status

- If the electrolyzer is currently OFF (Idling):
    - If $SOC < EL_{low}$, switch ON:
      Operate with $P_{ely,set} = P_{WECS} + N_{DEGS,min} P_{DEGS,max} + P_{FC,min} - P_{Load}$
    - Else, remain OFF (Idling)
- Else (electrolyzer is currently ON):
    - If $SOC > EL_{up}$, switch OFF (Idling)
    - Else, keep operating and $P_{ely,set} = P_{WECS} + N_{DEGS,min} P_{DEGS,max} + P_{FC,min} - P_{Load}$
- Constraints on $P_{Ely,set}$: If $P_{Ely,set} > P_{Ely,max}$ then $P_{Ely,set} = P_{Ely,max}$

2. Dump

- If $P_{Ely,max}$ was reached: $P_{dump} = P_{WECS} + N_{DEGS,min} P_{DEGS,max} + P_{FC,min} - P_{Load} - P_{Ely,set}$

POWER DEFICIT ($P_{BUSBAR} < 0$ IN EQ 5.4.2-1)

1. Switch off fuel cell if necessary, based on the H_2 storage tank level

- Switch Fuel cell to idling mode if the fuel cell is currently ON and $SOC < FC_{low}$
- Keep idling if the fuel cell is currently OFF and $SOC \leq FC_{up}$

2. DEGS, Electrolyzer and Dump

- If the fuel cell is currently OFF (idling):
    - Find N_{DEGS}, the minimum number of operating DEGS that generates a power excess, assuming the electrolyzer is idling. N_{DEGS} is the minimum value for which

      $(P_{WECS} + N P_{DEGS,max} + P_{FC,min} - P_{Load} - P_{Ely,min}) \geq 0$
    - Electrolyzer operates at $P_{Ely,set} = P_{WECS} + N P_{DEGS,max} + P_{FC,min} - P_{Load}$
    - No dumped power: $P_{Dump} = 0$
- Else (the fuel cell is currently ON):
    - Find N_{DEGS}, the minimum number of operating DEGS that generates a power excess, assuming the electrolyzer is idling and the fuel cell is at maximum power. N_{DEGS} is the minimum value for which

      $(P_{WECS} + N P_{DEGS,max} + P_{FC,max} - P_{Load} - P_{Ely,min}) \geq 0$
    - Assume electrolyzer is idling
    - Set Fuel cell power:
        - $P_{FC,set} = P_{Load} + P_{Ely,min} - P_{WECS} - N P_{DEGS,max}$
        - If $P_{FC,set} < P_{FC,min}$ then impose $P_{FC,set} = P_{FC,min}$
    - Set Electrolyzer power to use all power that would be dumped:
        - $P_{Ely,set} = P_{WECS} + N P_{DEGS,max} + P_{FC,max} - P_{Load}$

5.4.2.3   *Special considerations*

It is assumed DEGS can only operate at $P_{DEGS,max}$ or be switched off.

It is important to realize that the action from the controller is to calculate a power setpoint for the controlled components (in addition to the number of DEGS in operation). The power setpoint for the fuel cell and the electrolyzer should be connected to power conditioning devices (Type 175) which are connected to the electrolyzer and the fuel cell. The controller also has "switch" outputs that are used for numerical reasons, but those outputs should not be connected to the electrolyzer and fuel cell. Please study the example of Stand-Alone Power System to make sure you understand the operation of Type 105.

5.4.3 Type 160: Advanced Alkaline Electrolyzer

Type 160 is a mathematical model for a high pressure alkaline water electrolyzer. The model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships. A dynamic thermal model is also included. A temperature dependent current-voltage curve for a given pressure, and a Faraday efficiency relation independent of temperature and pressure form the basis of the electrochemical model. The electrolyzer temperature can be given as Input, or calculated from a simple or detailed thermal model [1,2].

A principle scheme of an electrolyzer is shown in Figure 5.4.3–1
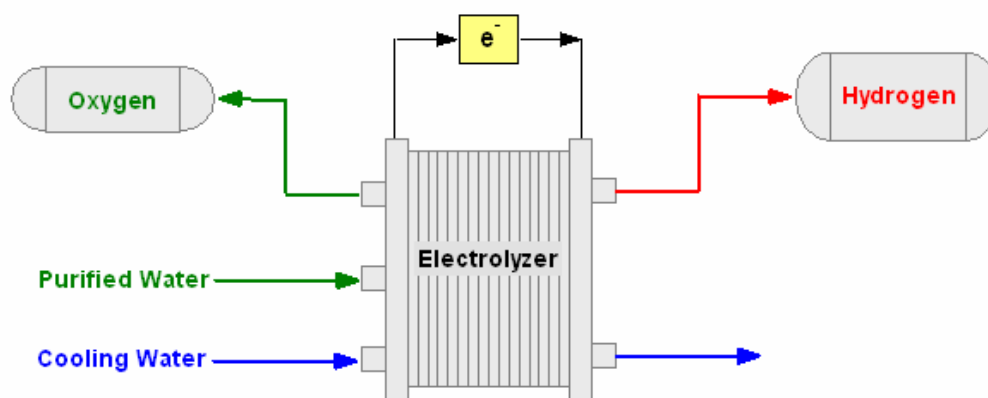
Figure 5.4.3–1: Electrolyzer principle

The decomposition of water into hydrogen and oxygen can be achieved by passing an electric current (DC) between two electrodes separated by an aqueous electrolyte with good ionic conductivity. The total reaction for splitting water is:

$$H_2O \text{ (l)} + \text{Electric Energy} \Rightarrow H_2 \text{ (g)} + \tfrac{1}{2} O_2 \text{ (g)}$$
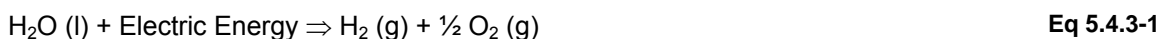
Eq 5.4.3-1

For this reaction to occur a minimum electric voltage must be applied to the two electrodes. This minimum voltage, or reversible voltage, can be determined from Gibbs energy for water splitting (Eq 5.4.3-12). In an alkaline electrolyzer the electrolyte is usually aqueous potassium hydroxide (KOH), where the potassium ion K^+ and hydroxide ion OH^- take care of the ionic transport. The anodic and cathodic reactions taking place here are:

$$\text{Anode: } 2\,OH^- \text{ (aq)} \Rightarrow \tfrac{1}{2} O_2\text{(g)} + H_2O \text{ (l)} + 2\,e^-$$

Eq 5.4.3-2

$$\text{Cathode: } 2\,H_2O \text{ (l)} + 2\,e^- \Rightarrow H_2\text{(g)} + 2\,OH^- \text{ (aq)}$$

Eq 5.4.3-3

In an alkaline solution the electrodes must be resistant to corrosion, and must have good electric conductivity and catalytic properties, as well as good structural integrity, while the diaphragm should have low electrical resistance. This can, for instance, be achieved by using anodes based on nickel, cobalt, and iron (Ni, Co, Fe), cathodes based on nickel with a platinum activated carbon catalyst (Ni, C-Pt), and nickel oxide (NiO) diaphragms.

5.4.3.1   Electrochemical model

The electrode kinetics of an electrolyzer cell can be modeled using empirical current-voltage (I-U) relationships. Several empirical I-U models for electrolyzers have been suggested [4,5,6,7]. In order to properly model the I-U curve for a given tempearture, overvoltages and ohmic resistance are taken into account, as proposed in [1].

CURRENT-VOLTAGE CHARACTERISTIC (PER CELL)

$$U_{cell} = U_{rev} + r` \cdot \frac{I_{ely}}{AREA} + s` \cdot \log\left[\frac{t` \cdot I_{ely}}{AREA} + 1\right] \qquad \text{Eq 5.4.3-4}$$

With:

$$r` = r_1 + r_2 \cdot T_{ely} \qquad \text{Eq 5.4.3-5}$$

$$s` = s_1 + s_2 \cdot T_{ely} + s_3 \cdot T_{ely}^2 \qquad \text{Eq 5.4.3-6}$$

$$t` = t_1 + \frac{t_2}{T_{ely}} + \frac{t_3}{T_{ely}^2} \qquad \text{Eq 5.4.3-7}$$

The Faraday efficiency is defined as the ratio between the actual and theoretical maximum amount of hydrogen produced in the electrolyzer. Since the Faraday efficiency comprises the parasitic current losses along the gas ducts, it is often called the current efficiency. The parasitic currents increase with decreasing current densities due to an increasing share of electrolyte and therefore also a lower electrical resistance [7]. Furthermore, the parasitic current in a cell is linear to the cell potential (Eq 5.4.3-1). Hence, the fraction of parasitic currents to total current increases with decreasing current densities. An increase in temperature leads to a lower resistance, more parasitic current losses, and lower Faraday efficiencies. An empirical expression that accurately depicts these phenomena for a given temperature is:

FARADAY EFFICIENCY

$$\eta_f = \left[\frac{I_{density}^2}{a_1 + I_{density}^2}\right] \cdot a_2 \qquad \text{Eq 5.4.3-8}$$

According to Faraday's law, the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which in turn is equivalent to the electrical current in the external circuit. Hence, the total hydrogen production rate in an electrolyzer, which consists of several cells connected in series, can be expressed as:

HYDROGEN PRODUCTION

$$\dot{n}_{H2} = \eta_f \cdot N_{cells} \cdot \frac{I_{ely}}{n \cdot F} \qquad \text{Eq 5.4.3-9}$$

The oxygen production rate is simply found from stoichiometry (Eq 5.4.3-3), which on a molar basis is:

OXYGEN PRODUCTION

$$\dot{n}_{O2} = 0.5 \cdot \dot{n}_{H2}$$

Eq 5.4.3-10

The generation of heat in an electrolyzer is mainly due to electrical inefficiencies. The energy efficiency can be calculated from the thermoneutral voltage (U_{tn}) and the cell voltage (U_{cell}):

ENERGY EFFICIENCY

$$\eta_e = \frac{U_{tn}}{U_{cell}}$$

Eq 5.4.3-11

For a given temperature, an increase in hydrogen production (i.e., an increase in current density) increases the cell voltage, which consequently decreases the energy efficiency. For a given current density, the energy efficiency increases with increasing cell temperature (see Figure 5.4.3–2).
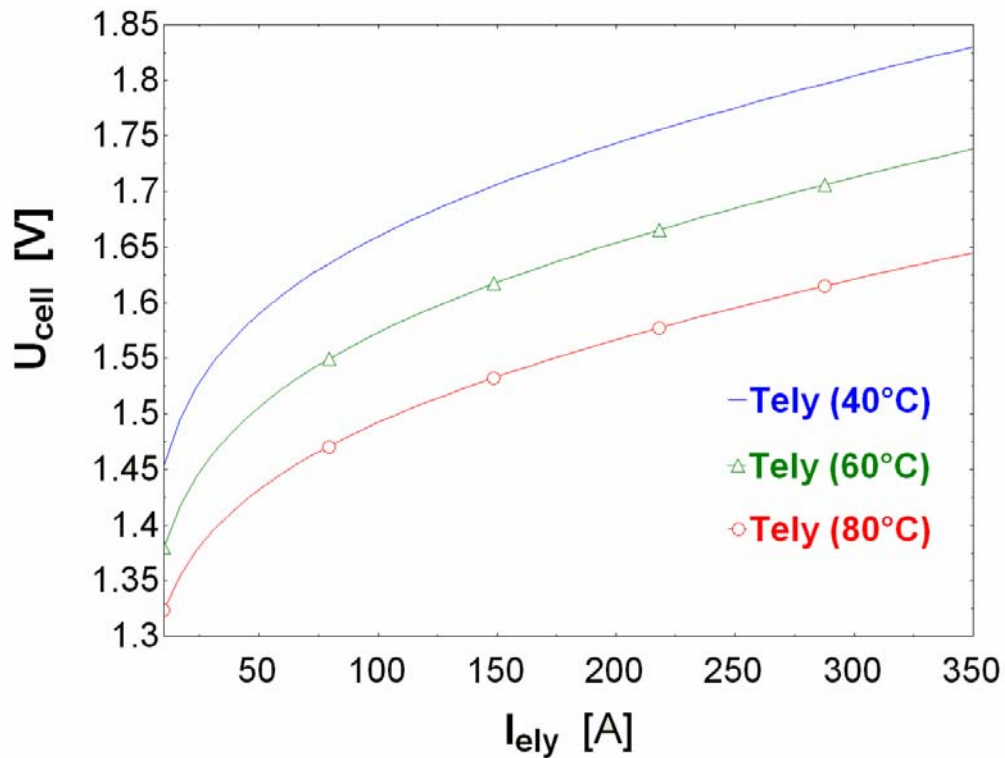
Figure 5.4.3–2: Electrolyzer – Cell voltage vs. Current for different Temperatures

It should be noted here that Eq 5.4.3-11 is only valid for systems where no auxiliary heat is added to the system. If auxiliary heat is added, the voltage may drop into the region between the reversible and thermoneutral voltage, and the efficiency would be greater than 100%. In low-temperature electrolysis, the cell voltage will during normal operation (50-80°C and 40-300 mA/cm^2) always be well above the thermoneutral voltage, as observed in Figure 5.4.3–2. However, some initial heating may be required during start-up if the electrolyzer has been allowed to cool down to ambient temperature.

In order to calculate the overall performance of an electrolyzer system, information about number of cells in series and/or parallel per stack and number of stacks per unit is needed. The rated voltage of an electrolyzer stack is found from the number of cells in series, while the number of

cells in parallel yields the rated current (and H_2-production). The total power is simply the product of the current and voltage.

5.4.3.2 Thermodynamic model

Thermodynamics provides a framework for describing reaction equilibrium and thermal effects in electrochemical reactors. It also gives a basis for the definition of the driving forces for transport phenomena in electrolytes and leads to the description of the properties of the electrolyte solutions [3]. Below is a description of the thermodynamics of the low-temperature hydrogen-oxygen electrochemical reactions used in the electrolyzer model.

The following assumptions can be made about the water splitting reaction: (a) Hydrogen and air (or oxygen) are ideal gases, (b) water is an incompressible fluid, and (c) the gas and liquid phases are separate. Based on these assumptions the change in enthalpy ΔH, Entropy ΔS and Gibbs Energy ΔG of the water splitting reaction can be calculated with reference to pure hydrogen (H_2), oxygen (O_2), and water (H_2O) at a standard temperature and pressure (25°C and 1 atm). The total change in enthalpy for splitting water is the enthalpy difference between the products (H_2 and O_2) and the reactants (H_2O). The same applies for the total change in entropy. The change in Gibbs energy is expressed by:

GIBBS FREE ENERGY

$$\Delta G = \Delta H - T_{ely} \cdot \Delta S \qquad\qquad \text{Eq 5.4.3-12}$$

At standard conditions (25°C and 1 atm) the splitting of water is a non-spontaneous reaction, which means that the change in Gibbs energy is positive. The standard Gibbs energy for water splitting is $\Delta G^0 = 237$ kJ mol^{-1}. For an electrochemical process operating at constant pressure and temperature the maximum possible useful work (i.e., the reversible work) is equal to the change in Gibbs energy ΔG. Faraday's law relates the electrical energy (emf) needed to split water to the chemical conversion rate in molar quantities. The emf for a reversible electrochemical process, or the reversible cell voltage, is expressed by:

REVERSIBLE VOLTAGE (PER CELL)

$$U_{rev} = \frac{\Delta G}{n \cdot F} \qquad\qquad \text{Eq 5.4.3-13}$$

The total amount of energy needed in water electrolysis is equivalent to the change in enthalpy ΔH. From Eq 5.4.3-4 it is seen that ΔG includes the thermal irreversibility $T\Delta S$, which for a reversible process is equal to the heat demand. The standard enthalpy for splitting water is $\Delta H^0 = 286$ kJ mol^{-1}. The total energy demand ΔH is related to the thermoneutral cell voltage:

THERMONEUTRAL VOLTAGE (PER CELL)

$$U_{tn} = \frac{\Delta H}{n \cdot F} \qquad\qquad \text{Eq 5.4.3-14}$$

At standard conditions $U_{rev} = 1.229$ V and $U_{tn} = 1.482$, but these will change with temperature and pressure. In the applicable temperature range U_{rev} decreases slightly with increasing temperature (U_{rev} @ 80°C, 1 bar = 1.184 V), while U_{tn} remains almost constant (U_{tn} @ 80°C, 1 bar = 1.473 V). Increasing pressure increases U_{rev} slightly (U_{rev} @ 25°C, 30 bar = 1.295 V), while U_{tn} remains constant.

5.4.3.3   Thermal model

The temperature of the electrolyte of the electrolyzer can be determined using simple or complex thermal models, depending on the need for accuracy. Assuming a lumped thermal capacitance model, the overall thermal energy balance can be expressed as a linear, first order, non-homogeneous differential equation. Type 160 can calculate Tstack in 3 different ways:

- TMODE=1: T is given as Input

- TMODE=2: T is calculated based on a simple quasi-static thermal model

- TMODE=3: T is calculated based on a complex lumped capacitance thermal model

OVERALL ENERGY BALANCE

$$C_T \cdot dTdt_{ely} = \dot{Q}_{gen} - \dot{Q}_{loss} - \dot{Q}_{cw}$$
$$\text{Eq 5.4.3-15}$$

GENERATED THERMAL ENERGY

$$\dot{Q}_{gen} = N_{cells} \cdot I_{ely} \cdot (U_{cell} - U_{tn})$$
$$\text{Eq 5.4.3-16}$$

HEAT LOSSES TO AMBIENT

$$\dot{Q}_{loss} = \frac{1}{R_T} \cdot (T_{ely} - T_{amb})$$
$$\text{Eq 5.4.3-17}$$

AUXILIARY COOLING REQUIREMENTS

$$\dot{Q}_{cw} = C_{p,H2O} \cdot (T_{cw,out} - T_{cw,in})$$
$$\text{Eq 5.4.3-18}$$

The first term on the right hand side of Eq 5.4.3-15 is the internal heat generation, the second term the total heat loss to the ambient, and the third term the auxiliary cooling demand. The overall thermal capacity C_t and resistance R_t for the electrolyzer, and the UA-product for the cooling water heat exchanger are the constants that need to be determined analytically or empirically prior to solving the thermal equations. It should be noted that the thermal model presented here is on a per stack basis. In Type 160, UA is given as a function of electrolyzer current:

$$UA_{HX} = h_1 + h_2 \cdot I_{ely}$$
$$\text{Eq 5.4.3-19}$$

5.4.3.4   Additional information

Type 160 is also described in an EES-based executable program distributed with TRNSYS 16: %TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.4.3.5   External data file

Type 160 reads the electrolyzer performance data from a data file. An example is provided in "Examples\Data Files". The data file should have the following information:

```
<Nb of electrolyzers>
<No of the electrolyzer>, <Name of electrolyzer>
<r1> <r2> <s1> <t1> <t2> <t3> <a1> <a2> <h1> <h2>
```
For each electrolyzer

The parameters that must be provided are described here below:

No	Parameter	Units	Description
1	r1	Ω m²	Ohmic resistance (Eq 5.4.3-5)
2	r2	Ω m² / °C	Ohmic resistance (Eq 5.4.3-5)
3	s1	V	Overvoltage on electrodes (Eq 5.4.3-6)
4	t1	m² / A	Overvoltage on electrodes (Eq 5.4.3-7)
5	t2	m² °C / A	Overvoltage on electrodes (Eq 5.4.3-7)
6	t3	m² °C² / A	Overvoltage on electrodes (Eq 5.4.3-7)
7	a1	mA / cm	Faraday efficiency (Eq 5.4.3-8)
8	a2	0..1	Faraday efficiency (Eq 5.4.3-8)
9	h1	W / °C	Convective heat transfer coefficient (Eq 5.4.3-19)
10	h2	W / °C per A	Convective heat transfer coefficient (Eq 5.4.3-19)

EXAMPLE

```
2
  1,Alkaline Electrolyzer PHOEBUS (KFA)
8.05031E-05 -2.50410E-07 0.1849 -0.10015 8.4242 247.2663 250.0 0.96 7.0 0.020
  2,GHW Electrolyzer (p=30 bar) (Munich Airport)
1.997990E-05  0.0 0.2113 0.01984 0.0 0.0 250.0  0.96  7.0  0.0200
```

5.4.3.6   References

1. Ulleberg Ø. (2002) Modeling of advanced alkaline electrolyzers: a system simulation approach. Int. J. Hydrogen Energy 28(1): 7-19.

2. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

3. Rousar I. (1989) Fundamentals of electrochemical reactors. In Electrochemical Reactors: Their Science and Technology Part A, Ismail M. I. (Eds), Elsevier Science, Amsterdam.

4. GriesshaberW. and Sick F. (1991) Simulation of Hydrogen-Oxygen-Systems with PV for the Self-Sufficient Solar House (in German). FhG-ISE, Freiburg im Breisgau.

5. Havre K., Borg P. and Tømmerberg K. (1995) Modeling and control of pressurized electrolyzer for operation in stand alone power systems. In Proceedings of 2nd Nordic Symposium on Hydrogen and Fuel Cells for Energy Storage, January 19-20, Helsinki, Lund P. D. (Ed.), pp. 63-78.

6. Vanhanen J. (1996) On the Performance Improvements of Small-Scale Photovoltaic-Hydrogen Energy Systems. Ph.D. thesis, Helsinki University of Technology, Espoo, Finland.

7. Hug W., Divisek J., Mergel J., Seeger W. and Steeb H. (1992) Highly efficient advanced alkaline electrolyzer for solar operation. Int. J. Hydrogen Energy 17(9): 699-705

5.4.4 Type 164: Compressed gas storage

Type 164 is a compressed gas storage model. The model calculates the pressure in the storage based on either the ideal gas law, or van der Waals equation of state for real gases [1,2].

5.4.4.1 Mathematical reference

The pressure gas storage model described below, referred to as Type 164, was originally developed by Griesshaber and Sick [3]. However, the model has been modified to also include van der Waals equation of state for real gases (PMODE=2, while PMODE=1 uses the ideal gas law).

According to the van der Waals equation of state, the pressure p of a real gas in a storage tank can be calculated from:

$$p = \frac{n \cdot R \cdot T_{gas}}{Vol - n \cdot b} - a \cdot \frac{n^2}{Vol^2}$$
Eq 5.4.4-1

Where n denotes the number of moles of gas, R is the universal gas constant, Vol is the volume of the storage tank, and T_{gas} is the temperature of the gas. The second term (comprising the constant a) account for the intermolecular attraction forces, while b accounts for the volume occupied by the gas molecules.

Note that the ideal gas law is obtained by setting a and b to 0:

$$p \ Vol = n R T_{gas}$$
Eq 5.4.4-2

In the Van der Waals equation, a and b are defined as

$$a = \frac{27 \cdot R^2 \cdot T_{cr}^2}{64 \cdot p_{cr`}}$$
Eq 5.4.4-3

$$b = \frac{R \cdot T_{cr}}{8 \cdot p_{cr`}}$$
Eq 5.4.4-4

Where T_{cr} and p_{cr} are respectively the critical temperature and pressure of the substance.

The model simply performs a mass (or moles) balance of gas entering and leaving the storage and calculates the pressure corresponding to the resulting mass of Hydrogen in the tank.

If the pressure rises beyond a fixed level, the excess of Hydrogen is dumped.

5.4.4.2 Additional information

Type 164 is also described in an EES-based executable program distributed with TRNSYS 16:
%TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.4.4.3   References

1. C¸ engel Y. A. and Boles M. A. (1989) Thermodynamics - An Engineering Approach. 1 edn, McGraw-Hill, London.

2. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

3. GriesshaberW. and Sick F. (1991) Simulation of Hydrogen-Oxygen-Systems with PV for the Self-Sufficient Solar House (in German). FhG-ISE, Freiburg im Breisgau, Germany.

5.4.5 Type 167: Multistage compressor

Type 167 is a multi-stage polytropic compressor model. The model calculates the work and cooling need for a polytropic compressor of 1 to 5 stages; [1, 2]. This manual uses a 2-stage compressor as an example.

5.4.5.1 Thermodynamic model

This model is based on an ideal gas model in a quasi-equilibrium compression process. A quasi-equilibrium process is a process in which all states through which the system passes may be considered equilibrium states. A polytropic process, is a quasi- equilibrium process which describes the relationship between pressure and volume during a compression. It can be expressed as:

$$(p \cdot V)^N = \text{constant} \qquad\qquad \text{Eq 5.4.5-1}$$

where p and V are the pressure and volume of the ideal gas, respectively, and the value of N is a constant for the particular prosess.

POLYTROPIC WORK (IDEAL GAS)

1st compression stage:

$$W_1 = \left| \left[\frac{N \cdot R \cdot T_{low}}{N - 1} \right] \cdot \left[1 - \left(\frac{p_x}{p_{in}} \right)^{\left(\frac{N - 1}{N} \right)} \right] \right| \qquad\qquad \text{Eq 5.4.5-2}$$

2nd compression stage:

$$W_2 = \left| \left[\frac{N \cdot R \cdot T_{low}}{N - 1} \right] \cdot \left[1 - \left(\frac{p_{out}}{p_x} \right)^{\left(\frac{N - 1}{N} \right)} \right] \right| \qquad\qquad \text{Eq 5.4.5-3}$$

Overall compression work:

$$P_{comp} = \dot{m}_{in} \cdot (W_1 + W_2) \qquad\qquad \text{Eq 5.4.5-4}$$

ISOTHERMIC WORK

$$W_{iso} = \left| - R \cdot T_{low} \cdot \ln\left[\frac{p_{out}}{p_{in}} \right] \right| \qquad\qquad \text{Eq 5.4.5-5}$$

$$P_{iso} = \dot{m}_{in} \cdot W_{iso} \qquad\qquad \text{Eq 5.4.5-6}$$

ISENTROPIC EFFICIENCY

$$\eta_{isen} = \frac{P_{iso}}{P_{comp}}$$

Eq 5.4.5-7

Isentropic efficiency involve a comparison between the actual performance of the compressor and an idealized performance which neglects the change in entropy.

5.4.5.2   Thermal model

Ramp factor - effect of step compression:

$$R_f = \left[\frac{p_{out}}{p_{in}}\right]^{\left[\frac{1}{N_{stages}}\right]}$$

Eq 5.4.5-8

Outlet temperature of a polytropic process:

$$T_{high} = T_{low} \cdot R_f^{\left[\frac{N-1}{N}\right]}$$

Eq 5.4.5-9

Heat produced by compression:

$$Q_{cool} = \dot{n}_{in} \cdot c_p \cdot (T_{high} - T_{low})$$

Eq 5.4.5-10

A few remarks about this process can be made. Intercooling means that the gas at the intermediate pressure (after the first compression stage) is cooled to the initial temperature T_{low} before it is passed on to the second compression stage. It should also be noted that the sign convention used in Eq 5.4.5-2 and Eq 5.4.5-3 is such that the required compressor work (work added to the system) is negative.

5.4.5.3   Additional information

Type 167 is also described in an EES-based executable program distributed with TRNSYS 16:
%TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.4.5.4   References

1. C̣engel Y. A. and Boles M. A. (1989) Thermodynamics - An Engineering Approach. 1 edn, McGraw-Hill, London.

2. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

5.4.6 Type 170: Proton-Exchange Membrane Fuel Cell

Type 170 is a generic mathematical model for a proton exchange membrane fuel cell (PEMFC). The model is largely mechanistic, with most terms being derived from theory or including coefficients that have a theoretical basis. The major non-mechanistic term is the ohmic over-voltage that is primarily empirically based. The main equations of the electrochemical model are described in published literature [2-4]. A thermal dynamic model is also included. The theory behind the thermal model is found in previous PEMFC-modeling work [5], while the recommended thermal coefficients were derived from experiments [6,7].
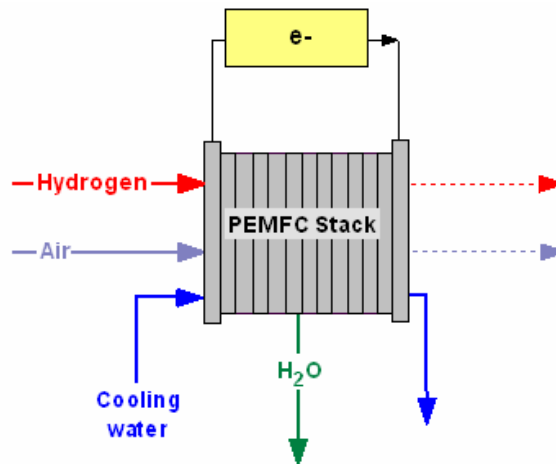
Figure 5.4.6–1: PEMFC principle (Air can be replaced with pure O_2)

A fuel cell (Figure 5.4.6–1) is an electrochemical device that converts the chemical energy of a fuel and an oxidant to electrical current (DC). The oxidant can be pure oxygen or a gas containing oxygen, such as air. An example of PEMFC geometry is shown in Figure 5.4.6–2 (page 5–187).

In the case of a hydrogen-air fuel cell (**OXMODE = 1**), hydrogen (H2) is the fuel and air (O2) is the oxidant [8]. In the case of a hydrogen-oxygen fuel cell (**OXMODE = 2**), hydrogen (H_2) is the fuel and oxygen (O_2) is the oxidant [8].

Eq 5.4.6-1 and Eq 5.4.6-2 show the anodic and cathodic reactions taking place in a PEM fuel cell, where its fed with hydrogen-containing anode gas and an oxygen-containing cathode gas.

Anode: $H_2(g) \Rightarrow 2\,H^+(aq) + 2\,e^-$ **Eq 5.4.6-1**

Cathode: $2\,H^+(aq) + 2\,e^- + \frac{1}{2}\,O_2(g) \Rightarrow H_2O\,(l)$ **Eq 5.4.6-2**

The total fuel cell reaction is:

$H_2\,(g) + \frac{1}{2}\,O_2\,(g) \Rightarrow H_2O\,(l)$ **Eq 5.4.6-3**

The products of this process (Eq 5.4.6-3) are electricity, liquid water and heat.

5.4.6.1   Electrochemical model

The performance of a fuel cell (output voltage) is defined as a function of the thermodynamical potential, the activation overvoltage, and the ohmic overvoltage, with mass transport losses incorporated in each of the terms [3]. The basic expression for the voltage of the single cell is:

CELL VOLTAGE

$$U_{cell} = E + \eta_{act} + \eta_{ohmic} \qquad \textbf{Eq 5.4.6-4}$$

Where: 'E' is the thermodynamic potential, η_{act} is the anode and cathode activation over-voltage, a measure of the voltage loss associated with the anode and cathode, and 'ETA ohmic' is the ohmic over-voltage, a measure of the IR losses associated with the proton conductivity of the solid polymer electrolyte and electronic internal resistances.

THERMODYNAMIC POTENTIAL

$$E = 1.23 - 0.00085 \cdot (T_{stack} - 298) + 0.0000431 \cdot T_{stack} \cdot \ln(p_{H2} \cdot p_{O2}^{0.5}) \qquad \textbf{Eq 5.4.6-5}$$

ACTIVATION OVERVOLTAGE

$$\eta_{act} = -0.95 + 0.00243 \cdot T_{stack} + 0.000192 \cdot T_{stack} \cdot \ln(A_{PEM}) - 0.000192 \cdot T_{stack} \cdot \ln(I_{FC}) + 0.000076 \cdot T_{stack} \cdot \ln(c_{O2})$$

$$\textbf{Eq 5.4.6-6}$$

OHMIC OVERVOLTAGE

$$\eta_{ohmic} = \frac{-I_{FC} \cdot t_{PEM}}{A_{PEM}} \cdot \frac{8}{\exp\left[3.6 \cdot \left(\frac{T_{stack} - 353}{T_{stack}}\right)\right]} \cdot \left[1 + 1.64 \cdot \frac{I_{FC}}{A_{PEM}} + \gamma \cdot \left(\frac{I_{FC}}{A_{PEM}}\right)^3\right]$$

$$\textbf{Eq 5.4.6-7}$$

The thermodynamical potential is defined through the Nernst equation. The parametric coefficients in the activation overvoltage term η_{act}, are based on the theoretical equations from kinetic, thermodynamic and electrochemistry fundamentals [2]. The parametric coefficients in the internal resistance term η_{ohmic}, are purely empirical, based on temperature and current experimental data [3].

5.4.6.2   Thermodynamic model

Thermodynamics provides a framework for describing reaction equilibrium and thermal effects in electrochemical reactors. It also gives a basis for the definition of the driving forces for transport phenomena in electrolytes and leads to the description of the properties of the electrolyte

solutions [1]. Below is a description of the thermodynamics of the low-temperature hydrogen-air or hydrogen-oxygen electrochemical reactions used in the fuel cell model.

The following assumptions can be made about the water splitting reaction: (a) Hydrogen and air (or oxygen) are ideal gases, (b) water is an incompressible fluid, and (c) the gas and liquid phases are separate. Based on these assumptions the change in enthalpy ΔH of the water splitting reaction can be calculated with reference to pure hydrogen (H_2), oxygen (O_2), and water (H_2O) at a standard temperature and pressure (25°C and 1 atm). The total change in enthalpy for splitting water is the enthalpy difference between the products (H_2 and O_2) and the reactants (H_2O). The same applies for the total change in entropy.

The total amount of energy released in the fuel cell reaction (Eq 5.4.6-3) is equivalent to the change in enthalpy ΔH. The standard enthalpy for splitting water is $\Delta H^0 = 286$ kJ mol^{-1}. The total energy demand ΔH is related to the thermo-neutral cell voltage by the expression:

THERMONEUTRAL VOLTAGE (PER CELL)

$$U_{tn} = \frac{\Delta H}{n \cdot F}$$

Eq 5.4.6-8

At standard conditions $U_{tn} = 1.482$ V, but it will change with temperature and pressure as shown below, in the appendix of Thermodynamic model. In the applicable temperature and pressure range, U_{tn} is almost constant, with negligible change [6]. The generation of heat in from a fuel cell is mainly due to electrical inefficiencies. The energy efficiency can be calculated from the thermoneutral voltage (Eq 5.4.6-8) and the cell voltage (Eq 5.4.6-1) by the expression:

ENERGY EFFICIENCY

$$\eta_e = \frac{U_{cell}}{U_{tn}}$$

Eq 5.4.6-9

It would appear from Eq 5.4.6-9 that a high operating voltage U_{cell} is required for high efficiency. At a fixed fuel flow rate. However, utilization declines with increasing operating voltage. Power also decreases as operating voltage is raised from the maximum power voltage which in common experience is slightly less than half the open circuit voltage. The greatest efficiency at any given fuel flow is obtained at the operating voltage which results in the highest power output.

HYDROGEN AND OXYGEN (AIR) FLOWRATES

According to Faraday's law, the consumption rates of hydrogen and oxygen (air) in a fuel cell is directly proportional to the transfer rate of electrons to the electrodes, which in turn is equivalent to the electrical current in the external circuit. Hence, the total consumption rate of hydrogen and oxygen(air) in a fuel cell, which consists of several cells connected in series, can be expressed as:

$$\dot{n}_{H2,a,cons} = \frac{N_{cells} \cdot I_{FC}}{n \cdot F}$$

Eq 5.4.6-10

$$\dot{n}_{O2,c,cons} = 1 / 2 \cdot \dot{n}_{H2,a,cons}$$

Eq 5.4.6-11

$$\dot{n}_{air,cons} = 4.76 \cdot \dot{n}_{O2,c,cons} \quad \text{(if OXMODE = 1)}$$

Eq 5.4.6-12

The inlet rates of hydrogen, oxygen and air are sized by empirical stoichiometric factors of the consumption rates. Hydrogen, oxygen and air inlet rates:

$$\dot{n}_{H2,a,in} = S_{H2} \cdot \dot{n}_{H2,a,cons} \qquad \textbf{Eq 5.4.6-13}$$

$$\dot{n}_{O2,c,in} = S_{O2} \cdot \dot{n}_{O2,c,cons} \qquad \textbf{Eq 5.4.6-14}$$

$$\dot{n}_{air,in} = \dot{n}_{air,cons} \cdot S_{O2} \quad \text{(if OXMODE = 1)} \qquad \textbf{Eq 5.4.6-15}$$

The flow rate of hydrogen on the fuel side and oxygen (air) on the oxidant side affects the performance of the PEM fuel cell. For instance, if the H_2 flow is kept fixed and the O_2 stoichiometry is increased, the overall performance of the fuel cell also increases. In the H_2/Air fuel cells, which have lower concentrations of O_2 on the cathode side than H_2/O_2 fuel cells, the air flow rates are typically kept about twice the O_2 flow rate.

HYDROGEN AND OXYGEN PRESSURE

In a H2/O2 PEMFC's, the hydrogen and oxygen pressure levels are usually kept fairly constant during operation. In an H2/Air PEMFC, a fan is usually used to force atmospheric air across the cathode side. Thus the need to model the influence of pressure on the I-U curve is limited (Eq 5.4.6-1). This leaves only temperature as a variable that needs to be modeled. A mechanistic form of expressing these pressures follows [2]:

Interfacial partial pressure of hydrogen

$$p_{H2} = p_{a,in} \cdot \textbf{exp}\left[\frac{-1.653 \cdot I_{FC}}{A_{PEM} \cdot T_{stack}^{1.334}}\right] - 0.5 \cdot p_{H2O,sat} \qquad \textbf{Eq 5.4.6-16}$$

Interfacial partial pressure of oxygen (OXMODE = 1, H_2/Air)

$$p_{O2} = p_{c,in} \cdot (1 - x_{H2O,sat} - x_{N2}) \qquad \textbf{Eq 5.4.6-17}$$

Interfacial partial pressure of oxygen (OXMODE = 2, H_2/O_2)

$$p_{O2} = p_{c,in} \cdot \textbf{exp}\left[\frac{-4.192 \cdot I_{FC}}{A_{PEM} \cdot T_{stack}^{1.334}}\right] - p_{H2O,sat} \qquad \textbf{Eq 5.4.6-18}$$

THERMAL RESISTANCE AND CAPACITANCE, FUEL CELL GEOMETRY

Type 170 has 3 modes to calculate overall thermal resistance (R_t) and capacitance (C_t) of a single FC stack:

- RTCTMODE = 1: Simple - Few FC geometry and thermal parameters needed
  - Square design cells assumed
  - Thermal properties for PEM assumed (graphite)
- RTCTMODE = 2: Detailed - Several FC geometry and thermal parameters needed
  - Thermal properties for PEM supplied
- RTCTMODE = 3: Experimental - R_t & C_t provided

The overall thermal resistance ($R_t = 1/UA_{FC}$) and thermal capacity C_t of the fuel cell are estimated according to [5] and [6].

A typical fuel cell geometry is shown in Figure 5.4.6–2 (page 5–187). The PEM is mounted on bipolar graphite plates; the overall assembly (MEA + graphite plate) is called a 'cell' . The width and height of the cell is usually slightly larger than the width and height of the MEA or PEM. In the calculation of the cells' outside surface area this is taken into consideration.

- MEA = Membrane Electrode Assembly (MEA = anode + PEM + cathode)
- PEM = Proton Exchange Membrane

THERMAL RESISTANCE

$$R_t = \frac{L_{frame}}{k_{cell} \cdot A_{FC}} + \frac{1}{h_{air} \cdot A_{FC}}$$

Eq 5.4.6-19

THERMAL CAPACITY

$$C_t = c_{p,cell} \cdot \rho_{cell} \cdot N_{cells} \cdot h_{cell} \cdot w_{cell} \cdot t_{cell} + c_{p,plate} \cdot \rho_{plate} \cdot 2 \cdot h_{plate} \cdot w_{plate} \cdot t_{plate}$$

Eq 5.4.6-20

The overall thermal capacity C_t and resistance R_t for the fuel cell, and the UA-product for the cooling water heat exchanger are the constants that need to be determined analytically or empirically prior to solving the thermal equations.

5.4.6.3   Thermal model

A heat balance of a fuel cell can be determined using simple or complex thermal models, depending on the need for accuracy. Assuming a lumped thermal capacitance model, the overall thermal energy balance can be expressed as a linear, first order, non-homogeneous differential equation. If TMODE = 1, the stack temperature is assumed to be constant (Tstack,in = Tstack,out). If TMODE = 2, the stack temperature is calculated.

OVERALL ENERGY BALANCE

$$C_t \cdot dTdt = \dot{Q}_{gen} - \dot{Q}_{loss} - \dot{Q}_{cool} - \dot{Q}_{evap}$$

Eq 5.4.6-21

The first term on the right hand side of Eq 5.4.6-21 is the internal heat generation (Q_{gen}), the second term the total heat loss to the ambient (Q_{loss}), the third term the auxiliary cooling demand(Q_{cool}) and the fourth term is the evaporation of water at the cathode (Q_{evap}). The left hand terms describes the accumulation of heat, defined by the thermal capacity (C_t) and the stack temperature gradient (dT/dt).

INTERNAL HEAT GENERATION

$$\dot{Q}_{gen} = P_{stack} \cdot \left[\frac{1 - \eta_e}{\eta_e} \right]$$

Eq 5.4.6-22

HEAT LOSSES TO AMBIENT

$$\dot{Q}_{loss} = \frac{1}{R_t} \cdot (T_{stack} - T_{amb})$$
Eq 5.4.6-23

EVAPORATIVE LOSSES (ON CATHODE SIDE)

$$\dot{Q}_{evap} = X_{evap} \cdot \dot{n}_{H2O} \cdot h_{fg,H2O} \cdot M_{H2O}$$
Eq 5.4.6-24

AUXILIARY COOLING REQUIREMENT

$$\dot{Q}_{cool} = V_{cool} \cdot \rho_{H2O} \cdot c_{p,H2O} \cdot (T_{cool,out} - T_{cool,in})$$
Eq 5.4.6-25

The internal heat generation (Q_{gen}), is calculated using the energy efficiency (η_e) to determine the fraction of heat produced from the stack power (P_{stack}). Heat loss to ambient (Q_{loss}), is calculated using the overall thermal resistance (R_t) of the fuel cell and the temperature difference to the ambient. The main cooling of the fuel cell is detemined by the heat absorbtion from the cooling water (Q_{cool}), using specific heat capacity of water (C_{pwater}), flow rate (V_{cool}) and a fixed temperature difference of the in/out flow. The heat consumption from the evaporation of outlet water (Q_{evap}), is calculated from the enthalpy of vaporization (h_{fgH2O}) and fraction of water vaporized (X_{vap}). It should be noted that the thermal model presented here is on a per stack basis.

5.4.6.4   Additional information

Type 170 is also described in an EES-based executable program distributed with TRNSYS 16: %TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe
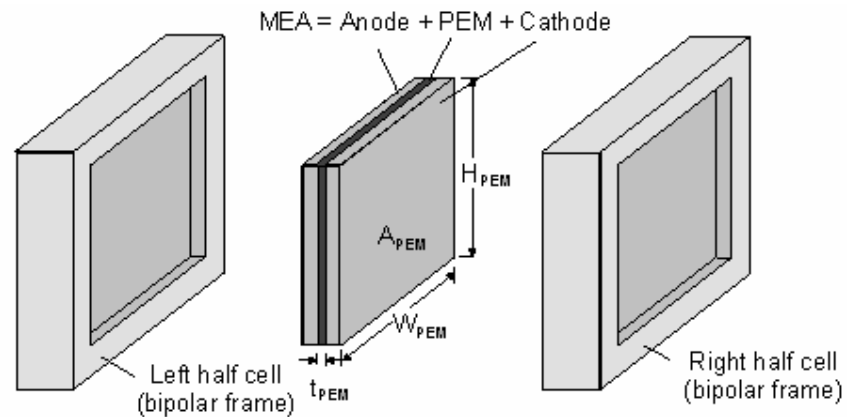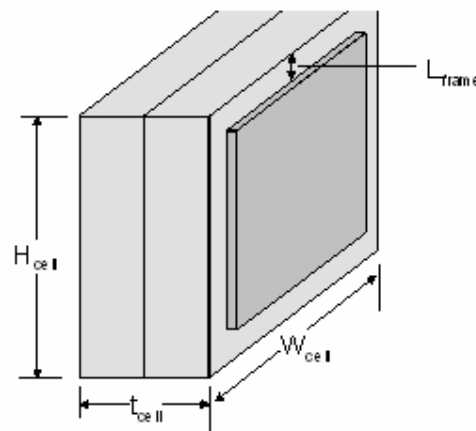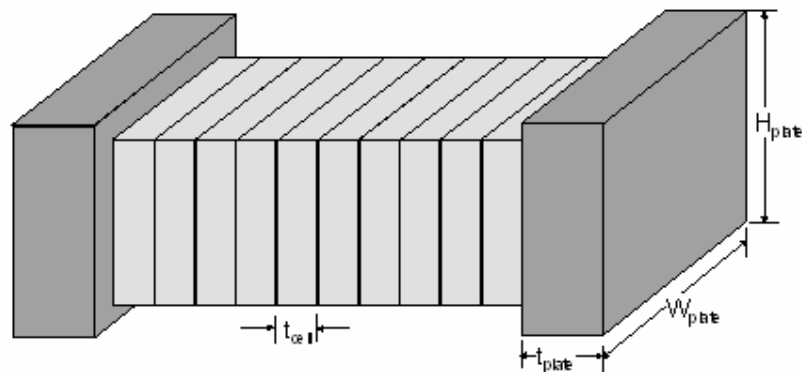
Figure 5.4.6–2: PEMFC geometry

5.4.6.5 References

1. Rousar I. (1989) Fundamentals of electrochemical reactors. In Electrochemical Reactors: Their Science and Technology Part A, Ismail M. I. (Eds), Vol pp. Elsevier Science, Amsterdam.

2. Amphlett J. C., Baumert R. M., Mann R. F., Peppley B. A., Roberge P. R. and Harris T. J. (1995) Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell. Part I - mechanistic model development. J. Electrochem. Soc. 142(1): 1-8.

3. Amphlett J. C., Baumert R. M., Mann R. F., Peppley B. A., Roberge P. R. and Harris T. J. (1995) Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell. Part II - empirical model development. J. Electrochem. Soc. 142(1): 9-15.

4. Amphlett J. C., Mann R. F., Peppley B. A., Roberge P. R., Rodrigues A. and Salvador J. P. (1996) A model predicting transient responses of proton exchange membrane fuel cells. J. Power Sources 61(1-2): 183-188.

5. Ulleberg Ø. (1998) Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems. PhD thesis, Norwegian University of Science and Technology, Trondheim.

6. Ulleberg Ø. (2001) Evaluation of IFE's 100 W PEM Fuel Cell Stack Performance. Internal report, Institute for Energy Technology,

7. Mann R. F., Amphlett J. C., Hooper M. A. I., Jensen H. M., Peppley B. A. and Roberge P. R. (2000) Development and application of a generalised steady-state electrochemical model for a PEM fuel cell. J. Power Sources 86(1-2): 173-180.

8. Kordesch K. and Simader G. (1996) Fuel Cells and their Applications. 1st edn, VCH, New York.

5.4.7 Type 173: Alkaline Fuel Cell

TYPE173 is a simple mathematical model for an alkaline fuel cell (AFC). The electrochemical model is based on an empirical relationship for the current-voltage characteristic at normal operating temperature. The heat generated by the AFC-stack is calculated, but no detailed dynamic thermal model is included. TYPE173 has been modeled with a specific AFC from ZeTek in mind [1,2].

A fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidant to electrical current (DC). In the case of a hydrogen-air fuel cell (**OXMODE = 1**), hydrogen (H_2) is the fuel and air (O_2) is the oxidant. In the case of a hydrogen-oxygen fuel cell (**OXMODE = 2**), hydrogen (H_2) is the fuel and oxygen (O_2) is the oxidant. A principle scheme of a Fuel Cell is given in Figure 5.4.6–1 (page 5–181).

Eq 5.4.7-1and Eq 5.4.7-2 show the anodic and cathodic reactions taking place in a PEM fuel cell, where its fed with hydrogen-containing anode gas and an oxygen-containing cathode gas.

Anode: $H_2(g) \Rightarrow 2\,H^+(aq) + 2\,e^-$ **Eq 5.4.7-1**

Cathode: $2\,H^+(aq) + 2\,e^- + \frac{1}{2}\,O_2(g) \Rightarrow H_2O\,(l)$ **Eq 5.4.7-2**

The total fuel cell reaction is:

$H_2\,(g) + \frac{1}{2}\,O_2\,(g) \Rightarrow H_2O\,(l)$ **Eq 5.4.7-3**
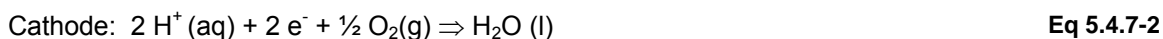
The products of this process (Eq 5.4.7-3) are electricity, liquid water and heat.

5.4.7.1 Electrical model

Cell, module and stack voltage:

$$U_{cell} = \frac{U_{mod}}{n_{c,ser}}$$ **Eq 5.4.7-4**

$$U_{mod} = U_o - b \cdot \mathbf{log}\,(\,I_{stack}\,) - R_{ohm} \cdot I_{stack}$$ **Eq 5.4.7-5**

$$U_{stack} = n_{m,ser} \cdot U_{mod}$$ **Eq 5.4.7-6**

Cell and stack current:

$$I_{cell} = \frac{I_{FC}}{n_{c,par} \cdot n_{s,par}}$$ **Eq 5.4.7-7**

$$I_{stack} = \frac{I_{FC}}{n_{s,par}}$$ **Eq 5.4.7-8**

Stack power:

$$P_{stack} = U_{stack} \cdot I_{stack}$$

Eq 5.4.7-9

Energy efficiency:

$$\eta_E = \frac{U_{cell}}{U_{tn}}$$

Eq 5.4.7-10

5.4.7.2 Thermodynamical model

Stoichiometric molar flow of hydrogen:

$$\dot{n}_{H2} = \frac{n_{c,ser} \cdot n_{m,ser} \cdot I_{FC}}{z \cdot F} \cdot \eta_F$$

Eq 5.4.7-11

Total hydrogen consumption:

$$\dot{V}_{H2} = \frac{\dot{n}_{H2}}{\rho_{gas}} \cdot S_{H2}$$

Eq 5.4.7-12

5.4.7.3 Thermal model

Total heat generated by fuel cell:

$$Q_{gen} = P_{stack} \cdot \left[\frac{1 - \eta_E}{\eta_E} \right]$$

Eq 5.4.7-13

5.4.7.4 Additional information

Type 173 is also described in an EES-based executable program distributed with TRNSYS 16: %TRNSYS16%\Documentation\HydrogenSystemsDocumentation.exe

5.4.7.5 References

1. Brown M. (2001) Testing of ZeTek stacks. Personal communication, Industrial Research Limited, Christchurch, New Zealand.

2. ZeTek (2001) ZeTek Mk2-4 stack specification sheet.

5.5   Hydronics

This section provides pumps, fans, pipes

- Type 3: Variable Speed Pump or Fan without Humidity Effects
- Type 11: Tee Piece, Flow Diverter, Flow Mixer, Tempering Valve
- Type 13: Pressure Relief Valve
- Type 31: Pipe Or Duct
- Type 110: Variable Speed Pump
- Type 111: Variable Speed Fan/Blower with Humidity Effects
- Type 112: Single Speed Fan/Blower with Humidity Effects
- Type 114: Constant Speed Pump

Pumps and fans:

If your simulation does not need to take humidity into account, you can use Type 3 for pumps and fans (Type 110 and 114 provide an alternative to Type 3). Otherwise, you have to use Types 111 or 114.

Pipes, connections and accessories:

Those components are provided by Type 31,11 and 13, which where coded with water loops in mind.

5.5.1 Type 3: Variable Speed Pump or Fan without Humidity Effects

This pump or fan model computes a mass flow rate using a variable control function, which must be between 0 and 1, and a fixed (user specified) maximum flow capacity. Pump or fan power consumption may also be calculated, either as a linear function of mass flow rate or by a user-defined relationship between mass flow rate and power consumption. With the release of TRNSYS version 14, a user-specified fraction of the pump/fan power is converted to fluid thermal energy. Due to this addition, Input files written for TRNSYS versions 13.1 and earlier that call the Type 3 subroutine will have to be modified. No modifications to TRNSYS 14 or TRNSYS 15 pump descriptions will be needed to run in TRNSYS 16.

In many systems, there is no continuous flow modulation and the control function is either 0 or 1. In this case, the outlet flow rate and the power used are either both zero or both at their maximum values.

It is imperative that the user realizes that the Type 3 routine sets the fluid flow rate for components downstream of the pump. The inlet fluid flow rate Input to the Type 3 routine is used for convergence checking only.

5.5.1.1 Nomenclature

c_i	coefficient of polynomial relating P/P_{max} to $\dot{m}/\dot{m}_{max}$
C_p	specific heat of fluid
F_{par}	fraction of pump/fan power converted to fluid thermal energy
$\dot{m}$	pump mass flow rate
$\dot{m}_{max}$	maximum flow rate (when $\gamma = 1$)
P	power consumption of pump or fan
P_{max}	maximum power consumption (when $\gamma = 1$)
T_i	inlet fluid temperature
T_o	outlet fluid temperature
γ	control function ($0 \leq \gamma \leq 1$)

5.5.1.2 Mathematical Description

The outlet temperature is calculated as

$$T_O = T_i + \frac{P * f_{par}}{\dot{m} \, C_p}$$

Eq. 5.5-1

The outlet mass flow rate is simply

$$\dot{m}_o = \gamma \dot{m}_{max}$$

Eq. 5.5-2

If only the required PARAMETERS are provided, a linear relationship between flow rate and power consumption is assumed:

$$P = \gamma P_{max}$$

Eq. 5.5-3

If more than four PARAMETERS are provided, the additional parameters are used as coefficients in a polynomial relating power consumption to flow rate:

$$P = 0, \quad T_o = T_{in} \quad \text{if } \dot{m} = 0 \qquad\qquad \textbf{Eq. 5.5-4}$$

or

$$P = P_{max}\left[c_0 + c_1\gamma + c_2\gamma^2 + \ldots + c_i\gamma^i\right] \quad \text{if } \dot{m} > 0 \qquad\qquad \textbf{Eq. 5.5-5}$$

where c0, cl, c2, ..., ci are entered as optional PARAMETERS 5, 6, 7, ...i+5.

5.5.2   *Type 11: Tee Piece, Flow Diverter, Flow Mixer, Tempering Valve*

The use of pipe or duct 'tee-pieces', mixers, and diverters, which are subject to external control, is often necessary in thermal systems. This component has ten modes of operation. Modes 1 through 5 are normally used for fluids with only one important property, such as temperature. Modes 6 through 10 are for fluids, such as moist air, with two important properties, such as temperature and humidity. Modes 1 and 6 simulate the function of a tee-piece that completely mixes two inlet streams of the same fluid at different temperatures and or humidities as shown in Figure 5.5.2–1. Modes 2 and 7 simulate the operation of a flow diverter with one inlet which is proportionally split between two possible outlets, depending on the value of g , an Input control function as shown in Figure 5.5.2–2. Modes 3 and 8 simulate the operation of a flow mixer whose outlet flow rate, temperature, and/or humidity is determined by mixing its two possible inlets in the proportion determined by g as shown in Figure 5.5.2–3. For modes 2, 3, 7, and 8, g must have a value between 0 and 1. Modes 4, 5, 9 and 10 are temperature controlled flow diverters that may be used to model tempering valves.

5.5.2.1   *Nomenclature*

$\dot{m}_i$	mass flow rate of inlet fluid
$\dot{m}_c$	mass flow rate of outlet fluid
$\dot{m}_1$	mass flow rate at position 1 (See Figures)
$\dot{m}_2$	mass flow rate at position 2 (See Figures)
T_h	heat source fluid temperature
T_i	temperature of inlet fluid
T_o	temperature of outlet fluid
T_{set}	maximum temperature of fluid supplied to load
T_1	temperature at position 1 (See Figures)
T_2	temperature at position 2 (See Figures)
γ	control function having a value between 0 and 1
ω_1	humidity ratio at position 1
ω_2	humidity ratio at position 2
ω_i	humidity ratio of inlet fluid
ω_o	humidity ratio of outlet fluid

5.5.2.2 Mathematical Description

$$T_o = \frac{\dot{m}_1 T_1 + \dot{m}_2 T_2}{\dot{m}_1 + \dot{m}_2}$$

$$\omega_o = \frac{\dot{m}_1 \omega_1 + \dot{m}_2 \omega_2}{\dot{m}_1 + \dot{m}_2} \quad \text{(Mode 6)}$$

$$\dot{m}_o = \dot{m}_1 + \dot{m}_2$$
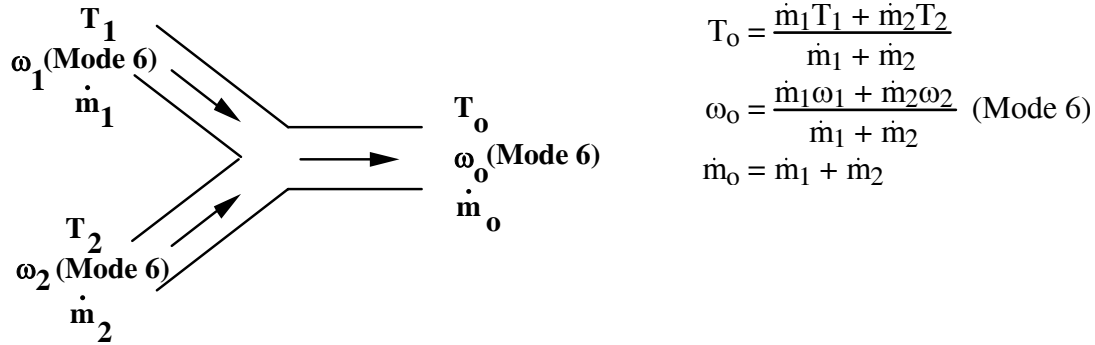
Figure 5.5.2–1: Mode 1 and 6: (Tee Piece)

$$T_1 = T_i$$
$$\omega_1 = \omega_i \quad \text{(Mode 7)}$$
$$\dot{m}_1 = \dot{m}_i \, (1\text{-}\gamma)$$
$$T_2 = T_i$$
$$\omega_2 = \omega_i \quad \text{(Mode 7)}$$
$$\dot{m}_2 = \dot{m}_i \, \gamma$$
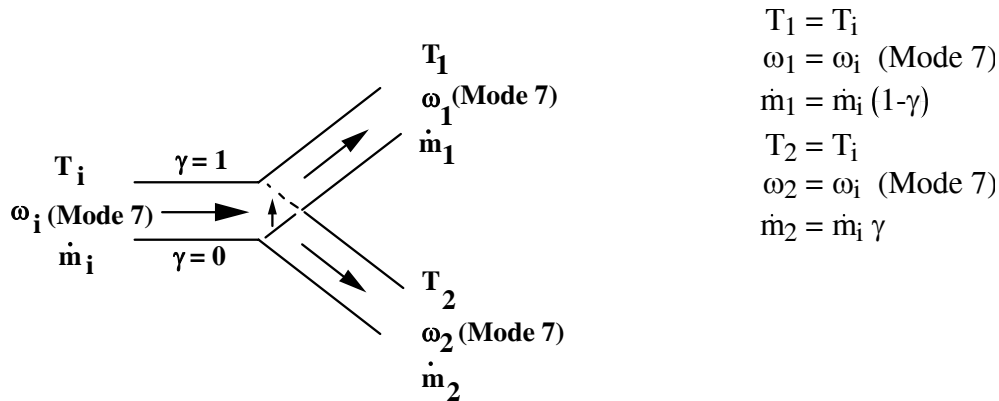
Figure 5.5.2–2: Mode 2 and 7: (Flow Diverter)

$$T_o = \frac{\dot{m}_1 T_1 \,(1\text{-}\gamma) + \dot{m}_2 T_2 \, \gamma}{\dot{m}_1 \,(1\text{-}\gamma) \, + \dot{m}_2 \, \gamma}$$

$$\omega_o = \frac{\dot{m}_1 \omega_1 \,(1\text{-}\gamma) + \dot{m}_2 \omega_2 \, \gamma}{\dot{m}_1 \,(1\text{-}\gamma) \, + \dot{m}_2 \, \gamma} \quad \text{(Mode 8)}$$

$$\dot{m}_o = \dot{m}_1 \,(1\text{-}\gamma) + \dot{m}_2 \, \gamma$$
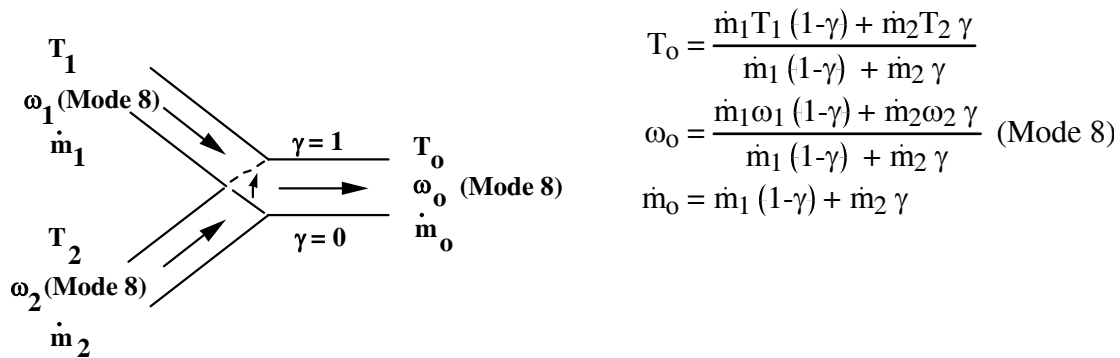
Figure 5.5.2–3: Mode 3 and 8:   (Flow Mixer)

WARNING: The outlet temperatures are left unchanged from the previous call under no-flow conditions to avoid unnecessary calls to downstream components. As a result, the outlet temperatures should not be used for any control decisions.

Modes 4, 5, 9 and 10 are similar to modes 2 and 7 except that γ is calculated by the Type 11 routine. In domestic, commercial and industrial heating applications, it is common to mix heated fluid with colder supply fluid so that the flow stream to the load is no hotter than necessary. Often this is accomplished by placing a "tempering valve" in the storage outlet stream (position A on Figure 5.5.2–4 below). Such a valve relies on the supply pressure to drive fluid through the heat source and bypass lines in proportion to the valve setting.

Although thermally equivalent, it is better for simulation purposes to place a temperature controlled flow diverter at point B (in the figure below) than to place a temperature controlled mixer at point A. Modes 4 and 5 of Type 11 are designed for this purpose. The control function γ is set so that if flow stream 1 displaces fluid of temperature T_h, the mixed fluid temperature will not exceed the temperature T_{set}. Modes 4 and 9 differ from 5 and 10 in that Modes 4 and 9 send the entire flow stream through outlet 1 when $T_h < T_i$, while Modes 5 and 10 send the entire flow stream through outlet 2 when $T_h < T_i$
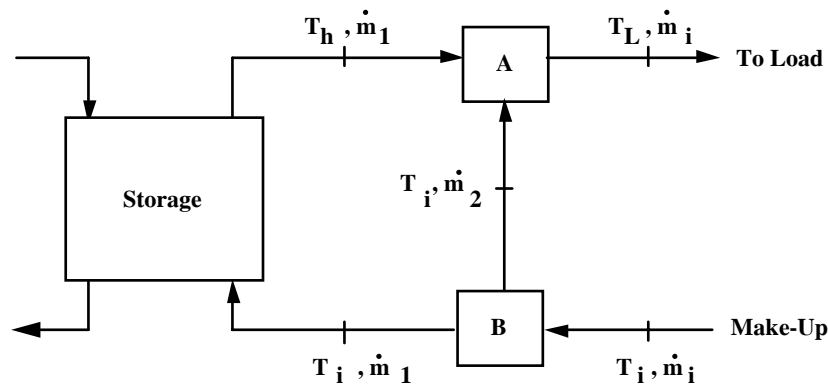
Figure 5.5.2–4: Example of Tempering Valve Use
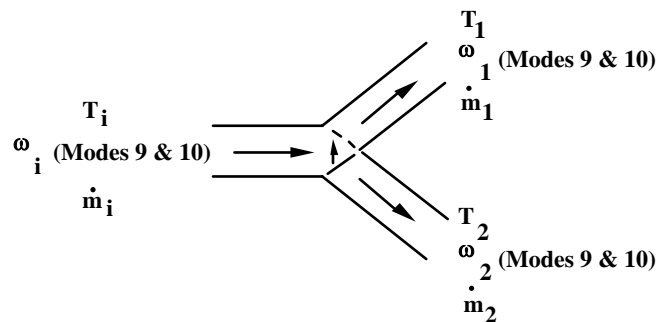
Figure 5.5.2–5: Modes 4, 5, 9, and 10 (Tempering Valve)

Table 5.5.2–1:

$T_1 = T_i$	$\gamma = (T_{set} - T_i)/(T_h - T_i)$	if $T_h > T_{set}$
$\omega_1 = \omega_i$ (Modes 9 & 10)	$\gamma = 1$	if $T_i \leq T_h \leq T_{set}$
$\dot{m}_1 = \dot{m}_i\ (\gamma)$	$\gamma = 1$	if $T_h < T_i$ (Modes 4 & 9)
$T_2 = T_i$	$\gamma = 0$	if $T_h < T_i$ (Modes 5 & 10)
$\omega_2 = \omega_i$ (Modes 9 & 10)	Note: The control function γ will not be changed after NSTK iterations at the same time step.	
$\dot{m}_2 = \dot{m}_1\ (1 - \gamma)$	Also Note: T_{set} must be $\geq T_i$ at all times.	

5.5.3   Type 13: Pressure Relief Valve

Thermal energy systems that use a liquid (e.g. water) for a heat transfer medium typically include a pressure relief valve to discard the vapor (e.g. steam) if the liquid begins to boil. As described below, TYPE 13 can be used to model either a pipe relief valve or a storage tank relief valve.

5.5.3.1   Nomenclature

c_p	Fluid specific heat
$\dot{m}_i$	Inlet mass flow rate
$\dot{m}_o$	Outlet mass flow rate
T_i	Inlet temperature
T_{boil}	Boiling point of fluid
T_{comp}	Comparison temperature
T_o	Outlet temperature
$\dot{Q}_{boil}$	Rate of energy discarded due to boiling

5.5.3.2   Mathematical Description

This model monitors inlet temperature, flow rate, and a comparison temperature, T_{comp}. Energy is discarded at a rate $\dot{Q}_{boil}$ whenever T_{comp} is greater than T_{boil}, the boiling point of the liquid. Loss of mass when the valve is open is assumed negligible; the outlet flow rate is always equal to the inlet flow rate.

If $T_{comp} > T_{boil}$ and $T_i > T_{boil}$ then

$$\dot{Q}_{boil} = \dot{m}C_p(T_i - T_{boil}) \qquad \textbf{Eq. 5.5-6}$$

and

$$To = T_{boil} \qquad \textbf{Eq. 5.5-7}$$

otherwise

$$\dot{Q}_{boil} = 0 \qquad \textbf{Eq. 5.5-8}$$

and

$$T_o = T_i \qquad \textbf{Eq. 5.5-9}$$

If T_{comp} is equal to T_i, the component models a pipe relief valve. If T_{comp} is the temperature of the top segment of a storage tank, the component models a tank relief valve, allowing boiling liquid to enter the storage tank and discarding energy only after the top of the tank begins to boil.

5.5.4   Type 31: Pipe Or Duct

This component models the thermal behavior of fluid flow in a pipe or duct using variable size segments of fluid. Entering fluid shifts the position of existing segments. The mass of the new segment is equal to the flow rate times the simulation time step. The new segment's temperature is that of the incoming fluid. The outlet of this pipe is a collection of the elements that are "pushed" out by the inlet flow. This "plug-flow" model does not consider mixing or conduction between adjacent elements.

A maximum of 25 segments is allowed in the pipe. When the maximum is reached, the two adjacent segments with the closest temperatures are combined to make one segment.

5.5.4.1   Nomenclature

c_p	[kJ/kg.K]	Fluid specific heat
M	[kg]	mass of fluid inside the pipe
$\dot{m}$	[kg/hr]	mass flow rate of fluid
Q_{env}	[kJ/hr]	energy loss rate from pipe
Q_{in_out}	[kJ/hr]	rate of energy change due to fluid flow
t	[hr]	time
T	[C]	temperature of fluid
T_i	[C]	inlet temperature of fluid
T_I	[C]	initial temperature of fluid in pipe
T_o	[C]	outlet temperature of fluid in pipe
$\bar{T}_f$	[C]	average temperature of fluid in pipe at end of current timestep
$\bar{T}_{f,t-\Delta t}$	[C]	average temperature of fluid in pipe at end of previous timestep
(UA)	[kJ/hr]	overall loss conductance
ΔE	[kJ]	change in internal energy of fluid in pipe
Δt	[hr]	simulation timestep
SUBSCRIPTS		
j,k		refer to segments of fluid in pipe

5.5.4.2   Mathematical Description

Figure 5.5.4–1 illustrates the concept behind this component. The pipe is initially composed of 3 segments with temperatures T1, T2, and T3 and lengths X1, X2, and X3 (Figure 5.5.4–1a). In one time period (Dt), a mass of fluid, Dt, enters the pipe, creating a new segment (Figure 5.5.4–1b). The existing profile is displaced such that the same quantity of fluid that enters the pipe also exits the pipe. The segments and/or fractions of segments that fall outside the pipe are removed from the profile (Figure 5.5.4–1c). The average outlet temperature is computed as the mass weighted average of leaving elements.

For the example of Figure 5.5.4–1:

$$T_o = \frac{M_3 T_3 + (\dot{m}\Delta t - M_3)T_2}{\dot{m}\Delta t}$$

<div align="right">**Eq. 5.5-10**</div>

In general:

$$T_o = \frac{1}{\dot{m}\Delta t}\left(\sum_{j=1}^{k-1} M_j T_j + aM_k T_k\right)$$

Eq. 5.5-11

where a and k must satisfy

$$0 < a < 1$$

$$\sum_{j=1}^{k-1} M_j + aM_k = \dot{m}\Delta t$$

Eq. 5.5-12

Energy losses are considered for each element by solution of the following differential equation

$$M_j C_\rho \frac{dT_j}{dt} = -(UA)_j (T_j - T_{env})$$

Eq. 5.5-13

For elements that enter or leave during a particular time step, only the duration of time within the pipe is considered. The total energy loss rate to the environment is the summation of the individual losses from each element given as:

$$\dot{Q}_{env,\,j} = (UA)_j (T_j - T_{env})$$

Eq. 5.5-14

The change in internal energy of the pipe since the beginning of the simulation is:

$$\Delta E = MC_p\left(\overline{T}_f - T_I\right)$$

Eq. 5.5-15
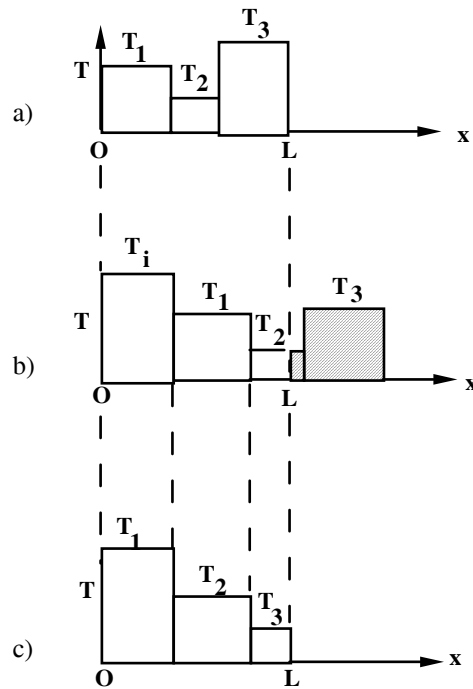
Figure 5.5.4–1: Fluid Flow in Pipe or Duct

It is possible to verify the energy balance on this model by calculating the following quantities:

- Rate of energy flow across boundaries:

$$Q_{in\_out} = \dot{m} C_p \left(T_o - T_i \right)$$

Eq. 5.5-16

- Rate of change of internal energy:

$$\Delta E / \Delta t = \frac{M C_p \left(\overline{T}_f - \overline{T}_{f,t-\Delta t} \right)}{\Delta t}$$

Eq. 5.5-17

Energy balance yields:

$$\Delta E / \Delta t = Q_{in\_out} - Q_{env}$$

Eq. 5.5-18

5.5.5 Type 110: Variable Speed Pump

Type110, formerly Type656 in the TESS Component Libraries 1.0, models a variable speed pump that is able to maintain any outlet mass flow rate between zero and a rated value. The mass flow rate of the pump varies linearly with control signal setting. Pump power draw, however, is modeled using a polynomial. Pump starting and stopping characteristics are not modeled, nor are pressure drop effects. As with most pumps and fans in TRNSYS, Type110 takes mass flow rate as an Input but ignores the value except in order to perform mass balance checks. Type110 sets the downstream flow rate based on its rated flow rate parameter and the current value of its control signal Input.

5.5.5.1 Nomenclature

$\dot{Q}_{fluid}$	[kJ/hr]	Energy transferred from the pump motor to the fluid stream passing through the pump.
η_{motor}	[0..1]	Pump motor efficiency
$\eta_{overall}$	[0..1]	Overall pump efficiency (motor efficiency * pumping efficiency)
$\eta_{pumping}$	[0..1]	Efficiency of pumping the fluid
$f_{motorloss}$	[0..1]	Fraction of pump motor inefficiencies that contribute to a temperature rise in the fluid stream passing through the pump. The remainder of these inefficiencies contribute to an ambient temperature rise.
$\dot{P}_{rated}$	[kJ/hr]	Rated power of the pump.
$\dot{P}$	[kJ/hr]	Power drawn by the pump at the current time.
$\dot{P}_{shaft}$	[kJ/hr]	Shaft power required by the pumping process (does not include motor inefficiency)
$a_0, a_1, a_2...$	[-]	Polynomial coefficients in the pump power curve
γ	[0..1]	Pump control signal.
$\dot{Q}_{ambient}$	[kJ/hr]	Energy transferred from the pump motor to the ambient air surrounding the pump.
$T_{fluid,out}$	[kJ/kg]	Temperature of fluid exiting the pump
$T_{fluid,in}$	[kJ/kg]	Temperature of fluid entering the pump
$\dot{m}_{fluid}$	[kg/hr]	Mass flow rate of fluid passing though the pump.

5.5.5.2 Mathematical Description

If the pump is determined to be off due to it's control signal being set equal to 0, the Type110 pump mass flow rate, power drawn, energy transferred from the pump to ambient and energy transferred from the pump to the fluid stream are all set to zero. The temperature of fluid exiting the pump under the OFF condition is set to the temperature of fluid at the pump inlet. If, however, the pump is determined to be ON (control signal greater than 0) then the power drawn by the pump is determined using equation 110.1.

$$\dot{P} = \dot{P}_{rated}\left(a_0 + a_1\gamma + a_2\gamma^2 + a_3\gamma^3 + a_4\gamma^4 + ...\right)$$

Eq. 5.5-19

The mass flow rate of fluid exiting the pump is a linear function of the control signal with a control signal of 1 resulting in the pump delivering its rated mass flow. The efficiency of pumping the fluid from its inlet to its outlet pressure is given by the equation below; both the motor and overall efficiency of the pump are entered by the user as Inputs to the model.

$$\eta_{pumping} = \frac{\eta_{overall}}{\eta_{motor}}$$

Eq. 5.5-20

The shaft power of the pump can now be calculated. The shaft power is the power required to perform the pumping operation, excluding the effects of motor inefficiency.

$$\dot{P}_{shaft} = \dot{P}\,\eta_{motor}$$

Eq. 5.5-21

Energy transferred from the pump motor to the fluid stream is calculated as.

$$\dot{Q}_{fluid} = \dot{P}_{shaft}\left(1-\eta_{pumping}\right) + \left(\dot{P}-\dot{P}_{shaft}\right)f_{motorloss}$$

Eq. 5.5-22

In which $\eta_{pumping}$ is the pumping process efficiency and $f_{motorloss}$ is a value between 0 and 1 that determines whether the pump motor inefficiencies cause a temperature rise in the fluid stream that passes through the pump or whether they cause a temperature rise in the ambient air surrounding the pump. Through use of the $f_{motorloss}$ fraction, the user can in effect specify whether the pump has an inline motor, in which case all waste heat would impact the fluid stream temperature and $f_{motorloss}$ would have a value of 1, or whether the pump motor is housed outside of the fluid stream such that it's waste heat impacts the ambient and $f_{motorloss}$ would have a value of 0.

The energy transferred from the pump motor to the ambient is given by.

$$\dot{Q}_{ambient} = \left(\dot{P}-\dot{P}_{shaft}\right)\left(1-f_{motorloss}\right)$$

Eq. 5.5-23

The temperature of fluid exiting the pump can now be calculated as.

$$T_{fluid,out} = T_{fluid,in} + \frac{\dot{Q}_{fluid}}{\dot{m}_{fluid}}$$

Eq. 5.5-24

Type110 does not model pump starting and stopping characteristics. As soon as the control signal indicates that the pump should be ON, the outlet flow of fluid jumps to the appropriate value between 0 and its rated condition. The reasoning is that the time constants with which pumps react to control signal changes is shorter than the typical time steps used in hydronic simulations. Type110 also operates as many pump and fan models do in TRNSYS. That is to say that they ignore the fluid mass flow rate provided as an Input to the model except so as to perform a mass balance on the pump. Therefore care must be taken in specifying fluid loops with multiple pumps that inlet mass flow rates greater than the rated mass flow rate for a given pump are not specified. The total number of time steps during which the fluid inlet mass flow rate for Type110 is not equal to its outlet flow rate is reported to the list file at the end of each simulation.

5.5.6 Type 111: Variable Speed Fan/Blower with Humidity Effects

Type111 models a fan that is able to turn at any speed between 0 (full stop) and its rated speed. While the mass flow rate of air moved by the fan is linearly related to the control signal, the power drawn by the fan at a given flow rate can be any polynomial expression of the control signal. As with most pumps and fans in TRNSYS, Type111 takes mass flow rate as an Input but ignores the value except in order to perform mass balance checks. Type111 sets the downstream flow rate based on its rated flow rate parameters and the current value of its control signal Inputs.

5.5.6.1 Nomenclature

$\dot{Q}_{air}$	[kJ/hr]	Energy transferred from the fan motor to the air stream passing through the fan.
η_{motor}	[0..1]	Fan motor efficiency
$f_{motorloss}$	[0..1]	Fraction of fan motor inefficiencies that contribute to a temperature rise in the air stream passing through the fan. The remainder of these inefficiencies contribute to an ambient temperature rise.
$\dot{P}$	[kJ/hr]	Power drawn by the fan at a given time.
$\dot{P}_{rated}$	[kJ/hr]	Fan power draw when operating at rated conditions.
$a_0, a_1, a_2...$	[kJ/hr]	Coefficients of the polynomial relating control setting to power draw.
γ	[0..1]	Fan control signal.
$\dot{Q}_{ambient}$	[kJ/hr]	Energy transferred from the fan motor to the ambient air surrounding the fan.
$h_{air,out}$	[kJ/kg]	Enthalpy of air exiting the fan
$h_{air,in}$	[kJ/kg]	Enthalpy of air entering the fan
$\dot{m}_{air}$	[kg/hr]	Mass flow rate of air passing though the fan.
$\dot{m}_{rated}$	[kg/hr]	Maximum air flow rate that can pass through the fan.

5.5.6.2 Mathematical Description

During any given time step, Type111 performs a simple set of calculations to determine the conditions of air exiting a fan. As Inputs, it takes air pressure, temperature, relative humidity and absolute humidity ratio. Depending upon the mode in which Type111 is operating, the value of either the relative humidity or the humidity ratio Input is ignored. The component passes pressure, temperature and either relative humidity or humidity ratio to the TRNSYS PSYCHROMETRICS routine, which returns values of temperature, humidity ratio, relative humidity, and enthalpy. If saturated conditions were passed to the PSYCHROMETRICS routine, PSYCHROMETRICS will return the saturated conditions corresponding to the specified temperature. This means that the humidity ratio and relative humidity used in calculations may be slightly different than those passed to the model by the user. If the air condition is saturated at any point in the simulation, the PSYCHROMETRCS routine will print a warning in the TRNSYS list file.

If the fan is determined to be off due to the control signal being set to 0, the temperature, humidity ratio, relative humidity, and pressure of air exiting the fan are set to the corresponding inlet conditions. Fan power, energy transferred from the fan motor to the air stream, energy transferred from the fan motor to ambient, and the outlet mass flow rate are all set to zero. If, on the other hand, the fan is ON due to the control signal having a value greater than 0 and less than 1, the power drawn by the fan is calculated by

$$\dot{P} = \dot{P}_{rated}\left(a_0 + a_1\gamma + a_2\gamma^2 + a_3\gamma^3 + a_4\gamma^4 + ...\right)$$

Eq. 5.5-25

With the current power drawn by the fan known the energy transferred to the fan air stream is calculated using.

$$\dot{Q}_{air} = \left(\eta_{motor} + \left(1 - \eta_{motor}\right)f_{motorloss}\right)\dot{P}$$

Eq. 5.5-26

In which η_{motor} is the motor efficiency and $f_{motorloss}$ is a value between 0 and 1 that determines whether the fan motor inefficiencies cause a temperature rise in the air stream that passes through the fan or whether they cause a temperature rise in the ambient air surrounding the fan. Through use of the $f_{motorloss}$ fraction, the user can in effect specify whether the fan has an inline motor, in which case all waste heat would impact the air stream temperature and $f_{motorloss}$ would have a value of 1, or whether the fan motor is housed outside of the air stream such that it's waste heat impacts the ambient and $f_{motorloss}$ would have a value of 0.

The energy transferred from the fan motor to the ambient is given by.

$$\dot{Q}_{ambient} = \dot{P} - \dot{Q}_{air}$$

Eq. 5.5-27

The mass flow rate of air passing through the fan at any given time is linearly related to the control signal as.

$$\dot{m} = \dot{m}_{rated}\gamma$$

Eq. 5.5-28

As with most pump and fan components in TRNSYS the flow rate of air exiting the fan is set by the component without regard to the value of the mass flow rate that is an Input to the model. The mass flow rate Input is retained to make connections around an air loop more intuitive and to allow for a mass balance check to be made on the fan. Care should be taken in setting up air loops that no more than the fan rated mass flow rate is passed to the model as an Input. Type111 prints a warning to the TRNSYS list file at the end of the simulation if the fan mass balance failed during the simulation. Type111 does not generate a simulation stopping error if the mass balance fails.

The enthalpy of air exiting the fan can be calculated as.

$$h_{air,out} = h_{air,in} + \frac{\dot{Q}_{air}}{\dot{m}_{air}}$$

Eq. 5.5-29

Lastly, the pressure rise of the fan is added to the inlet air pressure and the PSYCHROMETRICS routine is called to determine the remaining properties of the exiting air state (temperature, humidity ratio and relative humidity.) The absolute humidity ratio of outlet air is unaffected by the fan ($\omega_{in} = \omega_{out}$).

5.5.7 Type 112: Single Speed Fan/Blower with Humidity Effects

Type112 models a fan that is able to spin at a single speed and thereby maintain a constant mass flow rate of air. As with most pumps and fans in TRNSYS, Type112 takes mass flow rate as an Input but ignores the value except in order to perform mass balance checks. Type112 sets the downstream flow rate based on its rated flow rate parameter and the current value of its control signal Input.

5.5.7.1 Nomenclature

$\dot{Q}_{air}$	[kJ/hr]	Energy transferred from the fan motor to the air stream passing through the fan.
η_{motor}	[0..1]	Fan motor efficiency
$f_{motorloss}$	[0..1]	Fraction of fan motor inefficiencies that contribute to a temperature rise in the air stream passing through the fan. The remainder of these inefficiencies contribute to an ambient temperature rise.
$\dot{P}_{rated}$	[kJ/hr]	Rated power of the fan.
$\dot{Q}_{ambient}$	[kJ/hr]	Energy transferred from the fan motor to the ambient air surrounding the fan.
$h_{air,out}$	[kJ/kg]	Enthalpy of air exiting the fan
$h_{air,in}$	[kJ/kg]	Enthalpy of air entering the fan
$\dot{m}_{air}$	[kg/hr]	Mass flow rate of air passing though the fan.

5.5.7.2 Mathematical Description

During any given time step, Type112 performs a very simple set of calculations to determine the conditions of air exiting a fan. As Inputs, it takes air pressure, temperature relative humidity and absolute humidity ratio. Depending upon the mode in which Type112 is operating, the value of either the relative humidity or the humidity ratio Input is ignored. The component passes pressure, temperature and either relative humidity or humidity ratio to the TRNSYS PSYCHROMETRICS routine, which returns values of temperature, humidity ratio, relative humidity, and enthalpy. If saturated conditions were, for some reason, passed to the PSYCHROMETRICS routine, PSYCHROMETRICS will return the saturated conditions corresponding to the given temperature. This means that the humidity ratio and relative humidity used in calculations may be slightly different than those passed to the model by the user. If the air condition is saturated at any point in the simulation, the PSYCHROMETRCS routine will print a warning in the TRNSYS list file.

If the fan is determined to be off due to the control signal being set to 0, the temperature, humidity ratio, relative humidity, and pressure of air exiting the fan are set to the corresponding inlet conditions. Fan power, energy transferred from the fan motor to the air stream, energy transferred from the fan motor to ambient, and the outlet mass flow rate are all set to zero. If, on the other hand, the fan is ON due to the control signal being set to 1, the energy added to the air stream by the fan is calculated as

$$\dot{Q}_{air} = \left(\eta_{motor} + \left(1 - \eta_{motor}\right)f_{motorloss}\right)\dot{P}_{rated}$$

<div align="right">Eq. 5.5-30</div>

In which η_{motor} is the motor efficiency and $f_{motorloss}$ is a value between 0 and 1 that determines whether the fan motor inefficiencies cause a temperature rise in the air stream that passes through the fan or whether they cause a temperature rise in the ambient air surrounding the fan. Through use of the $f_{motorloss}$ fraction, the user can in effect specify whether the fan has an inline motor, in which case all waste heat would impact the air stream temperature and $f_{motorloss}$ would have a value of 1, or whether the fan motor is housed outside of the air stream such that it's waste heat impacts the ambient and $f_{motorloss}$ would have a value of 0.

The power drawn by the fan when it is operating is simply the rated power specified among the component parameters. The energy transferred from the fan motor to the ambient is given by

$$\dot{Q}_{ambient} = \dot{P}_{rated} - \dot{Q}_{air}$$

<div align="right">Eq. 5.5-31</div>

The enthalpy of air exiting the fan can now be calculated as

$$h_{air,out} = h_{air,in} + \frac{\dot{Q}_{air}}{\dot{m}_{air}}$$

<div align="right">Eq. 5.5-32</div>

Lastly, the pressure rise of the fan is added to the inlet air pressure and the PSYCHROMETRICS routine is called to determine the remaining properties of the exiting air state (temperature, humidity ratio and relative humidity.) The absolute humidity ratio of outlet air is unaffected by the fan ($\omega_{in} = \omega_{out}$) and as with most pump and fan components in TRNSYS the flow rate of air exiting the fan is set to the rated flow rate specified as one of the model's parameters regardless of the value of the mass flow rate that is an Input to this model. The Input is retained to make connections around an air loop more intuitive and to allow for a mass balance check to be made on the fan. Care should be taken in setting up air loops that no more than the fan rated mass flow rate is passed to the model as an Input.

5.5.8 Type 114: Constant Speed Pump

Type114 models a single (constant) speed pump that is able to maintain a constant fluid outlet mass flow rate. Pump starting and stopping characteristics are not modeled, nor are pressure drop effects. As with most pumps and fans in TRNSYS, Type114 takes mass flow rate as an Input but ignores the value except in order to perform mass balance checks. Type114 sets the downstream flow rate based on its rated flow rate parameter and the current value of its control signal Input.

Nomenclature

$\dot{Q}_{fluid}$	[kJ/hr]	Energy transferred from the pump motor to the fluid stream passing through the pump.
η_{motor}	[0..1]	Pump motor efficiency
$\eta_{overall}$	[0..1]	Overall pump efficiency (motor efficiency * pumping efficiency)
$\eta_{pumping}$	[0..1]	Efficiency of pumping the fluid
$f_{motorloss}$	[0..1]	Fraction of pump motor inefficiencies that contribute to a temperature rise in the fluid stream passing through the pump. The remainder of these inefficiencies contribute to an ambient temperature rise.
$\dot{P}_{rated}$	[kJ/hr]	Rated power of the pump.
$\dot{P}_{shaft}$	[kJ/hr]	Shaft power required by the pumping process (does not include motor inefficiency)
$\dot{Q}_{ambient}$	[kJ/hr]	Energy transferred from the pump motor to the ambient air surrounding the pump.
$T_{fluid,out}$	[kJ/kg]	Temperature of fluid exiting the pump
$T_{fluid,in}$	[kJ/kg]	Temperature of fluid entering the pump
$\dot{m}_{fluid}$	[kg/hr]	Mass flow rate of fluid passing though the pump.

5.5.8.1 Mathematical Description

If the pump is determined to be off due to it's control signal being set less than 0.5, the pump mass flow rate, power drawn, energy transferred from the pump to ambient and energy transferred from the pump to the fluid stream are all set to zero. The temperature of fluid exiting the pump under the OFF condition is set to the temperature of fluid at the pump inlet. If, however, the pump is determined to be ON (control signal greater than or equal to 0.5) then the mass flow rate of fluid exiting the pump and the power drawn by the pump are set to the respective rated conditions specified in the model's parameter list. The overall efficiency of the pump and the efficiency of the pump motor are used to calculate the efficiency of the pumping process as

$$\eta_{pumping} = \frac{\eta_{overall}}{\eta_{motor}}$$

Eq. 5.5-33

The power required at the pump shaft (excluding motor efficiency effects may then be calculated as

$$\dot{P}_{shaft} = \dot{P}_{rated}\,\eta_{motor}$$

Eq. 5.5-34

Energy transferred from the pump motor to the fluid stream is calculated as

$$\dot{Q}_{fluid} = \dot{P}_{shaft}\left(1 - \eta_{pumping}\right) + \left(\dot{P} - \dot{P}_{shaft}\right)f_{motorloss}$$

Eq. 5.5-35

In which $\eta_{pumping}$ is the pumping process efficiency and $f_{motorloss}$ is a value between 0 and 1 that determines whether the pump motor inefficiencies cause a temperature rise in the fluid stream that passes through the pump or whether they cause a temperature rise in the ambient air surrounding the pump. Through use of the $f_{motorloss}$ fraction, the user can in effect specify whether the pump has an inline motor, in which case all waste heat would impact the fluid stream temperature and $f_{motorloss}$ would have a value of 1, or whether the pump motor is housed outside of the fluid stream such that it's waste heat impacts the ambient and $f_{motorloss}$ would have a value of 0.

The energy transferred from the pump motor to the ambient is given by

$$\dot{Q}_{ambient} = \left(\dot{P} - \dot{P}_{shaft}\right)\left(1 - f_{motorloss}\right)$$

Eq. 5.5-36

The temperature of fluid exiting the pump can now be calculated as

$$T_{fluid,out} = T_{fluid,in} + \frac{\dot{Q}_{fluid}}{\dot{m}_{fluid}}$$

Eq. 5.5-37

Type114 does not model pump starting and stopping characteristics. As soon as the control signal indicates that the pump should be ON, the outlet flow of fluid jumps to its rated condition. The reasoning is that the time constants with which pumps react to control signal changes is shorter than the typical time steps used in hydronic simulations. Type114 also operates as many pump and fan models do in TRNSYS. That is to say that they ignore the fluid mass flow rate provided as an Input to the model except so as to perform a mass balance on the pump. Therefore care must be taken in specifying fluid loops with multiple pumps that inlet mass flow rates greater than the rated mass flow rate for a given pump are not specified. The total number of time steps during which the fluid inlet mass flow rate for Type114 is not equal to its outlet flow rate is reported to the list file at the end of each simulation.

5.6   Loads and Structures

Contained within this section are descriptions of components necessary for calculating both heating and cooling energy requirements. There are four possibilities for modeling the building energy loads with TRNSYS:

- Type 12: Steady-state, one-zone
- Type 88: single-zone lumped capacitance
- Type 19: single-zone, detailed (transfer functions for walls) – No visual interface.
- Type 56: detailed multizone building (with visual interface TRNBuild)

> Note that all the features in Type 19 are available in Type 56, which is easier to use thanks to its visual interface TRNBuild. Type 56 is the recommended model for most cases (except for very simple building loads modeled with Type 12 or Type 88).

The models for the other building components described in this section can be used in conjunction with the Type 12, Type 19 or Type 56 load models. Energy gains or losses from these components can be provided as Inputs to the load models. Except for Type 34 (overhang and wingwall), all other components in this category can be replaced to some extent by internal features in Type 56. Most often the solution that is integrated within Type 56 is preferable.

AVAILABLE BUILDING MODELS

For relatively quick estimates of heating or cooling requirements, the Energy/(Degree-Day) Type 12 model may be used. In this case, the building is modeled through the use of a single conductance (UA) for heat loss or gain, along with any additional gains due to solar, lights, people, etc. A single energy balance on the structure is performed each simulation timestep. Hourly energy loads calculated in this manner may be significantly in error. However, over a period of time, the model may provide reasonable estimates of overall energy quantities.

The Type 19 Single-Zone model, on the other hand, represents a fairly detailed analysis of a single zone. The walls (ceilings or floors, also) are modeled according to the ASHRAE transfer function approach; including provisions for windows and doors. The effects of both short-wave (solar) and long-wave radiation exchange both inside and outside the structure are considered. Multi-zone buildings can be considered by multiple use of Type 19 in a simulation.

The Type 56 Multi-zone Building model provides a more efficient way to calculate the interaction between 2 or more zones by solving the coupled differential equations utilizing matrix inversion techniques. The effects of both short-wave and long-wave radiation exchange are accounted for with an area ratios method. The walls, ceilings, and floors are modeled according to the ASHRAE transfer function approach. Providing the complex description of a multi-zone building is simplified with the use of the Visual interface TRNBuild (supplied with the TRNSYS program). Please refer to Volume 6 for detailed information on Type 56 and TRNBuild.

Type 88 is a simple, single-zone lumped-capacitance building model: all energy flows to the thermal zone (gains, HVAC system, etc.) are summed and applied to the same node. The model accounts for solar gains in a simplified way.

The Type 12, Type 19 and Type 56 models have two basic modes of operation, termed "energy rate" and "temperature level" control.

In energy rate control, the models calculate energy loads based only upon the net gains or losses from the space. The loads are considered to be independent of the heating or cooling equipment operation. The user specifies the set temperature for heating and/or cooling. The program determines the energy necessary to keep the room at these set points. The advantage of energy rate control is that a single determination of a structure's transient load can be made and re-used in subsequent simulations. However, much of the detailed switching dynamics are lost in a simulation with this approach. If, for example, the performance of a heating or cooling source component is strongly dependent on the return temperature from the load or the recent past on-off history of the source, it is desirable to use temperature level control strategy.

In temperature level control, the room state reflects both the ambient conditions and the heating or cooling equipment Input. A controller is generally used in conjunction with this mode to command the equipment. The advantage of temperature level control is a more detailed and realistic simulation of the interaction between the building and the equipment. However, since the load will be heat and cool-source dependent, it is not possible to calculate the load one time and re-use that data in subsequent simulations.

5.6.1 Type 12: Energy/(Degree Day) Space Heating or Cooling Load

The energy/(degree-day) concept has been shown by ASHRAE [l] to be useful in estimating the monthly heating load of a structure. In this space heating load model, the energy/(degree-day), or more appropriately the energy/(degree-hour), concept is extended to estimate the hour-by-hour heating load of a structure. It is generally recognized that the hour-by-hour space-heating load estimated in this manner may be significantly in error. The model however does provide an estimate of the space-heating load with minimal computational effort.

There are four modes of operation in TYPE 12 that give flexibility in control and auxiliary strategy. Modes 1, 2 and 3 are compatible with energy rate control. Modes 1 and 2 model a zero capacitance structure maintained at a constant set temperature for heating. Mode 3 allows the room temperature to float between set points for heating and cooling, T_{min} and T_{max}. A single lumped capacitance is used in this analysis. If the room temperature would rise above T_{max} or fall below T_{min}, then the energy required to maintain either limit is output as the cooling or heating requirement. Mode 4 models a single lumped capacitance house compatible with temperature level control. Normally heating and/or cooling equipment and a controller are used in conjunction with this mode. Refer to the Introduction of this section for further explanation.

5.6.1.1 Nomenclature

CAP	The effective capacitance. For computational stability this number should be selected so that maximum swing of room temperature in a timestep is on the order of the controller deadband ranges
Cmin	Minimum fluid capacitance rate of the load heat exchanger. If a load heat exchanger is not required (on air systems), ε should be 1 and Cmin should be $\dot{m}1Cp$. In a water system, Cmin is generally the capacitance rate of the air in the air-water cross flow heat exchanger
Cp	The specific heat of the flow stream
LHR	Ratio of latent load to total load
$\dot{m}h$	The mass flow rate of the heat exchanger source stream
ml	The mass flow rate of the entering source stream
$\dot{m}o$	The mass flow rate of the leaving source stream
$\dot{Q}_{aux}$	The instantaneous auxiliary energy
$\dot{Q}_{cool}$	Rate of cooling by air conditioner
$\dot{Q}_{gain}$	All time variant heat gains such as losses from storage tanks within the structure and fenestration
$\dot{Q}_{L}$	The instantaneous heat loss from the structure minus internal gains
$\dot{Q}_{lat}$	Rate at which cooling Input is used to reduce room humidity
$\dot{Q}_{sens}$	Rate at which cooling Input is used to reduce room temperature

$\dot{Q}_T$	Rate at which energy is transferred into the space across the load heat exchanger
Ta	The ambient temperature outside the structure
Ti	The temperature of the entering source stream
Tmin	The set temperature for heating
Tmax	The set temperature for cooling
To	The temperature of the source stream as it leaves the load
TR	The room temperature of the residence
$\overline{T}_R$	The average room temperature over timestep
$\overline{T}_{RC}$	The average room temperature during portion of timestep within the comfort zone
TRF	The temperature at the end of timestep
TRI	The initial room temperature
TRL	The temperature at the beginning of a timestep
UA	A constant having units of energy/(degree-hour) which characterizes the heating requirements of a specified structure.
ε	Effectiveness of the load heat exchanger
Δt	Simulation timestep
Δtc	period of time within a timestep that room temperature is in the comfort range

5.6.1.2   Mathematical description

This component provides the user with two methods of supplying auxiliary energy to the load. Mode 1 is the parallel auxiliary mode and Mode 2 is the series, or "bypass" auxiliary mode. Both of these modes are to be used for simulation of heating only. Modes 3 or 4 can be used for determining either heating or cooling energy requirements.

MODE 1: PARALLEL AUXILIARY (0 NODE)

Auxiliary energy makes up only that part of the load that cannot be extracted from the flow stream of capacitance rate $\dot{m}_h C_p$ and temperature T_i:
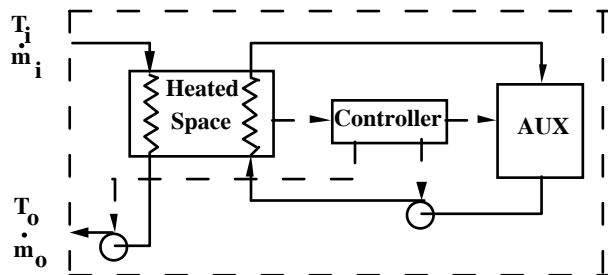
Mode 1 (parallel auxiliary)

$$\dot{Q}_L = \begin{cases} [\, UA(T_R\text{-}T_a) \text{-} \dot{Q}_{gain}] & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases}$$

(Eq 5.7.1.1)

$$\dot{m}_o = \begin{cases} \dot{m}_h & \text{if } \dot{Q}_L > 0 \\ 0 & \text{if } \dot{Q}_L < 0 \end{cases} \qquad \text{(Eq 5.7.1.2)}$$

$$\dot{Q}_L = \begin{cases} \min\left(\varepsilon C_{min}(T_i\text{-}T_R), \dot{Q}_L\right) & \text{if } T_i > T_R \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.3)}$$

$$\dot{Q}_{aux} = \dot{Q}_L - \dot{Q}_T \qquad \text{(Eq 5.7.1.4)}$$

$$T_o = T_i - \dot{Q}_T / \dot{m}_h \dot{C}_p \qquad \text{(Eq 5.7.1.5)}$$

MODE 2: SERIES AUXILIARY (0 NODE)

Auxiliary supplies the entire load via the by-pass circuit when the flow stream of flow rate $\dot{m}c$ and specific heat C_p cannot meet the load:
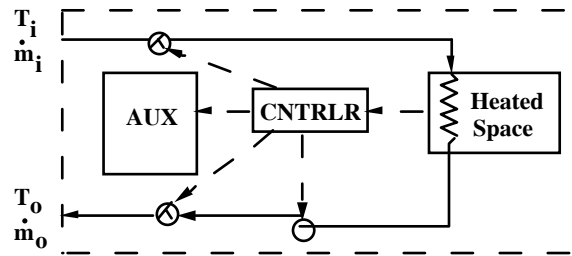
Mode 2 (series auxiliary)

$$\dot{Q}_L = \begin{cases} [UA\,(T_R - T_a) - \dot{Q}_{gain}] & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.6)}$$

$$\dot{Q}_T = \begin{cases} \dot{Q}_L & \text{if } \dot{Q}_L \leq \varepsilon C_{min}(T_i\text{-}T_R) \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.7)}$$

$$\dot{m}_o = \begin{cases} \dot{m}_h & \text{if } \dot{Q}_L \leq \varepsilon C_{min}(T_i - T_R) \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.8)}$$

$$\dot{Q}_{aux} = \begin{cases} 0 & \text{if } \dot{Q}_L \leq \varepsilon C_{min}(T_i - T_R) \\ \dot{Q}_L & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.9)}$$

$$T_o = \begin{cases} T_i - \dot{Q}_T / \dot{m}_h C_p & \text{if } \dot{Q}_T > 0 \\ T_i & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.10)}$$

MODE 3: FLOATING ROOM TEMPERATURE, ENERGY RATE AUXILIARY

Mode 3 models a one node house with a floating room temperature and built in heating and cooling equipment. The differential equation describing the rate of change of internal energy of a lumped capacity structure is

$$\text{CAP} \frac{dT_r}{dt} = \gamma \cdot \varepsilon\, C_{min}\, (T_i - T_R) + \dot{Q}_{gain} - UA\, (T_R - T_a) \qquad \text{(Eq 5.7.1.11)}$$

where,

$$\gamma = \begin{cases} 1 & \text{if } \dot{m}_1 > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.12)}$$

The above differential equation is solved for the final and average room temperature for each timestep, T_{RF} and $\overline{T}_S$ using subroutine DIFFERENTIAL_EQN (See Volume 08, Programmer's guide).

If $T_{RF} < T_{min}$

$$T_{RF} = T_{min} \qquad \text{(Eq 5.7.1.13)}$$

$$\overline{T}_R = \overline{T}_{RC} \cdot \frac{\Delta t_c}{\Delta t} + T_{min} \left(1 - \frac{\Delta t_c}{\Delta t}\right) \qquad \text{(Eq 5.7.1.14)}$$

If $T_{RF} > T_{max}$

$$T_{RF} = T_{max} \qquad \text{(Eq 5.7.1.15)}$$

$$\overline{T}_R = \overline{T}_{RC} \cdot \frac{\Delta t_c}{\Delta t} + T_{max} \left(1 - \frac{\Delta t_c}{\Delta t}\right) \qquad \text{(Eq 5.7.1.16)}$$

In any case,

$$\dot{Q}_T = \gamma\, \varepsilon\, C_{min}\, (T_i - \overline{T}_R) \qquad \text{(Eq 5.7.1.17)}$$

$$\dot{Q}_L = UA\, (\overline{T}_R - T_a) - \dot{Q}_{gain} \qquad \text{(Eq 5.7.1.18)}$$

$$\dot{Q}_{aux} = \begin{cases} \dot{Q}_L - \dot{Q}_T + \dfrac{\text{Cap}\,(T_{RF} - T_{RL})}{\Delta t} & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.19)}$$

$$\dot{Q}_{sens} = \begin{cases} \dot{Q}_T - \dot{Q}_L - \dfrac{\text{Cap}\,(T_{RF} - T_{RL})}{\Delta t} & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq 5.7.1.20)}$$

When degree-day loads are used for air conditioning calculations, ASHRAE (1) suggests multiplying the sensible load by a constant factor to account for latent loads. The optional parameter latent load

$$LHR = \frac{\text{latent load}}{\text{total load}}$$

(Eq 5.7.1.21)

may be used for this purpose. ASHRAE recommends (latent load)/(sensible load) ratios of about 0.3, or LHR = 0.23. The total and latent cooling loads are calculated as

$$\dot{Q}_{cool} = \frac{\dot{Q}_{sens}}{(1\text{-}LHR)}$$

(Eq 5.7.1.22)

$$\dot{Q}_{lat} = \dot{Q}_{cool} - \dot{Q}_{sens}$$

(Eq 5.7.1.23)

MODE 4: FLOATING ROOM TEMPERATURE, NO AUXILIARY

The analysis in mode 4 is similar to that of mode 3, except the room temperature reflects both the ambient conditions and the heating or cooling equipment Inputs. The differential equation for changing internal energy is

$$CAP \frac{dT_R}{dt} = \gamma \cdot \left[\varepsilon\, C_{min} (T_i - T_R) + \dot{Q}_{gain} - UA (T_R - T_a) + \dot{Q}_{aux} - \dot{Q}_{sens} \right]$$

(Eq 5.7.1.24)

where,

$$\gamma = \begin{cases} 1 & \text{if } \dot{m}_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

(Eq 5.7.1.25)

$$\dot{Q}_{sens} = (1 - LHR)\, \dot{Q}_{cool}$$

(Eq 5.7.1.26)

This differential equation is solved for the final and average room temperature for each timestep, T_{RF} and $\overline{T}_R$ using DIFFERENTIAL_EQN

$$\dot{Q}_T = \gamma \cdot \varepsilon C_{min} (T_i - \overline{T}_R)$$

(Eq 5.7.1.27)

$$\dot{Q}_L = UA (T_R - T_a) - \dot{Q}_{gain}$$

(Eq 5.7.1.28)

$$\dot{Q}_{lat} = \dot{Q}_{cool} - \dot{Q}_{sens}$$

(Eq 5.7.1.29)

5.6.1.3   References

1. ASHRAE, 2001. Handbook of Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

5.6.2 Type 18: Pitched Roof and Attic

General Description

A transfer function pitched roof and attic model has been developed to furnish a Type 19 room with a ceiling heat loss calculation. This model is far less expensive (computationally) to run than previous finite-difference (nodal) models. Transfer function coefficients have been built into this model since several geometric assumptions are necessary (see Figure 5.6.2–1).
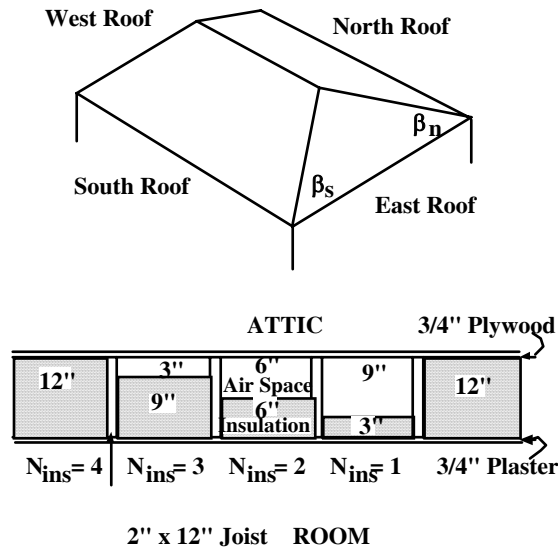
Figure 5.6.2–1: Roof Geometry and Ceiling Cross Section

5.6.2.1 Nomenclature

> NOTE: Because empirical equations are built into this component, the user must use the units specified.

A_i	Total area of surface i (m^2)
b_n	Coefficient of temperature difference term at time n (kJ/hr-m^2-° C)
C_{eff}	Effective conductance from $T_{sa, eff}$ to T_{attic} (kJ/hr-m-° C)
C_i	Conductance from surface i to T_{attic} (kJ/hr-m-° C)
C_I	Effective conductance of infiltration air (kJ/hr-° C)
C_p	Specific heat of air (kJ/kg-° C)
d_n	Coefficient of heat flux term at time n
$F_{i,gnd}$	View factor from surface i to ground and surroundings
$F_{i,sky}$	View factor from surface i to sky
$h_{i,\beta}$	inside heat transfer coefficient by convection for attic surface at slope β (kJ/hr-m^2-° C)
ho	Heat transfer coefficient by radiation and convection at the outer surface (kJ/hr-m2-° C)
I_{Ti}	Rate of total solar radiation incident per unit area upon surface i (kJ/m^2-hr)
N_{roof}	Parameter indicating whether collector is included in the model
N_{ins}	Parameter that specifies the amount of insulation in the ceiling

$\dot{Q}_o$	Total rate of heat gain or loss through ceiling (kJ/hr)
q_o''	Current heat flux entering or leaving a room (kJ/m^2-hr)
q_n''	Heat flux entering or leaving a room at time n (kJ/m^2-hr)
T_a	Ambient Temperature (° C)
T_c	Outlet temperature from collector (° C)
T_{sky}	Sky temperature (° K)
T_{gnd}	Temperature of ground and surroundings (° K)
$T_{sa,eff}$	Effective solar-air temperature of roof surfaces and infiltration air (° C)
$T_{sa,i}$	Solar-air temperature of surface i (° C)
T_{rc}	Room temperature (° C)
$\dot{V}$	Rate of attic infiltration of outside air (m^3/hr)
W	Wind speed (m/sec)
α	Solar absorptance of exterior surface (0 ≤ α ≤ 1.0)
β	Slope of surface from horizontal (degrees)
ε_l	Infrared emittance of surface i (0 ≤ ε ≤ 1.0)
σ	Stefan-Boltzmann constant (2.041 x 10^{-7} kJ/hr-m^2-° K^4)
ρ	Density of outside air (kg/m^3)
ΔR	Infrared radiation difference between surface and sky and surroundings (kJ/m^2-hr)

SUBSCRIPTS

n,s,e,w   refer to North, South, East, and West

5.6.2.2 Mathematical Description

Heat flux calculations are similar to those for a transfer function wall as described in the TYPE 19 documentation. The only difference is that an effective sol-air temperature, $T_{sa,eff}$, is calculated as a function of the sol-air temperatures of the various roof surfaces and the infiltration rate (see Figure 5.6.2–2). The effective sol-air temperature is then used as a heat source (or sink) to drive the heat flux equation:

$$T_{sa,eff} = \frac{C_s T_{sa,s} + C_e T_{sa,n} + C_w T_{sa,w} + C_i T_a}{C_{eff}} \quad [°C]$$

(Eq 5.7.2.1)

where

$T_{sa,i}$ is the sol-air temperature of surface i

C_i is the total conductance between $T_{sa,i}$ and the attic

The sol-air temperatures of surface i are found from

$$T_{sa,i} = T_a + \frac{\alpha I_{Ti}}{h_o} + \frac{\Delta R_i}{h_o}$$

(Eq 5.7.2.2)

where

$\Delta R_i = \varepsilon_i \sigma (F_{i,sky} (T_{sky}^4 - T_a^4) + F_{i,gnd} (T_{gnd}^4 - T_a^4))$

(Eq 5.7.2.3)

$\Delta R_e = \Delta R_w \; ^a \; 0$
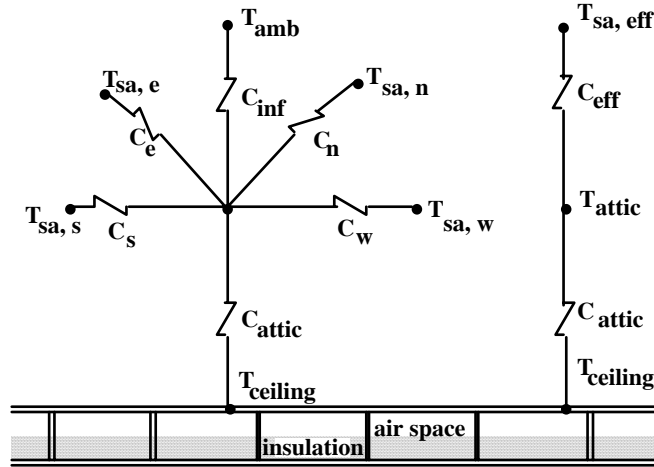
Figure 5.6.2–2: Effective Sol-Air Networks

The respective view factors from surface i are found by

$$F_{i,sky} = \frac{1 + \cos\beta}{2}$$

(Eq 5.7.2.4)

$$F_{i,gnd} = \frac{1 - \cos\beta}{2}$$

(Eq 5.7.2.5)

where

β = slope of surface i from horizontal.

The effective conductance, C_{eff} is calculated as

$$C_{eff} = C_s + C_e + C_n + C_w + C_l \quad (kJ/hr\text{-}^\circ C)$$

(Eq 5.7.2.6)

where C_l, the attic infiltration is calculated from

$$C_l = \dot{V} \rho\, C_p \quad (kJ/hr\text{-}^\circ C)$$

(Eq 5.7.2.7)

The outside heat transfer coefficient is calculated

$$h_o = 10.08 + 10.8W \quad (kJ/hr\text{-}m^2\text{-}^\circ C)$$

The inside heat transfer coefficients are from the <u>ASHRAE Handbook of Fundamentals</u>:

$$h_{i,90} = 29.84 \quad (kJ/hr\text{-}m^2\text{-}^\circ C)$$

(Eq 5.7.2.8)

$$h_{i,45} = 32.70 \quad (kJ/hr\text{-}m^2\text{-}^\circ C)$$

(Eq 5.7.2.9)

$$h_{i,0} = 33.32 \quad (kJ/hr\text{-}m^2\text{-}^\circ C)$$

(Eq 5.7.2.10)

The current heat flux entering or leaving a room through the ceiling, q_0'', is then calculated as follows:

$$q_0'' = \sum_{n=0} b_n \left(T_{sa,eff,n} - T_{rc} \right) - \sum_{n=1} d_n \, q_n'' \quad [kJ/h - m^2]$$ (Eq 5.7.2.11)

and the total rate of heat loss or gain is

$$\dot{Q}_0 = A_c \, q_0''$$ (Eq 5.7.2.12)

The values and number of coefficients are stored internally and are obtained by specifying the amount of ceiling insulation.

5.6.3　　Type 19: Detailed Zone (Transfer Function)

This model is useful for estimating heating or cooling loads for a single zone. Walls, windows, flat roofs, doors, and floors are included in this component. The set of equations for heat transfer from and within the zone are formulated in a matrix and solved in a computationally efficient manner each simulation timestep.

In order to describe a zone using this component, the user specifies separate sets of parameters and Inputs describing the internal space, the walls (also floors and ceilings), windows, and doors. The walls are modeled using the ASHRAE transfer function approach (1). Exterior walls, interior partitions (walls within a zone at one temperature), or walls separating zones at different temperatures can be handled. The user may select from the list of standard walls, partitions, ceilings, or floors, taken from the ASHRAE Handbook of Fundamentals (1) and listed near the end of this section. The transfer function coefficients are in the file ASHRAE.COF, which is accessed by the program at the beginning of the simulation through logical unit. Alternatively, the program PREP is included with TRNSYS for the purpose of generating transfer function coefficients for arbitrarily constructed walls. If the user wishes to consider a wall or floor that is not appropriately modeled according to the transfer function concept, then conduction from this wall must be provided as an Input to the TYPE 19 zone. An example of such a wall would be a TYPE 36 Thermal Storage Wall.

This model has two basic modes of operation that make it compatible with the energy rate or temperature level control strategies discussed in the introduction to this section. In mode 1, the user specifies limits on the maximum and minimum zone temperatures, T_{max} and T_{min}. These are the set points for cooling and heating, respectively. When the calculated value of the zone temperature falls between these limits, no load is output. If the zone temperature would rise above T_{max} or fall below T_{min}, then the energy required to maintain the zone at either limit is output along with the limit temperature. Cooling loads are positive, while heating is negative. The implicit assumption in Mode 1 is that the load is exactly met since the required zone temperature is assumed. The load that is output is independent of any heating or cooling equipment operation. Latent loads are also calculated in Mode 1 on an energy rate basis. The zone humidity ratio is allowed to float between a maximum and minimum limit specified by the user, ω_{max} and ω_{min}. If the calculated humidity ratio would fall outside these limits, then the humidification or dehumidification energy required to maintain a ratio of ω_{min} or ω_{max} is output. Otherwise, the latent load is zero.

In temperature level control (Mode 2), the zone temperature and humidity reflect both the ambient conditions and the heating or cooling equipment Input. Heat may be added or removed by use of a ventilation flow stream or an instantaneous heat gain Input (heat added is positive, while heat removed is negative). There are no minimum or maximum limits on the zone temperature or humidity. Normally, a controller is used in conjunction with this mode to command the heating or cooling equipment.

> Note: Type 19 component configuration and instructions to use PREP are located in a supplement to this manual. The supplement can be found in %TRNSYS16%\Documentation\Type19Supplement.pdf
>
> Note that all the features in Type 19 are available in Type 56, which is easier to use thanks to its visual interface TRNBuild. Type 56 is the recommended model for most cases (except for very simple building loads modeled with Type 12 or Type 88).

5.6.3.1   Nomenclature

A	-	overall surface area of wall or window exposed to inside of zone
b	-	transfer function coefficient for current and previous sol-air temperature
Cap	-	effective capacitance of room air plus any mass not considered with transfer functions
C_{pa}	-	specific heat of air
c	-	transfer function coefficient for current and previous equivalent zone air temperature
d	-	transfer function coefficient for current and previous heat flux to zone
F_{ki}	-	view factor from surface k to i
$\hat{F}_{ki}$	-	net exchange factor from surface k to i
$h_{c,i}$	-	convection coefficient at inside surface
$h_{c,o}$	-	outside convection coefficient
$h_{r,ij}$	-	linearized radiative coefficient between surfaces i and j
I_T	-	total incident solar radiation
K_1	-	constant air change per hour
K_2	-	proportionality constant for air change due to indoor-outdoor temperature difference
K_3	-	proportionality constant for air change due to wind effects
$\dot{m}_{infl}$	-	mass flow rate of air infiltration
$\dot{m}_v$	-	mass flow rate of ventilation stream
N	-	total number of surfaces comprising zone
$\dot{q}_I$	-	heat transfer rate per unit area at the inside surface of a wall or window
$\dot{Q}$	-	total heat transfer rate at the inside surface of a wall or window
$\dot{Q}_{infl}$	-	rate of energy gain into the zone due to infiltration
$\dot{Q}_{int}$	-	rate of energy transfer to the zone due to internal gains other than people or lights
$\dot{Q}_{lat}$	-	latent load; energy required to keep humidity levels within the comfort zone. Dehumidification is a positive latent load, while humidification is negative.
$\dot{Q}_{sens}$	-	sensible load; energy required by auxiliary heating or cooling equipment to keep zone temperature within the comfort zone. Cooling is positive, heating is negative.
$\dot{Q}_{spepl}$	-	rate of energy transfer to the zone due to sensible gains from people
$\dot{Q}_v$	-	rate of energy gain to the space due to the ventilation flow stream
$\dot{Q}_z$	-	rate of energy gain to the space due to convection from attached zones
s	-	sum of radiative energy absorbed at an inside surface due to solar, lights, and people
T_a	-	ambient temperature
T_{eq}	-	equivalent zone temperature; inside air temperature which, in the absence of radiative exchange at the inside surface, gives the same heat transfer as actually occurs
T_{min}	-	minimum allowable zone temperature; set point for heating
T_{max}	-	maximum allowable zone temperature; set point for cooling
T_{sa}	-	sol-air temperature; outside air temperature, which in the absence of radiative exchange at outside surface gives the same heat transfer as actually occurs
T_s	-	surface temperature
T_z	-	zone temperature
$T_z^{'}$	-	temperature of an adjacent zone
U_g	-	loss coefficient of window from inside to outside surface
$U_{g,o}$	-	overall loss coefficient of window including convection at inside and outside surfaces

V_a -   volume of air in the zone

W   -   windspeed

ω_{min} -   minimum allowable zone humidity ratio; set point for humidification

ω_{max} -   maximum allowable zone humidity ratio; set point for dehumidification

ω_a -   humidity ratio of ambient air

$\dot{\omega}_I$ -   rate of internal moisture gains to zone other than people

ω_v -   humidity ratio of entering ventilation flow stream

ω_z -   humidity ratio of zone air

X   -   vector containing time varying Inputs that affect surface and zone temperatures

Z   -   matrix containing time independent factors affecting surface and zone temperatures

Δh_{vap} -   heat of vaporization of water

α -   absorptance of the outside of a surface for solar radiation

ρ -   reflectance term of inside surface for solar radiation

ρ_a -   density of zone air

σ -   Stephan-Boltzman constant

SUBSCRIPTS

i, j, or k   -   refer to surfaces i, j, k

h   -   denotes the term of a transfer function. 0 is the current hour, I is the previous hour, etc.

5.6.3.2   *Mathematical Description*

In order to solve the basic equations modeling the heat transfer through and between all elements in the zone, the problem is reduced to the following matrix equation.

$$[Z_{i,j}] \, [T_{s,i}] = [X_i] \tag{Eq 5.7.3.1}$$

where $T_{s,i}$ represents the inside surface temperature of element i, unless i is equal to the number of surfaces plus one (n+1), in which case it is the zone air temperature. The factor X_i includes time varying Inputs that affect $T_{s,i}$., $Z_{i,j}$ is a coefficient relating the heat transfer between elements i and j.

The objective is to formulate the problem in terms of (Eq 5.7.3.1), making simplifying assumptions that result in a time independent $Z_{i,j}$ matrix. In this manner, the $Z_{i,j}$ matrix is inverted once at the beginning of the simulation and stored for later use. The solution of the set of equations is then reduced to multiplication of the inverted $Z_{i,j}$ matrix and the time varying X_i vector as given by (Eq 5.7.3.2) and formulated by Madsen (3).

$$[T_{s,i}] = [Z_{i,j}]^{-1} \, [X_i] \tag{Eq 5.7.3.2}$$

EXTERIOR WALL

The instantaneous heat flux entering or leaving the zone for an exterior wall can be modeled according to the following transfer function relationship.

$$\dot{q}_i = \sum_{h=0} b_{h,i} \, T_{sa,i,h} - \sum_{h=0} c_{h,i} \, T_{eq,i,h} - \sum_{h=1} d_{h,i} \, \dot{q}_{i,h} \tag{Eq 5.7.3.3}$$

The coefficients b_h, c_h, and d_h are transfer function coefficients for current and previous values of the sol-air temperature ($T_{sa,i}$), equivalent zone temperature ($T_{eq,i}$), and heat flux, $\dot{q}_i$. A value of h equal to zero represents the current time interval, h equal to one is the previous hour and so on. The sol-air temperature, $T_{sa,i}$, is the temperature of the outdoor air which, in the absence of all radiation exchanges, would give the same heat transfer at the outside surface as actually occurs. For a vertical wall, it is generally expressed as:

$$T_{sa,i} = T_a + \frac{(\alpha I_T)_i}{h_{c,o}}$$

(Eq 5.7.3.4)

The following expression is used to evaluate the heat transfer coefficient for convection over the building:

$$h_{c,o} = 5.7 + 3.8\ W$$

(Eq 5.7.3.5)

where the windspeed W has the units of m/s and $h_{c,o}$ is in W/m^2-° C.

The equivalent zone temperature, $T_{eq,i}$, is analogous to a sol-air temperature for the inside surface. It is the inside air temperature, which in the absence of radiative exchange at the inside surface, gives the same heat transfer as actually occurs. This is expressed as:

$$T_{eq,i} = T_z + \frac{s_i + \sum_{j=1}^{N} h_{r,ij}(T_{s,j} - T_{s,i})}{h_{c,i}}$$

(Eq 5.7.3.6)

The quantity s_i is the sum of radiative gains absorbed by the surface due to solar, lights, equipment, and people. A discussion of the calculation of these gains appears in a following section. Long-wave radiation between surfaces in the zone is considered through the use of a linearized radiative heat transfer coefficient, $h_{r,ij}$. All surfaces are assumed to be black for long-wave radiation, such that

$$h_{r,ij} = 4\sigma F_{ij}\overline{T}^3$$

(Eq 5.7.3.7)

This radiative coefficient is assumed to be constant throughout the simulation. It is evaluated at the initial temperature of the zone specified by the user. View factors between all surfaces in the zone are calculated for a rectangular parallelpiped by subroutine ENCL, as described in Section 3.4.5. The user specifies the dimensions of the zone, along with the location of any windows or doors.

(Eq 5.7.3.3) expressed the heat transfer at the inside surface in terms of a transfer function relationship. However, it can also be given according by the following heat transfer equation:

$$\dot{q}_i = h_{c,i}(T_{s,i} - T_{eq,i})$$

(Eq 5.7.3.8)

If (Eq 5.7.3.8) is substituted into (Eq 5.7.3.3), the result can be arranged in the form of (Eq 5.7.3.1) as

$$T_{s,i} \left(1 - \frac{c_{o,i}^*}{h_{c,i}} \sum_{j=1}^{N} h_{r,ij} \right) + \frac{c_{o,i}^*}{h_{c,i}} \sum_{j=1}^{N} h_{r,ij} T_{s,j} + c_{o,i}^* T_z$$

$$= \sum_{h=0} b_{h,i}^* T_{sa,i,h} - \sum_{h=1} c_{h,i}^* T_{eq,i,h} - \sum_{h=1} d_{h,i} T_{s,i,h} - \frac{c_{o,i}^* s_i}{h_{c,i}}$$ (Eq 5.7.3.9)

where,

$$c_{o,i}^* = \frac{c_{o,i}}{h_{c,i}} - 1$$

$$c_{h,i}^* = \frac{c_{h,i}}{h_{c,i}} - d_h$$

$$b_{h,i}^* = \frac{b_{h,i}}{h_{c,i}}$$

In terms of the nomenclature of (Eq 5.7.3.1):

$$Z_{i,j} = \frac{c_{o,i}^*}{h_{c,i}} h_{r,ij} \quad \text{for } i \neq j$$ (Eq 5.7.3.10)

$$Z_{i,i} = 1 - \frac{c_{o,i}^*}{h_{c,i}} \sum_{j=1}^{N} h_{r,ij}$$ (Eq 5.7.3.11)

$$Z_{i,N+1} = c_{o,i}^*$$ (Eq 5.7.3.12)

$$X_i = \sum_{h=0} b_{h,i}^* T_{sa,i,h} - \sum_{h=1} c_{h,i}^* T_{eq,i,h} - \sum_{h=1} d_{h,i} T_{s,i,h} - \frac{c_{o,i}^* s_i}{h_{c,i}}$$ (Eq 5.7.3.13)

INTERIOR PARTITION

An interior partition is assumed to be a wall that is exposed to identical conditions at both surfaces. With this criterion, the wall is adiabatic at the centerline and the heat transfer at the surface is given as

$$\dot{q}_i = \sum_{h=0} \left(b_{h,i} - c_{h,i} \right) T_{eq,i,h} - \sum_{h=1} d_{h,i} \dot{q}_{i,h}$$ (Eq 5.7.3.14)

The heat transfer is also given by (Eq 5.7.3.8). If this expression is substituted into equation (4.3.8.14), the result can be rearranged in the form of equation (4.3.8.1) such that:

$$Z_{ij} = \frac{\left(c_{o,i}^* - b_{o,i}^*\right) h_{r,ij}}{h_{c,i}} \quad \text{for } i \neq j$$

(Eq 5.7.3.15)

$$Z_{i,i} = 1 - \frac{\left(c_{o,i}^* - b_{o,i}^*\right) \sum h_{r,ij}}{h_{c,i}}$$

(Eq 5.7.3.16)

$$Z_{i,N+1} = c_{o,i}^* - b_{o,i}^*$$

(Eq 5.7.3.17)

$$X_i = -\sum_{h=1} c_{h,i}^* T_{eq,i,h} - \sum_{h=1} d_{h,i} T_{s,i,h}$$

If both sides of the wall under consideration are exposed to the inside of zone, then the user should specify the surface area to include both faces.

WALL BETWEEN ZONES

An interior wall separating two adjacent zones at different temperatures is modeled in the same manner as an external wall, except that the sol-air temperature is replaced by an equivalent zone temperature. The equivalent zone temperature, $T_{eq,i}'$, is the temperature of adjacent zone which, in the absence of all radiation exchanges, gives the same heat transfer at the inside of adjacent zone surface as actually occurs. (Eq 5.7.3.10) - (Eq 5.7.3.13) apply for an interior wall between zones if $T_{sa,i}$ is replaced with $T_{eq,i}'$. The equivalent zone temperature for any wall is provided as an optional output of the TYPE 19.

CONDUCTION INPUT

Walls or other structures not appropriately modeled using transfer function relationships must appear as separate components in a simulation. The energy conduction at the inside surface of this wall must be provided as an Input to the TYPE 19 Zone. The expression for surface heat transfer given in (Eq 5.7.3.8) can be rearranged in the form of (Eq 5.7.3.1) such that

$$Z_{i,j} = \frac{-h_{r,ij}}{h_{c,i}} \text{ for } i \neq j$$

(Eq 5.7.3.19)

$$_{i,i} = 1 + \frac{\sum h_{r,ij}}{h_{c,i}}$$

(Eq 5.7.3.20)

$$Z_{i,N+1} = -1$$

(Eq 5.7.3.21)

$$X_i = \frac{\dot{Q}_i/A_i + s_i}{h_{c,i}}$$

(Eq 5.7.3.22)

The heat transfer, $\dot{Q}_i$ is provided as an Input. The equivalent zone temperature for this wall, $T_{eq,i}$ should be used as the zone condition for evaluating $\dot{Q}_i$ in the separate wall component. If the actual zone temperature were used instead, then the effects of the absorption of radiation on the inside surface would not be correctly accounted for.

WINDOW

There are two window modes. In mode 1, the solar transmission and the thermal heat gain are determined internally. The solar energy passing through the window is the product of the incident solar radiation and the transmittance provided as an Input. The thermal conduction through the window from the ambient is given as

$$\dot{Q}_i = A_i \, U_{g,o,i} \, (T_a - T_{eq,i}) \qquad\qquad\qquad\text{(Eq 5.7.3.23)}$$

The loss coefficient from the inside to the outside surface of window is an Input. The overall loss coefficient, $U_{g,o}$, is the reciprocal of the sum of the resistances of the window ($1/U_g$), the outside air ($1/h_{c,o}$) and the inside air ($1/h_{c,i}$). The energy transfer is evaluated with the above equation using the last estimate of $T_{eq,i}$. With this assumption, (Eq 5.7.3.19) - (Eq 5.7.3.22) are applicable. This procedure allows a variable overall loss coefficient while retaining the time independence of the Z_{ij} matrix.

In the second window mode, both solar energy transmitted through the wall and the thermal heat gain are Inputs. These may be calculated using a more detailed window model such as the TYPE 35. (Eq 5.7.3.19) - (Eq 5.7.3.22) are also applicable in this mode.

RADIATIVE GAINS

Radiation gains to each surface in the room originate from lights, people, and solar radiation entering windows. Solar radiation passing through windows is assumed to be diffusely reflected. Consider beam radiation striking a surface k. The diffuse radiation leaving k that strikes surface i is determined using the total exchange factor from Beckman (5). This factor $\hat{F}_{ki}$, is defined as the fraction of energy striking surface i which diffusely originated at surface k. For an enclosure with N diffusely reflecting surfaces, $\hat{F}_{ki}$ is expressed as:

$$\hat{F}_{ij} = F_{ij} + F_{i1} \, \rho_1 \, \hat{F}_{ij} + \ldots + F_{ii} \, \rho_i \, \hat{F}_{ij} + \ldots + F_{ij} \, \rho_i \, \hat{F}_{jj} + \ldots + F_{iN} \, \rho_N \, \hat{F}_{Nj} \qquad\text{(Eq 5.7.3.24)}$$

The solution to equation (24) can be written in matrix notation as

$$[\hat{F}_{ij}] = [\delta_{ij} - F_{ij} \, \rho_i] \, [F_{ij}]$$

where:

$\delta_{ij} = 1$ for i=j

$\delta_{ij} = 0$ otherwise

Diffuse radiation entering windows is assumed to be isotropic. With this assumption, the fraction of the diffuse radiation transmitted through a window k that strikes surface is $\hat{F}_{ki}$.

All surfaces are assumed to be black (i.e. perfect absorbers) for radiation from lights and people. Radiation from these sources is also considered to be isotropic. Radiative gains from people are assumed to be 70% of their total sensible energy output.

INTERNAL SPACE

An energy balance on the zone air plus any furnishings considered as a lumped system yields

$$\text{Cap} \frac{T_{ZF} - T_{ZI}}{\Delta t} = \sum_{j=1}^{N} h_{c,j} A_j (T_{s,j} - T_z) + \dot{Q}_v + \dot{Q}_{infl} + 0.3 \, \dot{Q}_{spepl} + \dot{Q}_{int} + \dot{Q}_z \tag{Eq 5.7.3.26}$$

In order to arrange the above expression in the form of (Eq 5.7.3.1) while maintaining the time independence of Zij, it is necessary to make two simplifying assumptions. First of all, the zone temperature variation is considered to be linear over each simulation timestep. Secondly, the ventilation and infiltration energy gains are evaluated using the last estimate of the zone temperature. With these assumptions, (Eq 5.7.3.26) can be rearranged such that

$$Z_{N+1,j} = h_{c,j} A_j \tag{Eq 5.7.3.27}$$

$$\overset{\Sigma\Sigma}{Z}_{N+1,N+1} = \sum_{j=1}^{N} h_{c,j} A_j - \frac{2 \, \text{Cap}}{\Delta t} \tag{Eq 5.7.3.28}$$

$$X_{N+1} = -\dot{Q}_z - \dot{Q}_v - \dot{Q}_{infl} - 0.3 \, \dot{Q}_{spepl} - \dot{Q}_{int} - \frac{2 \, \text{Cap}}{\Delta t} T_{ZI} \tag{Eq 5.7.3.29}$$

The ventilation and infiltration gains are expressed as

$$\dot{Q}_v = \dot{m}_v C_{pa} (T_v - T_z) \tag{Eq 5.7.3.30}$$

$$\dot{Q}_{infl} = \dot{m}_{infl} C_{pa} (T_a - T_z) \tag{Eq 5.7.3.31}$$

The ventilation flow is an Input, while the infiltration rate is determined to be

$$\dot{m}_{infl} = \rho_a V_a (K_1 + K_2 |T_a - T_z| + K_3 W) \tag{Eq 5.7.3.32}$$

K_1, K_2, and K_3 are empirical constants. Typical values for different construction qualities from the ASHRAE Handbook of Fundamentals are given in Table 5.7.3.1 (SI units).

Table 5.6.3–1: Coefficients for Multiple Linear Regression Infiltration, Eq. 5.7.3.32

Construction	K_1	K_2	K_3	Description
Tight	0.10	0.011	0.034	New building where special precautions have been taken to prevent infiltration.
Medium	0.10	0.017	0.049	Building constructed using conventional construction procedures.
Loose	0.10	0.023	0.07	Evidence of poor construction on older buildings where joints have separated.

The energy convected from people in the space is assumed to be 30% of the total sensible gain from people. The additional 70% is in the form of radiation to the interior surfaces. The number of people in the zone at any time is specified as an Input. Both the sensible and latent gain from people depends upon the level of activity. Table 5.7.3.2 gives the possible activity levels that may be specified. This table was taken from Chapter 26 of the 1981 ASHRAE Handbook of Fundamentals.

Table 5.6.3–2: Rates of Heat Gain from Occupants of Conditioned Spaces[a]

No	Degree of Activity	Typical Application	Total heat adjusted[b]		Sensible Heat		Latent Heat	
			W	BTU/h	W	BTU/h	W	BTU/h
1	Seated at rest	Theatre, movie	100	350	60	210	40	140
2	Seated, very light writing	Office, hotels, apts.	120	420	65	230	55	190
3	Seated, eating	Restaurant[c]	170	580[c]	75	255	95	325
4	Seated, light work, typing	Offices, hotels, apts.	150	510	75	255	75	255
5	Standing, light work or walking slowly	Retail store, bank	185	640	90	315	95	325
6	Light bench work	Factory	230	780	100	345	130	435
7	Walking, 1.3m/s (3mph) light machine work	Factory	305	1040	100	345	205	695
8	Bowling[d]	Bowling alley	280	960	100	345	180	615
9	Moderate dancing	Dance hall	375	1280	120	405	255	875
10	Heavy work, heavy machine work, lifting	Factory	470	1600	165	565	300	1035
11	Heavy work, athletics	Gymnasium	525	1800	185	635	340	1165

a   Tabulated values are based on 25.5°C (78°F) room dry-bulb temperature. For 26.6°C (80°F) room dry bulb, the total heat remains the same, but the sensible heat value should be decreased by approximately 8% and the latent heat values increased accordingly.

b   Adjusted total heat gain is based on normal percentage of men, women and children for the application listed, with the postulate that the gain from an adult femail is 85% of that for an adult male, and that the gain from a child is 75% of that for an adult male.

c   Adjusted total heat value for eating in a restaurant includes 17.6W (60 BTU/h) for food per individual (8.8W (30BTU/h) sensible and 8.8W (30BTU/h) latent).

d   For bouling figure one person per alley actually bowling and all others as sitting 117W (400BTU/h) or standing and walking slowly 231W (790 BTU/h).

All values rounded to nearest 5W or to nearest 10 BTU/h.

(Eq 5.7.3.27) to (Eq 5.7.3.29) apply for a floating room temperature. This is characteristic of temperature level control or when the room temperature is in the comfort zone (no load) in energy rate control. If, however, the zone temperature would be above the maximum or below the minimum limits imposed by the user, then the zone temperature is set equal to the limit and the following expressions are used.

$$Z_{N+1,j} = 0 \qquad\qquad\qquad\text{(Eq 5.7.3.34)}$$

$$Z_{N+1,N+1} = 1 \qquad\qquad\qquad\text{(Eq 5.7.3.35)}$$

$$X_{N+1} = T_Z \qquad\qquad\qquad\text{(Eq 5.7.3.36)}$$

The sensible energy required to maintain the set temperature (i.e. the load) in mode 1 is

$$\dot{Q}_{sens} = \dot{Q}_Z + \dot{Q}_V + \dot{Q}_{int} + 0.3\ \dot{Q}_{spepl} + \dot{Q}_{inf}$$

$$+ \sum_{j=1}^{N} h_{c,j}\ A_j\ (T_{s,j} - T_z) - \frac{Cap\ (T_{ZF} - T_{ZI})}{\Delta t} \qquad\qquad\text{(Eq 5.7.3.37)}$$

As described above, ventilation, infiltration and thermal energy gains through windows are calculated using the most recent estimate of the zone temperature. If the zone temperature is changing rapidly and these energy quantities represent a significant portion of the energy gain to the space, this may not be adequate. As a result, the TYPE 19 uses an internal iteration if the energy balance on the zone does not close to within 2%.

LATENT LOADS

A moisture balance on the room air at any instant yields the following differential equation.

$$\rho_a V_a \frac{d\omega_z}{dt} = \dot{m}_{infl}\ (\omega_a - \omega_z) + \dot{m}_V\ (\omega_V - \omega_z) + \dot{\omega}_I \qquad\qquad\text{(Eq 5.7.3.38)}$$

(Eq 5.7.3.38) is solved each simulation timestep for the zone humidity ratio. In temperature level control, the ventilation flowstream or moisture generation should include moisture addition or removal due to heating or cooling equipment. For this case, the latent load should be calculated external to the TYPE 19, possibly with a TYPE 32 cooling coil. In energy rate control, the latent load is the energy required to maintain the zone humidity ratio within the humidity comfort zone (i.e. between ω_{min} and ω_{max}). If the zone humidity ratio would fall outside the limits imposed by the user, then the zone humidity ratio is set equal to the limit and the latent load is calculated as:

$$\dot{Q}_{lat} = \Delta h_{vap} \left[\dot{m}_{infl}\ (\omega_a - \omega_z) + \dot{m}_V\ (\omega_V - \omega_z) + \dot{\omega}_I \right] \qquad\qquad\text{(Eq 5.7.3.39)}$$

Otherwise the latent load is zero. Note that V_a (zone parameter number 3) may be artificially increased to account for the moisture capacitance of furnishings, etc. This will not affect any other calculation.

5.6.3.3   TRNSYS Component Configuration

In order to describe a zone, it is necessary to specify characteristics of the internal space, external weather conditions, walls, windows, and doors. To facilitate this description, the parameters and inputs for this component are organized in separate lists according to type. In terms of the component description, the parameters and inputs may appear as single lists following single parameter and input cards or may be presented as separate lists, each with an individual parameter and input cards.

The first lists of parameters and inputs for the TYPE 19 pertain to the internal space and external conditions. These lists must appear first in the component description. For each surface in the zone, another set of parameters and inputs is necessary. There are five possibilities for surface types. They include transfer function representations for exterior walls, interior partitions, and walls separating zones at different temperatures. Coefficients for the standard walls, partitions, ceilings, or floors taken from the ASHRAE Handbook of Fundamentals (1) are in the file ASHRAE.COF (accessed through logical unit 8) and listed at the end of the component description. The user may choose from these lists or may provide the coefficients generated by the stand-alone program PREP (see %TRNSYS16%\Documentation\Type19Supplement.pdf) for other constructions. A wall may also be modeled using a separate TRNSYS component with conduction through this wall provided as an input to the zone. The fifth type of surface available is a window. The user must specify the properties of the window, along with specifics concerning the illumination of the interior surfaces due to beam radiation passing through the window. A door or any other wall that has negligible thermal capacitance can be considered by specifying a transfer function wall with one b and c coefficient and no d coefficients. In this case, both bo and co should be set equal to the U value of the door or wall.

The last parameters that must be supplied define the geometry of the zone for radiation exchange calculations. There are three principal geometry modes. In the first mode, the program calculates view factors for a parallelpiped (box) geometry. There is a set of parameters that describe the size of the room and relative locations of wall surfaces. For each window or door, an additional set of parameters is necessary to describe its location on a wall. Figure 5.6.3–1 shows the dimensions and definitions of the zone geometry that are using in specifying the Type19 parameters. In the second geometry mode, the user specifies the number of entries required. A third geometry mode is 0. In this case, the program uses area ratios to determine view factors. Although this is not a correct procedure, it may be adequate when the inside surfaces are close in temperature and infrared energy exchange is not significant. When the geometry mode is specified as 0, no additional geometry parameters are required.

There are 10 standard outputs of the TYPE 19. Up to 10 additional surface dependent quantities may be specified as outputs using optional parameters that follow the geometry description. The first parameter specifies the number of additional outputs that are desired. For each output, two parameters are then required. The first one specifies the type of output desired as chosen (by number) from Table 5.6.3–2. The second parameter in this group of two is the surface number for which this quantity is desired. The additional outputs begin at the eleventh output and may range to the twentieth.
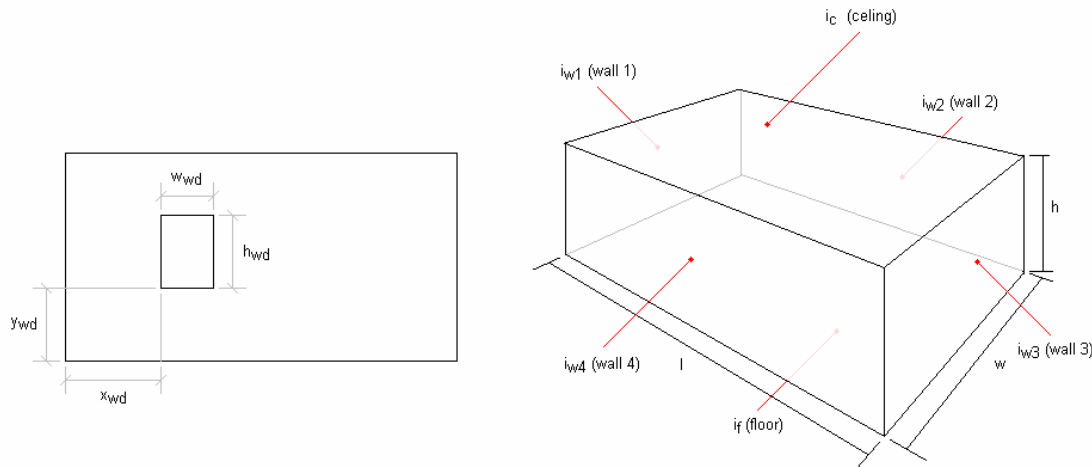
Figure 5.6.3–1: Roof Geometry and Ceiling Cross Section

Table 5.6.3–3:Additional Output Options for Surface i

Output Number	Output Name	Output Description
1	Ts,i	Temperature at inside surface [C]
2	Teq,i	Equivalent inside room temperature for surface i [C]
3	Si	Absorbed radiative gains from solar, lights, and people for surface i [kJ/m2.hr]
4	Qc,i	Energy convected to room from surface i [kJ/hr]
5	Qr,i	Radiative gains to surface i due to infrared exchange [kJ/hr]

5.6.3.4 References

1. ASHRAE, Handbook of Fundamentals, (2001).

2. Madsen, J.M. "Modeling Heat Transfer in Rooms Using Transfere Function Methods," M.S. Thesis, University of Wisconsin – Madison (1982).

3. McAdams, W.H., Heat Transmission, 3rd edition, McGraw-Hill, New York, (1954).

4. Beckman, W.A., "The Solution of Heat Transfer Problems on a Digital Computer," Solar Energy, 13, 3, (1971).

5.6.4 Type 34: Overhang and Wingwall Shading

Buildings directly heated by solar radiation often include a shading device to shield receiver surfaces from direct radiation in summer months. This component computes the solar radiation on a vertical receiver shaded by an overhang and/or wingwall. The geometry of a shaded receiver is shown in Figure 5.7.4.1.

5.6.4.1 Nomenclature

A	-	receiver area
A_i	-	receiver area irradiated by direct beam
A_s	-	receiver area shaded from direct beam
e_b	-	wingwall extension past the bottom of the receiver
e_l	-	overhang extension past the left edge of the receiver
e_r	-	overhang extension past the right edge of the receiver
e_t	-	wingwall extension past the top of the receiver
f_i	-	fraction of the receiver area irradiated by direct beam
F_{A-G}	-	receiver radiation view factor of the ground
F_{A-O}	-	receiver radiation view factor of the overhang
F_{A-S}	-	receiver radiation view factor of the sky
F_{A-Wl}	-	receiver radiation view factor of the left wingwall
F_{A-Wr}	-	receiver radiation view factor of the right wingwall
g	-	gap between the edge of the receiver and the base of the overhang or wingwall
h	-	receiver height
I	-	horizontal total solar radiation
I_{bT}	-	beam component of solar radiation incident on the receiver surface
I_d	-	diffuse component of solar radiation incident on a horizontal surface
$(I_T)_S$	-	average solar radiation incident on a shaded receiver
	-	overhang or wingwall projection from receiver surface
w	-	receiver width
γ_s	-	solar azimuth angle
θ_Z	-	solar zenith angle
γ	-	receiver azimuth angle
ρ_{gnd}	-	ground reflectance
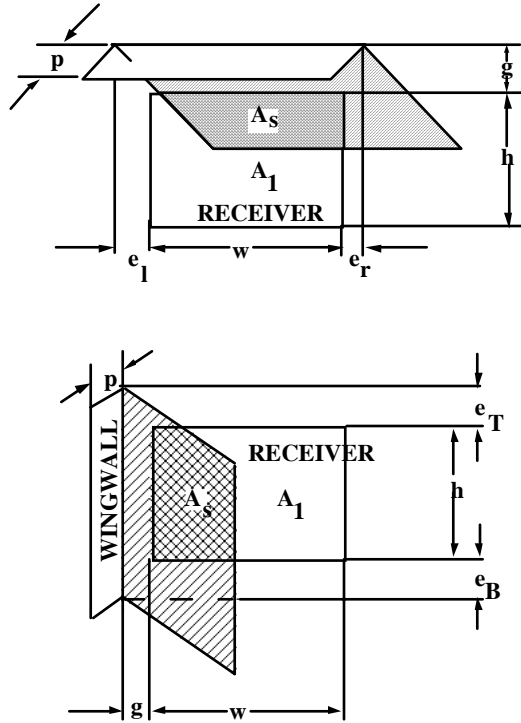
Figure 5.6.4–1: Shading Geometry

5.6.4.2 Mathematical Description

Solar radiation incident on a shaded receiver consists of beam, diffuse and ground reflected components. (Solar radiation reflected from the overhang or wingwalls onto the receiver is not considered in this model.)

$$(I_T)_S \quad = \quad I_{bT}f_i + \quad I_{dT}F_{A\text{-}S} + \quad I_d\,\rho_{gnd}\,F_{A\text{-}G} \qquad\qquad \text{(Eq 5.7.4.1)}$$

(TOTAL)   (BEAM)   (DIFFUSE)   (REFLECTED)

The fraction of the receiver area irradiated by direct beam, f_i, is a function of shading geometry and the position of the sun relative to the receiver. The irradiated fraction is given by

$$f_i = \frac{A_i}{A} \qquad\qquad \text{(Eq 5.7.4.2)}$$

An ASHRAE algorithm (1) that determines Ai is used in TYPE 34 to compute fi.

Sky and ground radiation view factors are calculated assuming diffuse and reflected radiation to be isotropic. For unshaded vertical surfaces, the receiver radiation view factors of the sky and ground are both equal to one half. These view factors are reduced when wingwalls or an overhang are present. The view factor between the receiver and the wingwall, $F_{A\text{-}W}$ is computed by integrating the differential receiver area radiation view factor of the wingwall over the receiver area. Figure5.7.4.2 describes the receiver-wingwall radiation geometry.
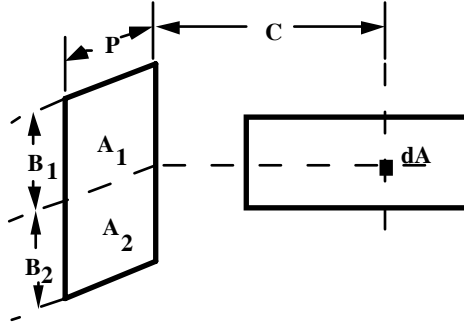
Figure 5.6.4–2: Radiation Geometry

The receiver radiation view factor of the wingwall is given by

$$F_{A-W} = \int_A F_{dA-A_1} dA + \int_A F_{dA-A_2} dA$$

(Eq 5.7.4.3)

where F_{dA-A_1} and F_{dA-A_2} are given by Siegel and Howell (2) as

$$F_{dA-Ai} = \frac{1}{2\pi} \left[\tan^{-1}\left(\frac{B_i}{C}\right) - \left[\frac{\frac{C}{B_i}}{\sqrt{\left(\frac{P}{B_i}\right)^2 + \left(\frac{C}{B_i}\right)^2}} \right] \tan^{-1}\left[\frac{1}{\sqrt{\left(\frac{P}{B_i}\right)^2 + \left(\frac{C}{B_i}\right)^2}} \right] \right]$$

(i = 1, 2)

(Eq 5.7.4.4)

The receiver radiation view factor of the overhang is computed in a similar manner. The total sky and ground view factors F_{A-S} and F_{A-G} are given by:

$$F_{A-S} = \frac{1}{2} - F_{A-O} - \int_A F_{dA-A_1} dA - \int_A F_{dA-A_1} dA$$

(Eq 5.7.4.5)

           left wingwall   right wingwall

$$F_{A-G} = \frac{1}{2} - \int_A F_{dA-A_2} dA - \int_A F_{dA-A_2} dA$$

(Eq 5.7.4.6)

      left wingwall   right wingwall

Type 34 uses numerical integration to compute the receiver radiation view factors once during a simulation.

5.6.4.3 References

1. Sun, Tseng-Yao, 'SHADOW 1', Procedure for Determining Heating and Cooling   Loads for Computerizing Energy Calculations, ASHRAE Task Group on Energy Requirements, 1975, pp. 48-56.

2. Siegel, R. and Howell, J., Thermal Radiation Heat Transfer, McGraw-Hill, 1972, p. 784.

5.6.5 Type 35: Window with Variable Insulation

This component models the window transmittance of solar radiation and the thermal energy transfer across the window. The total heat transfer coefficient of the window is an Input, allowing changes of the coefficient due to insulating curtains on the window.

5.6.5.1 Nomenclature

A	-	Window area
I_T	-	Total solar radiation incident on window
I_{bT}	-	Beam solar radiation incident on window
I_{dT}	-	Diffuse and ground reflected solar radiation incident on window
KL	-	Product of the thickness and extinction coefficient of one glazing
N_g	-	Number of glazings
$\dot{Q}_s$	-	Rate of solar energy gain through window
$\dot{Q}_t$	-	Rate of thermal energy transfer across window
$\dot{Q}_n$	-	Net rate of energy transfer across window
T	-	Environment air temperature
T_R	-	Room temperature
U	-	Heat transfer coefficient across window
η_R	-	Refractive index of one glazing
θ	-	Angle of incidence of beam radiation
τ	-	Average transmittance of total incident solar radiation
τ_b	-	Transmittance of incident beam radiation
τ_{60}	-	Transmittance of incident diffuse and ground reflected radiation
ρ_d	-	Window reflectance of diffuse and ground reflected radiation

5.6.5.2   *Mathematical Description*

There are two modes of operation of TYPE 35. In Mode 1, the total incident solar radiation and average transmittance are set as Inputs. In Mode 2, transmittance of beam and diffuse radiation are considered separately; τ_b and $\tau_6{}^{o*}$ are determined using function subroutine TALF, described in Chapter 3. This component does not consider reflection of solar radiation from the room back through the window. The energy rates across the window are calculated for each mode as follows.

MODE 1: $$\dot{Q}_s = \tau A I_T$$

$$\dot{Q}_t = UA(T_a - T_R)$$

$$\dot{Q}_n = \dot{Q}_s + \dot{Q}_t$$

MODE 2: $$\dot{Q}_s = A \tau_b I_{bT}$$

$$\dot{Q}_t = UA(T_a - T_R)$$

$$\dot{Q}_n = \dot{Q}_s + \dot{Q}_t$$

Values of U for various types of windows are listed in the <u>ASHRAE Handbook of Fundamentals</u>.

---

* The transmittance of diffuse and ground reflected radiation is computed as the transmittance of beam radiation incident at an angle of 60°

5.6.6 Type 36: Thermal Storage Wall

A thermal storage wall is essentially a high capacitance solar collector directly coupled to the room. Absorbed solar radiation reaches the room by either of two paths. One path is conduction through the wall. From the inside wall surface, the energy is convected and radiated into the room. The second path is convection from the hot outer wall surface to air in the gap. Room air flowing through the gap is heated, carrying energy into the room. The wall also loses energy by conduction, convection and radiation to the environment through the glazing covers.

This component offers four modes of operation. In Mode 1, the total solar radiation and glazing transmittance are Inputs as is the mass flow rate of air in the gap. Mode 2 is the same as Mode 1 except that the mass flow rate is driven by air temperature differences and is computed internally. In Mode 3, the mass flow rate of air is Input and the transmittance of beam and diffuse radiation are considered separately. The transmittance-absorptance product is determined in function subroutine TALF, described in Chapter 3. Mode 4 is the same as Mode 3 except that the mass flow rate of air in the gap is driven by temperature differences and computed internally. Only one TYPE 36 is allowed per TRNSYS simulation.

5.6.6.1 Nomenclature

A	-	Wall collector area
A_g	-	Total cross sectional area of the gap
A_v	-	Total outlet area of the vent
C_{pa}	-	Specific heat of air
C_p	-	Specific heat of wall
C_1	-	Vent pressure loss coefficient
C_2	-	Gap pressure loss coefficient
$\dfrac{dU}{dt}$	-	Rate of change of wall internal energy
g	-	Acceleration of gravity
G_r	-	Grashof number
h	-	Wall height
h_v	-	Height between inlet and outlet vents
h_c	-	Gap air heat transfer coefficient
h_r	-	Radiation heat transfer coefficient between wall and glazing
I_{bT}	-	Incident beam radiation
I_{dT}	-	Incident diffuse and reflected radiation
I_T	-	incident total radiation
k	-	Air thermal conductivity
k_w	-	Wall thermal conductivity
KL	-	Product of glazing thickness and extinction coefficient
L	-	Gap between wall and first glazing
$\dot{m}$	-	Mass flow rate of air in the gap
N_g	-	Number of covers
N	-	Number of wall nodes ($3 \leq N \leq 10$)
Pr	-	Prandtl number
$\dot{Q}_{amb}$	-	Rate of energy flow from the wall to the environment
$\dot{Q}_b$	-	Rate of energy flow from inside wall surface to the room
$\dot{Q}_R$	-	Rate of energy flow from the wall to the room

$\dot{Q}_s$ -   Rate of absorption of solar radiation

$\dot{Q}_t$ -   Rate of energy flow through the glazings to the environment

$\dot{Q}_v$ -   Rate of energy flow by ventilation of gap air

R	-	Thermal resistance of air flow to energy transfer
Re	-	Reynold's number
T_a	-	Ambient air temperature
T_g	-	First glazing temperature
T_m	-	Mean air temperature in the gap
T_R	-	Room air temperature
U_b	-	Heat transmission coefficient between wall and room
U_t	-	Heat transmission coefficient between glazing and environment
$\overline{v}$	-	Average air velocity in gap
w	-	Wall width
W	-	Wind velocity
X	-	Wall thickness
α	-	Solar absorptance of wall
γ	-	Control function
ε_g	-	Thermal emittance of glazing
ε_w	-	Thermal emittance of wall
η_R	-	Glazing refractive index
θ	-	Angle of incidence of beam radiation
$\overline{\rho}$	-	Average air density in gap
ρ_w	-	Density of wall
τ	-	Transmittance of glass

5.6.6.2 *Mathematical Description*

The thermal circuit used to model the performance of the thermal storage wall is shown in Figure 5.7.6.1. Depending on the control strategy used, air in the gap can be exchanged with either the room air or the environment, or the flow of air through the gap may be stopped. The flow of air may be driven by a fan or by thermosiphoning. Thermosiphoning is the result of higher air temperatures in the gap than in the room. This method of moving air is not easily quantified, and the resulting model incorporates several assumptions as described below. Analytical studies of the thermosiphoning air have been confined to the case of laminar flow and have neglected pressure losses in the inlet and outlet vents. The only published measurements of thermosiphon mass flow rates are those of Trombe et. al. (1). These measurements indicate that most of the pressure losses are due to expansion, contraction and change of direction of flow, all associated with the inlet and outlet vents.

The thermosiphon mass flow of air in this model has been determined by applying Bernoulli's equation to the entire air flow system. For simplicity, it is assumed that the density and temperature of the air in the gap varies linearly with height. Solution of Bernoulli's equation for the mean air velocity in the gap yields

$$\overline{v} = \sqrt{\frac{2gh}{\left(C_1\left(\frac{A_g}{A_v}\right)^2 + C_2\right)} \cdot \frac{(T_m - T_s)}{|T_m|}}$$

(Eq 5.7.6.1)

where T_s is either T_a or T_R, depending on whether air is exchanged with the environment or the room. The term $(C1(A_g/A_v)^2 + C_2)$ represents the pressure losses of the system. The ratio $(A_g/A_v)^2$ accounts for the difference between the air velocity in the vents and the air velocity in the gap.
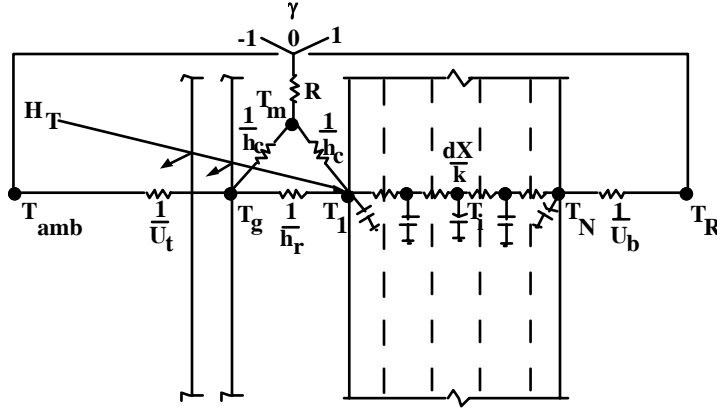
Figure 5.6.6–1: TYPE 36 Thermal Circuit Diagram

The thermal resistance to energy flow between the gap and the room when $\dot{m}$ is finite is given by

$$R = \frac{A\left[\left(-\frac{\dot{m}C_{pa}}{2h_cA}\right)\left(\exp\left(-\frac{2h_cA}{\dot{m}C_{pa}}\right) - 1\right) - 1\right]}{\dot{m}C_{pa}\left(\exp\left(-\frac{2h_cA}{\dot{m}C_{pa}}\right) - 1\right)}$$

(Eq 5.7.6.2)

If gap air is exchanged with the environment, T_a replaces T_R.

The control function, γ determines whether mass flow of air is allowed and to what sink the air is exchanged.

MODE 1 AND 3:

If $\gamma = 1$ $\dot{m} = $ Input

$$\dot{Q}_v = 2\dot{m}C_{pa} (T_m - T_R)$$

(Eq 5.7.6.3)

$$\dot{Q}_R = \dot{Q}_v + \dot{Q}_b$$

(Eq 5.7.6.4)

$$\dot{Q} = \dot{Q}_t$$

(Eq 5.7.6.5)

If $\gamma = -1$ $\dot{m} = $ Input

$$\dot{Q}_v = 2\dot{m}C_{pa} (T_m - T_a)$$

(Eq 5.7.6.6)

$$\dot{Q} = \dot{Q}_v + \dot{Q}_t$$

(Eq 5.7.6.7)

$$\dot{Q}_R = \dot{Q}_b \tag{Eq 5.7.6.8}$$

otherwise $\dot{Q}_v = 0$

$$\dot{m} = 0$$

$$\dot{Q} = \dot{Q}_t$$

$$\dot{Q}_R = \dot{Q}_b$$

MODE 2 AND 4:

If $\gamma = 1$ and $T_m > T_R$ $\dot{m} = \overline{v}\rho A_g$ \hfill (Eq 5.7.6.9)

$$\dot{Q}_v = 2\dot{m}C_{pa}(T_m - T_R) \tag{Eq 5.7.6.10}$$

$$\dot{Q}_{amb} = \dot{Q}_t \tag{Eq 5.7.6.11}$$

$$\dot{Q}_R = \dot{Q}_v + \dot{Q}_b$$

If $\gamma = -1$ and $T_m > T_a$ $\dot{m} = \overline{v}\rho A_g$

$$\dot{Q}_v = 2\dot{m}C_{pa}(T_m - T_a)$$

$$\dot{Q}_{amb} = \dot{Q}_v + \dot{Q}_t \tag{Eq 5.7.6.12}$$

$$\dot{Q}_R = \dot{Q}_b$$

otherwise $\dot{Q}_v = 0$

$$\dot{m} = 0$$

$$\dot{Q}_{amb} = \dot{Q}_t$$

$$\dot{Q}_R = \dot{Q}_b$$

The value of h_c, the heat transfer coefficient between the gap air and the wall and glazing, depends on whether or not there is air flow through the gap.

If $\dot{m} = 0$

$$h_c = \frac{k_a}{L}\left(0.01711\left(Gr \cdot Pr\right)^{0.29}\right) \qquad \text{Reference 2} \tag{Eq 5.7.6.13}$$

If $\dot{m} \neq 0$ and Re > 2000

$$h_c = \frac{k_a}{L}\left(0.0158 \; Re^{0.8}\right) \qquad \text{Reference 3} \qquad \text{(Eq 5.7.6.14)}$$

If $\dot{m} \neq 0$ and Re $\leq$ 2000

$$h_c = \frac{k_a}{L}\left[4.9 + \frac{0.0606(x^*)^{-1.2}}{1 + 0.0856(x^*)^{-0.7}}\right] \; \text{Reference 5} \qquad \text{(Eq 5.7.6.15)}$$

where

$$x^* = \frac{h}{Re \; Pr \; D_h} \qquad \text{(Eq 5.7.6.16)}$$

$$D_h = \frac{2 \; Ag}{1 + w} \qquad \text{(Eq 5.7.6.17)}$$

The heat transfer coefficient between the first glazing and the environment, U_t, can be set as in Input or can be determined from a correlation developed by Klein (4) and described in Section 5.10.5, page 5–357. If the Klein top loss correlation is to be used, the Input value of U_t must be negative. If U_t is zero or positive, the correlation is bypassed. This allows a user to simulate the application of a night insulating cover and use the loss correlation during the day.

5.6.6.3   References

1. Trombe, F., Robert, J.F., Cabanot, M., and Sesolis, B., "Concrete Walls to Collect   and Hold Heat", Solar Age, Vol. 2, No. 8, Aug. 1977, pp. 13-19.

2. Randall, K.R., Mitchell, J.W., and El-Wakil, M.M. "Natural Convection Heat   Transfer Characteristics of Flat-Plate Enclosures," Journal of Heat Transfer, vol. 101, Feb. 1979, pp. 120-125.

3. Kays, W.M., Convective Heat and Mass Transfer, McGraw-Hill Book Co. 1966, p. 180. (Curve fit of Kays' data by Duffie and Beckman).

4. Klein, S.A., "Calculation of Collector Loss Coefficients," Solar Energy Journal, Vol. 17, 1975,   pp. 79-80.

5. Mercer, W.E., Pearce, W.M., Hitchcock, J.E., "Laminar Forced Convection in the Entrance   Region Between Parallel Flat Plates." J. Heat Transfer 89, 251-257 (1967).

5.6.7　Type 37: Attached Sunspace

An attached sunspace can be thought of as a large solar collector where the space between the glazing and absorbing surface is large enough to be used as additional living space. After passing through the glazing(s), solar radiation is absorbed by the sunspace wall and floor. Absorbed solar radiation reaches the attached building by conduction through the common wall. In addition, optional wall vents allow convection of heated sunspace air into the building. The sunspace loses energy to the ground by conduction through the floor and to ambient by conduction, convection, radiation, and infiltration through the glazed surfaces.

The losses through the glazings may be reduced by using moveable insulation. A user supplied control function governs the use of the insulation. When glazing insulation is in use, no solar radiation is allowed to enter the sunspace. Venting of the sunspace air is also controlled by user supplied Inputs. A control function determines the venting air sink: ambient or building conditions, and another Input controls the venting air mass flow rate. Additional thermal mass storage devices may be included in the sunspace.

The geometry of the sunspace considered by this component is shown in Figure 5.6.7–1. The sunspace is assumed to face due south. The end walls may be glazed or reflective. Only one TYPE 37 is allowed per TRNSYS simulation.

5.6.7.1　Nomenclature

$\dot{m}_v$ - ventilation mass flow rate

$\dot{Q}_{amb}$ - rate of heat loss to ambient

$\dot{Q}_c$ - rate of heat transfer to adjoining room by conduction through wall

$\dot{Q}_{inf}$ - rate of heat loss to ambient due to infiltration

$\dot{Q}_{L,g}$ - rate of heat loss by conduction through glazings

$\dot{Q}_R$ - total rate of heat gain to adjoining room

$\dot{Q}_v$ - rate of heat gain to adjoining room due to ventilation flow stream

T_a - ambient temperature

T_{GL} - temperature of glazing

T_{GR} - temperature of ground

T_R - temperature of adjoining room air

T_{SS} - sunspace air temperature

γ_v - control function for ventilation fan
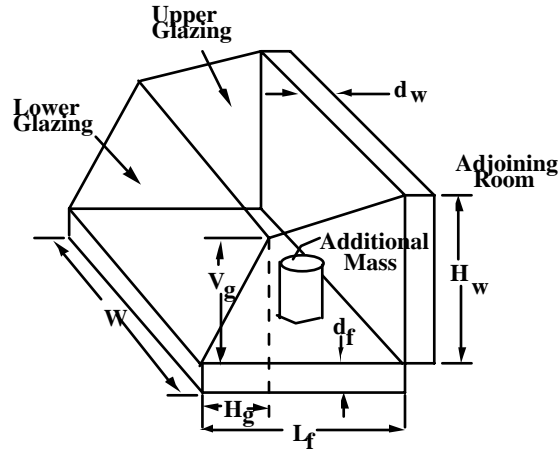
Figure 5.6.7–1: Sunspace Geometry

5.6.7.2   *Mathematical Description*

Figure 5.6.7–2 is the conductance network used to model the sunspace energy flows. Thermal conductances are calculated from user supplied geometry, thermal properties and heat transfer coefficients.

The calculations of the sunspace interior infrared conductance uses net exchange factors (1). This involves using the view factors between the various nodes. The routine calculates view factors using Hottel's crossed string method (2). These calculations assume infinitely long surfaces.

The sink temperature for infrared radiation from the glazing outside surface is assumed to be equal to ambient temperature and the surroundings are assumed to be black.

Input 1 is the control function for sunspace venting. The following equations describe the heat fluxes.

If $\gamma_V = 1$

$\dot{m}_V = \text{Input}$

$$\dot{Q}_R = \dot{Q}_c + \dot{Q}_v \qquad\qquad\qquad \text{(Eq 5.7.7.1)}$$

$$\dot{Q}_v = m_V C_p (T_{SS} - T_R) \qquad\qquad\qquad \text{(Eq 5.7.7.2)}$$

$$\dot{Q}_{amb} = \dot{Q}_{L,g} + \dot{Q}_{inf} \qquad\qquad\qquad \text{(Eq 5.7.7.3)}$$

If $\gamma_V = 0$

$\dot{m}_V = 0$

$$\dot{Q}_R = \dot{Q}_c \qquad\qquad\qquad \text{(Eq 5.7.7.4)}$$

$$\dot{Q}_V = 0$$

$$\dot{Q}_{amb} = \dot{Q}_{L,g} + \dot{Q}_{inf}$$

If $\gamma_V = -1$

$$\dot{m}_V = \text{Input}$$

$$\dot{Q}_R = \dot{Q}_c$$

$$\dot{Q}_V = \dot{m}_V C_p (T_R - T_a) \qquad\qquad\qquad \text{(Eq 5.7.7.5)}$$

$$\dot{Q}_{amb} = \dot{Q}_{L,g} + \dot{Q}_{inf} + \dot{Q}_V \qquad\qquad\qquad \text{(Eq 5.7.7.6)}$$
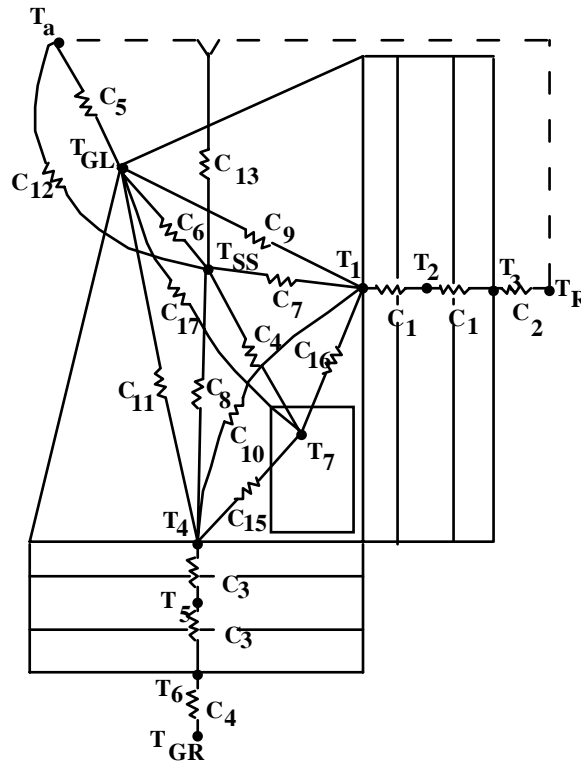
Figure 5.6.7–2: Sunspace Conductance Network

The solar radiation treatment is different for beam and diffuse radiation. The beam transmitted fraction for each glazing sheet is calculated using the function TALF (see Chapter 3) and Input incidence angles. For diffuse radiation, the angle of incidence is assumed to be 60°. Diffuse radiation is distributed to the sunspace surfaces using Hottel's crossed string view factors. Beam radiation is distributed by projecting solar geometry onto a vertical north-south plane. Vertical and horizontal projections of the beam radiation from each south facing glazings are compared to the sunspace geometry to determine the incident beam fractions on each surface.

Absorbed solar radiation is computed from incident radiation and net exchange factors similar to that used for infrared conductances.

Sunspace heat flows and temperatures are computed from node energy balances. The floor, wall, and extra mass nodes have the ability to store energy as sensible heat and the glazing and air nodes are assumed to have negligible thermal capacity.

The sunspace component utilizes an internal integration routine to allow simulation timesteps greater than the critical sunspace timestep.

A detailed description of this model is given in reference 3.

5.6.7.3   References

1.   Beckman, W.A., "The Solution of Heat Transfer Problems on a Digital Computer", Solar Energy, 13, 3 (1971).

2.   Siegel, R. and Howell, J.R., Thermal Radiation Heat Transfer, McGraw-Hill, New York, 1981.

3.   Parsons, B.K., "The Simulation and Design of Building Attached Sunspaces", University of Wisconsin-Madison, M.S. Thesis (1983).

5.6.8 *Type 56: Multi-Zone Building and TRNBuild*

Please refer to Volume 06,

Multizone Building (Type 56 – TRNBuild)

5.6.9 Type 88: Lumped Capacitance BuildingType

This component models a simple lumped capacitance single zone structure subject to internal gains. It differs from the Type12 simple building model in that it makes no assumption about the control scheme. Furthermore, it neglects solar gains and assumes an overall U value for the entire structure. Its usefulness comes from the speed with which a building heating and/or cooling load can be added to a system simulation.

5.6.9.1 Nomenclature

U	building loss coefficient (kJ/hr-m^2-C)
Cap	building capacitance (kJ/C)
Cp_{air}	specific heat of building air (kJ/kg-C)
ρ_{air}	density of building air (kg/m^3)
Area	building surface area (m^2)
Vol	building volume (m^3)
ω_{mult}	humidity ratio multiplier (-)
$T_{initial}$	initial temperature (C)
$\omega_{initial}$	initial humidity ratio (-)
h_{fg}	latent heat of vaporization (kJ/kg)
Tvent	temperature of ventilation air (C)
ωvent	humidity ratio of ventilation air (-)
mvent	ventilation air mass flow rate (kg/hr)
Tamb	ambient temperature (C)
ωamb	ambient humidity ratio (-)
minf	mass flow rate of infiltration air (kg/hr)
Qlights	rate of energy gain from lights (kJ/hr)
Qequip	rate of energy gain from equipment (kJ/hr)
Qpeop	rate of sensible energy gain from people (kJ/hr)
ωgain	rate of humidity gain (kg/hr)
Tzone	zone temperature (C)
ωzone	zone humidity ratio (-)
mvent	mass flow rate of ventilation air (kg/hr)
minfil	mass flow rate of infiltration air (kg/hr)
Qinfls	sensible energy gain from infiltration (kJ/hr)
Qinfll	latent energy gain from infiltration (kJ/hr)
Qvents	sensible energy gain from ventilation (kJ/hr)
Qventl	latent energy gain from ventilation (kJ/hr)

5.6.9.2 Mathematical Description

The component is governed by two balance equations. An energy balance that predicts the zone temperature and a moisture balance that predicts the humidity content of the zone.

The energy balance for the zone is:

$$\frac{dT}{dt} = \frac{UA}{cap}\left(T_{amb} - T\right) + \frac{\dot{m}_{vent}Cp_{air}}{cap}\left(T_{vent} - T\right) + \frac{\dot{m}_{inf}Cp_{air}}{cap}\left(T_{inf} - T\right) + \sum Q_{gains}$$

Eq 5.6.9-1

with internal sensible gains coming from people, equipment and lights.

The moisture balance equation is similar in form to the energy balance:

$$\frac{d\omega}{dt} = \frac{\dot{m}_{inf}}{\rho V}\left(\omega_{inf} - \omega\right) + \frac{\dot{m}_{vent}}{\rho V}\left(\omega_{vent} - \omega\right) + \frac{\sum \omega_{gains}}{\rho V}$$

Eq 5.6.9-2

with internal moisture gains coming from people and equipment.

5.7 Obsolete

This section in the TRNSYS Studio proformas includes components or component modes that have been deemed obsolete:

Type 7 The old Absorption Air Conditioner has been replaced with Type 108, which is much more flexible

Type 61 This Type was used to Call External DLL's. This is not necessary anymore since any component can be programmed in any language and compiled into an external DLL

Type 44 Convergence Promoter. The same features can be performed by an ACCELERATE statement if required. Furthermore, numerical relaxation in Solver 0 can help solving convergence problems

Type 9 The special configuration reading French Weather Data provided by CSTB has been replacd with Type 109 (CSTB now provides TMY2 files)

Type 26 The text-based Plotter has been superseded by the online plotter since TRNSYS 14.2

Type 16 Radiation Processors With Smoothing. Smoothing is not available anymore in Type 16. Type 109 performs smoothing if required.

5.8   *Output*

This section contains the output devices that can be used in TRNSYS simulations:

Type 25 is a generic printer that can generate text files in different formats. It can print with a time step that is different from the simulation time step and it can be combined with Type 24 to print integrated values.

Type 28 is probably a more convenient way of outputting integrated results, even though it may look harder to use at the first sight. Type 28 integrates its Inputs and then performs arithmetic operations before printing selected results. Type 28 is also the ideal component to perform energy balances.

Type 27 prints tabulated time or frequency distributions of its Input variables

Type 29 performs life cycle costs analysis based upon simulations results and cost data. It only prints results at the end of a simulation (other components can be cofigured to print at different times).

Type 65 produces an online plot of some variables, providing a quick way to nalyze results on the fly.

Note that the TRACE statement (see Volume 07, TRNEdit and Input file syntax reference) can also print simulation variables for debugging purposes.

Types 25, 27, 28, 29 and 65 were implemented as kernel routines in TRNSYS 15 and before. In TRNSYS 16, these components are now implemented as standard Types, which provides more flexibility and makes it easier for users to use them as templates for user-written output producing components.

5.8.1   Type 25: Printer

The printer component is used to output (or print) selected system variables at specified intervals of time. Like Types 27, 28, 29 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

The maximum number of variables per Type 25 has been increased to 500 and there is no specific limit on the number of Type 25 units that can be used in a simulation. It is important to remember that the number of variables per printer is also limited by the maximum line length (or file width) in TRNSYS (See Volume 08, Programmer's Guide, for a reference on TRNSYS global constants).

5.8.1.1   Nomenclature

L_{unit} -   the logical unit number on which printer output is to occur

Δt -   the TRNSYS simulation time step

Δt_p -   the time interval at which the INPUTS to the printer are to be printed out

t_{on} -   the time in the simulation at which the printer is to begin printing

t_{off} -   the time at which the printer is to stop printing

TIME   -   the current value of time in the simulation

X_i -   the value of the ith INPUT to be printed

5.8.1.2   Mathematical Description

- if Δt_p = 0 or not specified, printing occurs only at the end of the simulation.

- if $0 < \Delta t_p \leq \Delta t$, printing will occur at intervals of Δt (every time step).

- if $\Delta t_p > \Delta t$, printing will occur every N time steps where N must be a positive integer and N = $\Delta t_p/\Delta t$.

- if t_{on} is <=0, printing begins at the start of the simulation. Otherwise, printing begins when TIME ≥ t_{on}.

- if t_{off} is >= t_{end}, printing stops at the end of the simulation. Otherwise, printing stops when TIME > t_{off}.

- if $L_{unit} \leq$ 0 or not specified, the standard logical unit number for the Listing File (6) is used. if L_{unit} > 0, the number is used as the logical unit number for printer output. This allows the output of the printer to be written onto a separate file.

- if UNITS = 1, user-supplied units are printed to the supplied logical unit. If UNITS = 2, TRNSYS-supplied units are printed to the designated logical unit

5.8.1.3 Special Considerations

- Type 25 has one parameter that controls whether the print intervals are relative or absolute: for example, if the simulation start time is 0.5, the simulation time step is 0.25 and the printing time step is 1: if this parameter is set to 0, printing will occur at 0.5, 1.5, 2.5, etc. If this parameter is set to 1, printing will occur at 1, 2, 3, etc.

- Type 25 is also capable to append to the output file instead of re-creating it, which can be very useful for parametric runs (all parametric runs can write to the same file).

- The 2nd data card following the INPUTS control card must contain an identifying label, or variable descriptor, for each of the INPUTS rather than initial values as for most other components. (The INPUTS are printed beneath their identifying labels.) Each descriptor consists of up to maxDescripLength (25) characters. Labels must be separated from one another by a comma or one or more blanks.

- If the 5th parameter is specified as 1, the user must supply the entire set of variable units in a manner similar to the identifying labels previously described. The units are printed below the identifying labels. Each unit consists of up to maxVarUnitLength (20) characters. Variable units must be separated from one another by a comma or one or more blanks.

- If the 8th paramerter is specified as 2, the printer will write a special header that allows EES to open the date file and recognize it as a lookup table. Units can be specified in the labels, and they must be in square braquets for EES to recognize them.

- If the parameter 6 is set to 2, the printer allows for printing at a specific time of the day.

5.8.2 Type 27: Histogram plotter

The Type 27 Histogram Plotter prints tabulated, user-specified time or frequency distributions for as many as 25 Inputs. Like Types 25, 28, 29 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

5.8.2.1 Operating modes

There are two modes of Type 27.

In Mode 1 the user specifies a range for each Input consisting of a minimum, a maximum, and the number of intervals between. Type 27 will print the total integrated time (hours) that the Input variable was within each of the corresponding intervals. This mode can be used, for example, to determine the frequency distribution of a system temperature, or to assess the frequency of occurrence of various system modes or control functions.

In Mode 2 the user specifies a daily time range for each Input, consisting of a start time, a stop time and the number of intervals between. For each Input, Type 27 will print the total integrated values of the Input that were present within each of the corresponding time intervals. This mode can be used, for example, to determine the daily distribution of an energy flux. (For meaningful results in Mode 2, the user should specify the start and stop times and the number of intervals such that an integer number of time steps occur in each interval).

Both modes of Type 27 can be printed and 'reset' at user specified time intervals. The beginning, end, and intervals of the ranges in either mode need not be respecified for subsequent Inputs if they are the same as the last range values specified.

The user can elect to have the Type 27 output sent to a disk file for subsequent processing of results by specifying L_{unit} as an optional last parameter. Whenever L_{unit} is specified, output consists of only two columns indicating the interval and the result. No plot or heading information will appear. The default value of L_{unit} is 6 (the listing file).

5.8.3   Type 28: Simulation Summary

Type 28 integrates its inputs over the time interval of the summary, performs user specified arithmetic operations on the integrals, and prints the results. Like Types 25, 27, 29 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

Type 28 can be conveniently used to generate daily, weekly, monthly or seasonal summaries of information computed in a simulation. It is especially useful for obtaining "derived" quantities, arithmetically reduced from "raw" TRNSYS output. Efficiencies, fraction run time, time averages, and energy balances are examples of the types of information obtainable from Type 28. It is equivalent to a combination of equations, Type 24 (Integrator) and Type 25 (Printer).

Type 28 can handle up to 10 inputs (for backwards compatibility reasons) and an unlimited number of outputs. There is no specific limit on the number of Type 28 units that can be used in a simulation.

5.8.3.1   Component configuration

The first 5 parameters specify the summary interval, start time, and end time, the Fortran logical unit number for output, and an output mode. Type 28 typically outputs its results to an external file, but it can also be configured to print to the listing file, which is not recommended and may be unsupported in future versions.

There are two modes for output. In Mode 1, one table with a heading is produced for the whole simulation. For example, running the "Shading" example for a year with monthly summaries produces the following output:

```
Time                      Quseful-unshaded          Quseful-shaded
 0.7440000000000000E+0003  0.2691661730332975E+0006  0.6801398991703584E+0005
 0.1416000000000000E+0004  0.3346451047390851E+0006  0.9986525629429739E+0005

 …
 0.7296000000000000E+0004  0.3494940883789239E+0006  0.1187033571959028E+0006
 0.8016000000000000E+0004  0.2472546177407783E+0006  0.6366422903990559E+0005
 0.8760000000000000E+0004  0.2470276724538152E+0006  0.5797111710341804E+0005
 0.8760000000000000E+0004  0.4433211959658687E+0007  0.2429448716222191E+0007
```

In Mode 2, a table with a single heading is produced for every 12 sets of summaries (this is best adapted to monthly summaries, in which case Type 28 also print the month name). With the same example, the result is:

```
Simulation Summary in intervals of         1.000000 month
-----------------------------------------------------------------------------
Month  Time                      Quseful-unshaded          Quseful-shaded
  Jan  0.7440000000000000E+0003  0.2691661730332975E+0006  0.6801398991703584E+0005
  Feb  0.1416000000000000E+0004  0.3346451047390851E+0006  0.9986525629429739E+0005
  …
  Oct  0.7296000000000000E+0004  0.3494940883789239E+0006  0.1187033571959028E+0006
  Nov  0.8016000000000000E+0004  0.2472546177407783E+0006  0.6366422903990559E+0005
  Dec  0.8760000000000000E+0004  0.2470276724538152E+0006  0.5797111710341804E+0005
  Sum  0.8760000000000000E+0004  0.4433211959658687E+0007  0.2429448716222191E+0007
```

Like Type 25, Type 28 can be set to append to the output file rather than re-creating it (add 10 to the mode, e.g. 11 instead of 1).

When Type 28 prints the results to the listing file, the first characters are the unit number corresponding to the instance that wrote to the listing file. This may help understanding to which unit corresponds to the outputs printed in the listing file.

5.8.3.2 Labels

A special control statement called a LABELS statement is required for use of Type 28. Unlike Type 25, the number of printed Outputs is not necessarily equal to the number of Inputs so Labels (variable descriptors) cannot be specified on the initial values line following the Inputs line. Instead, the user must specify 2 lines of the form:

```
Labels    n
label1    label2    label3 … labeln
```

after the Unit X Type 28 line. (n) is the number of Outputs of Type 28 and labeln is the LABEL used to identify the nth Output.

5.8.3.3 Energy Balances

The relative accuracy of a simulation can often be estimated by comparing the energy flows across a system or subsystem boundary with the change in system internal energy. If the energy flows between several components balance, then the timestep and convergence tolerances are adequate. If an energy balance does not close, then the system model or simulation parameters have not been specified properly.

To facilitate checking system energy balances, an energy balance checking routine is included in TRNSYS. A control statement, called a CHECK statement, is used to specify an energy balance between several quantities printed by the simulation summary component. If the energy balance does not close within the tolerance given on the CHECK statement, the simulation is terminated.

> All TRNSYS Units can have check statements. However, Type 28 is best adapted to use check statements because of its ability to integrate some (or all) of its inputs.

The use of the CHECK statement is best illustrated with an example:

Suppose a Type 28 calculates and prints out QU, the energy supplied by the collector to the tank; DE, the change in internal energy of the tank; QLOSS, the loss from the tank; and QLOAD, the energy supplied to the load from the tank. Allowing for moderate error, we can say that the energy added to the tank (QU) should be within 2% of the energy drawn from the tank (QLOSS + QLOAD) plus the change in internal energy (DE). Output 1 minus outputs 2 through 4 should be close to 0. The line

```
CHECK  .02  1,  -2,  -3,  -4
```

will cause QCHECK = QU-DE-QLOSS-QLOAD to be calculated. If QCHECK is greater than 2% of (|QU| + |DE| + |QLOSS| + |QLOAD|)/2, then the simulation will stop. As with other TRNSYS tolerances, a positive number following the word CHECK is treated as a relative tolerance and a negative number as an absolute tolerance.

5.8.3.4 Operation Codes

Type 28 Parameters 6 and higher are the operation codes. These codes enter integrated Inputs, Parameters, and Time into an operational stack (in reverse Polish notation), command operations

on these values, and place results into the OUT array so they may be printed. (**Note that the operations are performed after the Inputs have been integrated**). The operation codes are explained here below:

All operations are performed on the value on the top of the stack for unary operations, or on the top two values in the stack for binary operations. The Parameters are processed sequentially and the values determine what operations to perform on the Inputs.

In the following,

- P_j is parameter j (i.e. the parameter being processed)
- S_k is variable number k in the stack (starting from the top)
- X_i is the ith input (i is incremented when an input is accessed, it starts at 1)
- Y_j is the jth input (j is incremented when an output is accessed, it starts at 1)
- R_i is the register (memory spot) i

OPERATIONS THAT ADD VARIABLES TO THE STACK

P_i	Interpretation

-2   put (Elapsed Time since last summary) on top of stack (S_k = Elasped Time).

-1   the value of the next Parameter is placed on top of the stack as a constant. ($j = j + 1$, $S_k = P_j$)

0   the value of the next Input is placed on top of the stack. ($i = i + 1$, $S_k = X_i$)

BINARY OPERATIONS

P_i	Interpretation

1   the two values on top of the stack are replaced with their product. (Sk-1 = Sk1*Sk)

2   the two values on top of the stack are replaced by the result of the division of the second value from the top of the stack by the value on top of the stack. ($S_{k-1} = S_{k-1}/S_k$)

3   the two values on top of the stack are replaced by their sum. ($S_{k-1} = S_{k-1} + S_k$)

4   the two values on top of the stack are replaced by their difference. The top value on the stack is subtracted from the second value from the top of the stack. ($S_{k-1} = S_{k-1} - S_k$)

5   the two values on top of the stack are replaced by the second value from the top of the stack raised to the power of the top value in the stack. ($S_{k-1} = S_{k-1}\wedge S_k$)

UNARY OPERATIONS

P_i	Interpretation

6   the top value in the stack is replaced by the $\log_{10}$ of the top value in the stack. ($S_k = \log_{10}S_k$)

7   the top value in the stack is negated ($S_k = -S_k$)

8   the top value in the stack is left unchanged unless it is negative, in which case it is replaced by 0. (S_k = S_k if $S_k \geq 0$, S_k = 0 if $S_k < 0$).

FUNCTIONS USING LOGICAL RELATIONSHIPS

Some of the functions here below take their name from the case where all inputs are either 0 or 1 (Boolean variables). If inputs are outside that range, no error is generated, the same equations are applied.

P_i	Interpretation

9   the two values on top of the stack are replaced with 1 if the second value is greater than or equal to the top value, and 0 otherwise. ($S_{k-1} = 1$ if $S_{k-1} > S_k$, $S_{k-1} = 0$ if $S_{k-1} < S_k$).

10   the top value in the stack is NOT'ed ($S_k = 1 - S_k$)

11   the two values on top of the stack are replaced by their Boolean AND ($S_{k-1} = min(S_{k-1},S_k)$)

12   the two values on top of the stack are replaced by their Boolean OR ($S_{k-1} = max(S_{k-1},S_k)$)

UNARY OPERATORS (2)

P_i	Interpretation

13   The top value in the stack is replaced by the log_e of the top value in the stack ($S_k = ln(S_k)$).

14   The top value in the stack is replaced by e to the power of the top value in the stack ($S_k = exp(S_Z)$).

15   The top value in the stack is replaced by the sine of the top value in the stac ($S_k=sin(S_k)$) [S_k must be in degrees]

16   The top value in the stack is replaced by the cosine of the top value in the stack ($S_k = cos(S_k)$)   [S_k must be in degrees]

17   The top value in the stack is replaced by the arcsine of the top value in the stack ($S_k = arcsin(S_k)$)   [in degrees]

18   The top value in the stack is replaced by the arccosine of the top value in the stack ($S_k = arccos(S_k)$)   [in degrees]

19   The top value in the stack is replaced by the arctangent of the top value in the stack ($S_k = arctan(S_k)$)   [in degrees]

OUTPUTS

P_i	Interpretation

-3   the value on the top of the stack is set as the next Output ($j = j + 1$, $Y_j = S_k$).

-4   like -3, but top value of the stack is removed from stack ($j = j + 1$, $Y_j = S_k$, $S_k = S_{k-1}$).

OTHER FUNCTIONS

P_i	Interpretation
-5	decrement top of stack "pointer" ($S_k = S_{k-1}$)
-6	increment top of stack "pointer" ($S_{k-1} = S_k$).
-7	switch top two values on stack (Temp = S_k, $S_k = S_{k-1}$, S_{k-1} = Temp).
-11	place the 1st Input on top of the stack ($S_k = X_1$).
-12	place the 2nd Input on top of the stack ($S_k = X_2$).
-20	place the 10th Input on top of the stack ($S_k = X_{10}$).
-(20+i)	set register i to the value on the top of the stack; $1 \leq i \leq 10$ ($R_i = S_k$, k = k- 1)
-(30+i)	place the value in register i on the top of the stack; $1 \leq i \leq 10$ (k = k + 1, $S_k = R_i$)

5.8.4 Type 29: Economic analysis

This component performs a standard life cycle cost analysis based on the simulation of one year of solar system operation. It compares the capital and back-up fuel costs of a solar system to the fuel costs of a conventional non-solar system. It is assumed that the solar back-up system is identical to the conventional heating system, in that only the incremental costs of adding solar to the conventional system are considered. Like Types 25, 27, 28 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

The detail of the economic output is dependent on the mode and parameters used. Mode 1 is the simplest method of calculating the life cycle costs and life cycle savings. It uses the P1 and P2 method as described by Brandemuehl and Beckman (1) and Duffie and Beckman (2).

Mode 2 uses various economic parameters to calculate the yearly cash flows, life cycle costs, life cycle savings and payback periods. It also provides the user with options to calculate the rate of return on the solar investment, to consider income producing buildings, and to include federal and state tax credits.

Type 29 only performs operations twice in each simulation, once at the beginning of the simulation to check its parameter list, and again at the end to perform the economic analysis. There is no specific limit on the number of Type 29 Units in a simulation.

5.8.4.1 Nomenclature

A	collector area (m^2). This may be the gross or aperture collector area, but it must be consistent with all other parameters in the simulation.
BREAK	state tax credit tier one break ($).
C	commercial or non-commercial flag (0 = non-commercial, 1 = commercial).
C_A	total area dependent costs ($/$m^2$). These costs include the cost of the collector and part of the cost of storage.
C_E	total cost of equipment which is independent of collector area ($). Examples are costs for piping or ducts, controls, blowers, etc.
$\dot{C}_{FA}$	instantaneous auxiliary fuel cost rate ($/kJ).
$\dot{C}_{FL}$	instantaneous conventional fuel cost rate ($/kJ).
C_S	total cost of all installed solar energy equipment. $C_S = C_A A + C_E$.
d	market discount rate
D	ratio of down payments to total system investment.
DEG	thermal performance degradation of the solar system (% yr).
DP	methods of depreciation:
	1 - straight lin
	2 - declining balance
	3 - sum of years digits
	4 - none
f	fraction by solar.
F	Federal income tax rate (%).
i_g	general inflation rate (%/yr)
i_{FBUP}	backup (auxiliary) fuel inflation rate (%/yr)
i_{FCF}	conventional fuel inflation rate (%/yr)
i_p	property tax inflation rate (%/yr)
LCC	life cycle solar costs
LCS	life cycle solar savings

LIST   parameter listing, Yes = 1, No = 2
m   mortgage interest rate (%/yr)
M_S extra insurance, maintenance, etc. in year one (% of original investment)
N_D depreciation lifetime (years)
N_E period of economic analysis (years)
N_L period of loan (years)
N_{min} years over which the mortgage payments contribute to the analysis (minimum of N_E and N_L) (years)
N'_{min} minimum of N_E and N_D (years)
POFSL   declining balance depreciation rate (%/yr)
PWF   present worth factor
P_1 ratio of the life cycle fuel cost savings to the first year fuel cost savings
P_2 ratio of the life cycle expenditures incurred because of additional capital investment to the initial capital investment
Q_{AUX} total auxiliary use for one year (kJ)
$\dot{Q}_{AUX}$ instantaneous auxiliary use (kJ/hr)
Q_{LOAD} total load for one year (kJ)
$\dot{Q}_{LOAD}$ instantaneous load (kJ/hr)
R   rate of return on solar investment calculation; Yes = 1, No = 2
S   state income tax rate (%)
SAL   ratio of salvage value to initial investment
S_1 state tax credit in tier 1
S_2 state tax credit in tier 2
$\underline{t}$ true property tax rate per dollar of original investment (%)
$\bar{t}$ effective Federal-State income tax rate (%). This is assumed constant throughout the analysis
TAX   consider federal tax credits; Yes = 1, No = 2
TAXMAX   -   state tax credit tier two break ($)
TYPE   economic output; yearly printout = 1, cumulative = 2
V   ratio of the assessed valuation of the solar energy system in the first year to the initial investment in the system

5.8.4.2 *Mathematical Description*

MODE 1:

The life cycle costs and life cycle savings are calculated using P1 and P2 as defined by Brandemuehl and Beckman (1).

$$LCC = P_1\left[\int_0^t \dot{C}_{FA}\dot{Q}_{AUX}dt\right] + P_2\left[C_A \cdot A + C_E\right]$$

(Eq 5.9.4..1)

$$LCS = P_1\left[\int_0^t \dot{C}_{FL}\dot{Q}_{LOAD}dt - \int_0^t \dot{C}_{FA}\dot{Q}_{AUX}dt\right] + P_2\left[C_A \cdot A + C_E\right]$$

(Eq 5.9.4..2)

$$P1 = (1-C\bar{t}) \cdot PWF(NE, iFCF, d)$$

(Eq 5.9.4..3)

$$P_2 = D + (1\text{-}D)\frac{PWF(N_{min}, 0, d)}{PWF(N_L, 0, m)}$$

$$- (1\text{-}d)\bar{t}\left[\text{PWF} (N_{min}, m, d) \left(m - \frac{1}{\text{PWF} (N_L, 0, m)} \right) + \frac{\text{PWF} (N_{min}, 0, d)}{\text{PWF} (N_L, 0, m)} \right]$$

$$+ (1\text{-}C\bar{t})M_S \cdot \text{PWF} (N_E, i_g, d) + t(1\text{-}\bar{t})V \cdot \text{PWF} (N_E, i_g, d)$$

$$- \frac{C\bar{t}}{N_D} \text{PWF} \left(N'_{min}, 0, d \right) - \frac{\text{SAL}}{(1 + d)^{N_E}} \qquad \text{(Eq 5.9.4..4)}$$

$$\text{PWF}(a,b,c) = \begin{cases} \dfrac{1}{c - b}\left[1 - \left(\dfrac{1 + b}{1 + c} \right)^{a} \right] & \text{if } b \neq c \\[2mm] \dfrac{a}{(1 + b)} & \text{if } b = c \end{cases} \qquad \text{(Eq 5.9.4..5)}$$

$\int_0^t \dot{C}_{FA} \, \dot{Q}_{AUX} \, dt$ is the total auxiliary fuel cost for the first year

$\int_0^t \dot{C}_{FA} \, \dot{Q}_{LOAD} \, dt$ is the total fuel cost of the conventional system for the first year

State income taxes paid are deductible on Federal returns, therefore the effective federal-state income tax rate is calculated as:

$\bar{t}(\%) = [(F+S) - (F*S)] * 100$

In states which allow income tax deductions for federal taxes paid, the effective tax rate is:

$$\bar{t}(\%) = \frac{(F+S) - 2(F*S)}{1 - (F*S)} * 100$$

where:

F = federal income tax rate (fraction of yearly income)

S = state income tax rate (fraction of yearly income)

MODE 2:

Mode 2 does a detailed yearly cash flow analysis. The annual costs for both solar and non-solar systems to meet an energy demand are:

Yearly costs = Mortgage payment

+ Fuel expense

+ Maintenance and insurance

+ Property taxes

+ Parasitic energy costs

- Income tax savings

Income tax savings = $\bar{t}$ (Interest payment + Property tax)

The difference between the cost of a conventional system and a solar system is the solar savings:

Solar Savings = Cost of Conventional System - Cost of Solar System

It is assumed that the solar back-up system is identical to the conventional heating system, therefore it is not necessary to evaluate costs that are common to both systems. The incremental cost of installing a solar system is the only cost that needs to be estimated.

Solar savings = Fuel savings

+ Income tax savings

+ Tax credits

- Incremental mortgage payment

- Incremental insurance & maintenance

- Incremental parasitic energy cost

- Incremental property tax

All of these costs and savings can be assumed to inflate at a fixed percentage each year. If a cost D is to be incurred at the end of year one, the cost at the end of year N is:

DN = D(1+i)N

where i = Inflation rate

The discounted cost (present worth) at the end of year N is:

$$PW_N = \frac{D(1 + i)^{N-1}}{(1 + d)^N}$$

where d = market discount rate

These equations can be used to calculate the present worth of any cost in a series of inflating costs. For a more detailed account of solar process economics see Duffie and Beckman (2).

The state tax credit for a solar system is calculated using a two tier system:
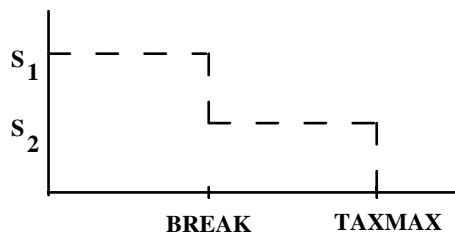
TAX CR = $(S_1*A + S_2*B)/100$

where

A = minimum of BREAK and the original investment

B = minimum of (TAXMAX - BREAK) and (original investment - BREAK)

= 0 if the above is less than zero

5.8.4.3   Economic Analysis Output

Output of the TYPE 29 component depends on the Mode selected and, in the case of Mode 2, the printing option selected.

TYPE 29 Mode 1 output is presented in Figure 5.9.4.1. The inputs and parameters 2 through 6 are listed here, as well as the total initial cost of the system, life cycle costs and life cycle savings.

When Mode 2 is used, output may take several different forms, depending on the value of parameters 25 and 26. Parameter 26, when set to 1, allows a listing of inputs and parameters to be produced along with the economic output. Life cycle costs are printed by year when parameter 25 is set to 1 or as cumulative totals when it is set to 2. Full detail output (parameters 25 and 26 set to 1) is presented in Figure 5.9.4.2.

Following the parameter listing, the output contains the following information (bracketed numbers in the figure refer to numbered sections below):

1. Collector area is specified via parameter 2.

2. Initial cost of the system is the sum of area dependent costs and fixed costs.

3. The amount of down payment is set by parameter 9.

4. Tax credits depend on the values of parameters 27 thru 31. (Note that tax credits are considered as income in year zero and contribute to the cash flow at that time rather than being used to reduce the mortgage liability.)

5. Resale value is set by parameter 18 for non-income producing buildings. Income producing buildings use the larger of the depreciated book value of the salvage value.

6. The mortgage payment is determined using the system cost less down payment and the values of parameters 9 and 10.

7. This column lists the principal remaining on the loan at the end of each year.

8. This is the amount of the annual payment that went to interest in each year.

9. This is the amount of depreciation deduction taken by an income producing system in each year and is dependent on the value of parameters 18, 20, 21 and 22.

10. In year zero of the analysis, this is the down payment. In subsequent years it is the annual mortgage payment. If the length of the analysis is less than the term of the mortgage, the value in this column for the last year of the analysis will be the last year's mortgage payment plus the remaining mortgage principal.

11. The amount of insurance and maintenance costs depend on the value of parameters 12 and 13.

12. The property tax payments depend on the value of parameters 15 and 16.

13. This is the difference between input 2 and input 1, inflated at a rate set by parameters 23 and 24.

14. In year zero, this column lists the total tax credit received. In years 1 and following, the reduction (+) or increase (-) in income tax liability due to system interest and property tax payments is printed here. If the system is income producing, changes due to depreciation and fuel cost deductions are also included. In the final year of the analysis, the resale value is also included in this column.

15. The net annual cash flow is the sum of columns 13 and 14 minus columns 10, 11 and 12.

16. This is a running sum of the values in column 15.

17. This is the value printed in column 15 discounted back to year zero at the market discount rate (parameter 11).

18. If Parameter 17 is set to 1, the rate of return is printed here.

19. Payback period.

20. Payback period.

21. This is the total out of pocket cost of the system.

22. This is the present worth of all costs associated with the solar system.

23. This is the present worth of the fuel costs of the conventional system.

24. This is the constant cost per unit of delivered energy of the system.

25. This is the constant cost per unit of delivered energy for the conventional system.

26. This is the difference between items 23 and 22.

```
          ****TRNSYS ECONOMIC ANALYSIS****
                      ------
                      MODE 1
                      ------

INPUT 1. FIRST YEAR SOLAR BACK-UP ENERGY COST......$    414.80
INPUT 2. FIRST YEAR CONV. SYSTEM ENERGY COST.......$    881.18
PAR 2. COLLECTOR AREA...............................     50.00 M2
PAR 3. COLLECTOR AREA DEPENDENT COST................    200.00 $/M2
PAR 4. FIXED COST...................................$   4000.00
PAR 5. P1 FACTOR....................................     20.0400
PAR 6. P2 FACTOR....................................      0.6630


TOTAL COST OF SYSTEM................................$  14000.00
LIFE CYCLE COST WITH SOLAR.........................$  17594.68
LIFE CYCLE FUEL COST OF CONV. SYSTEM...............$  17658.82
LIFE CYCLE SAVINGS.................................$     64.14
```

Figure 5.9.4-1

```
****TRNSYS ECONOMIC ANALYSIS****
                                 ------
                                 MODE 2
                                 ------

****ECONOMIC PARAMETERS****
 INPUT 1. FIRST YEAR FUEL COST OF SOLAR BACKUP FUEL .    414.80 $
 INPUT 2. FIRST YEAR FUEL COST OF CONV. SYSTEM ......    881.18 $
 INPUT 3. ANNUAL SYSTEM ENERGY REQUIREMENT...........    138.77 GJ/YR
 P3. AREA DEPENDENT COSTS............................    200.00 $/M2
 P4. FIXED COSTS.....................................   4000.00 $
 P6. SOLAR SYSTEM THERMAL PERFORMANCE DEGRADATION....      0.00 %/YR
 P7. PERIOD OF THE ECONOMIC ANALYSIS.................     20.00 YEARS
 P8. DOWN PAYMENT(% OF ORIGINAL INVESTMENT)..........     10.00 %
 P9. ANNUAL INTEREST RATE ON MORTGAGE................     12.00 %
 P10. TERM OF MORTGAGE...............................     20.00 YEARS
 P11. ANNUAL NOMINAL(MARKET) DISCOUNT RATE...........      9.00 %
 P12. EXTRA INSUR.,MAINT. IN YEAR 1(% OF ORIG.INV.)..      1.00 %
 P13. ANNUAL % INCREASE IN ABOVE EXPENSES............     10.00 %
 P14. EFFECTIVE FEDERAL-STATE INCOME TAX RATE........     35.00 %
 P15. TRUE PROP. TAX RATE PER $ OF ORIGINAL INVEST...      0.00 %
 P16. ANNUAL % INCREASE IN PROPERTY TAX RATE.........      0.00 %/YEAR
 P17. CALC.RT. OF RETURN ON SOLAR INVTMT?YES=1,NO=2..      1.00
 P18. RESALE VALUE  (% OF ORIGINAL INVESTMENT).......      0.00 %
 P19. INCOME PRODUCING BUILDING? YES=1,NO=2..........      2.00
 P20. DPRC.: STR.LN=1,DC.BAL.=2,SM-YR-DGT=3,NONE=4...      1.00
 P21. IF 2, WHAT % OF STR.LN DPRC.RT.IS DESIRED?.....    150.00 %
 P22. USEFUL LIFE FOR DEPREC. PURPOSES...............     20.00 YEARS
 P23. THE ANNUAL RATE OF BF RISE.....................     10.00 %/YEAR
 P24. THE ANNUAL RATE OF CF RISE.....................     10.00 %/YEAR
 P25. ECONOMIC PRINT OUT BY YEAR=1, CUMULATIVE=2.....      1.00
 P27. CONSIDER FEDERAL TAX CREDIT?YES=1,NO=2.........      1.00
 P28. STATE CREDIT IN TIER ONE.......................     18.00 %
 P29. STATE CREDIT IN TIER TWO.......................      0.00 %
 P30. STATE CREDIT TIER ONE BREAK.................... 10000.00 $
 P31. STATE CREDIT TIER TWO BREAK.................... 10000.00 $

COLLECTOR AREA=      50. M2                                    [1]
INITIAL COST OF SYSTEM  = $  14000.                            [2]
DOWN PAYMENT            = $   1400.                            [3]
STATE + FEDERAL CREDITS = $   5800.                            [4]
RESALE OR SALVAGE VALUE = $      0.                            [5]
THE ANNUAL MORTGAGE PAYMENT FOR  20 YEARS = $     1687.        [6]
```

	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]
	****INFORMATION****			*******COSTS*******			***SAVINGS***		**NET CASH FLOW***		
	END	IN-	COMM				FUEL	CREDIT			PRE-
	OF YR	TEREST	DEPREC	LOAN	MAINT	PROP	BILL	CHG TX	AN-	CUMU-	SENT
YR	PRINC	PAID	DEDUCT	PAYMT	& INS	TAX	SAVED	RESALE	NUAL	LATIVE	WORTH
0	12600	0	0	1400	0	0	0	5800	4400	4400	4400
1	12425	1512	0	1687	140	0	466	529	-832	3568	-762
2	12229	1491	0	1687	154	0	513	522	-806	2762	-677
3	12010	1468	0	1687	169	0	564	514	-778	1984	-600
4	11764	1441	0	1687	186	0	621	504	-748	1236	-529
5	11489	1412	0	1687	205	0	683	494	-715	521	-464
6	11181	1379	0	1687	225	0	751	483	-678	-157	-404
7	10836	1342	0	1687	248	0	826	470	-639	-796	-349
8	10449	1300	0	1687	273	0	909	455	-596	-1392	-298
9	10016	1254	0	1687	300	0	1000	439	-548	-1940	-251
10	9531	1202	0	1687	330	0	1100	421	-496	-2436	-209
11	8988	1144	0	1687	363	0	1210	400	-440	-2876	-170

12	8380	1079	0	1687	399	0	1331	377	−378	−3254	−133
13	7698	1006	0	1687	439	0	1464	352	−310	−3564	−100
14	6935	924	0	1687	483	0	1610	323	−237	−3801	−70
15	6081	832	0	1687	532	0	1771	291	−157	−3958	−42
16	5124	730	0	1687	585	0	1948	255	−69	−4027	−16
17	4052	615	0	1687	643	0	2143	215	28	−3999	6
18	2851	486	0	1687	708	0	2357	170	132	−3867	28
19	1506	342	0	1687	778	0	2593	120	248	−3619	48
20	0	181	0	1687	856	0	2852	63	372	−3247	66
TOTALS		21140	0	35140	8016	0	26712	13197	−3247		−526

```
THE RATE OF RETURN IS LESS THAN 0.0%                                [18]
YRS UNTIL UNDISC. FUEL SAVINGS = INVESTMENT              15.        [19]
CUMULATIVE SAVINGS NEVER EXCEEDED THE MORTGAGE PRINCIPAL            [20]
UNDISCOUNTED CUMULATIVE NET CASH FLOW = $           -3247.          [21]
PRESENT WORTH OF TOTAL COSTS WITH SOLAR = $         18184.          [22]
PRESENT WORTH OF ENERGY COSTS W/O SOLAR  = $        17658.          [23]
ANNUALIZED TOTAL COST WITH SOLAR = $/GJ                14.          [24]
ANNUALIZED ENERGY COST W/O SOLAR = $/GJ                14.          [25]
PRESENT WORTH OF CUMULATIVE NET CASH FLOW = $        -526.          [26]
```

Figure 5.9.4-2

5.8.5　　　Type 65: Online plotter

The online graphics component is used to display selected system variables at specified intervals of time while the simulation is progressing. This component is highly recommended and widely used since it provides valuable variable information and allows users to immediately see if the system is not performing as desired. The selected variables will be displayed in a separate plot window on the screen.

If Parameter 10 is positive, a file containing the values of all the printed variables will be created during the simulation. Like Types 25, 27, 28 and 29, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type. Note however that the Fortran code only passes the variables to be plotted to the calling executable program (TRNExe.exe), which handles graphical output.

The online plotter can be disabled without removing the Type declaration from the input file by setting parameter 9 to -1. If all online plotters in a simulation are disabled, the default progress bar will be displayed instead. Note that if the online plotter is configured to produce an output file at the same time, that output file will still be generated if the online plotter is disabled.

5.8.5.1　　　Special Considerations

The following points should be noted carefully because a Type 65 component differs from most other component types in several ways.

- There can now be up to 5 TYPE65s included in a simulation.

- A TYPE 65 component may have between 1 and 20 inputs. (up to 10 on left axis and up to 10 on right axis)

- The 2nd data card following the INPUTS control card must contain an identifying label for each of the INPUTS rather than initial values as for most other components. Each label consists of up to maxDescripLength (25) characters. Labels must be separated from one another by a comma or one or more blanks.

- A LABELS card is required in order to supply the variable units for the two plots as well as the plot titles. Type 65 always requires 3 labels in TRNSYS 16. The first line beneath the LABELS card must contain the title for the left y-axis. The second line is the title for the right y-axis. The third line below the LABELS card must contain the text that will appear in the online plot identifying tab ("plot title").

- The number of inputs is equal to the sum of the first two parameters.

5.8.5.2 Quick overview of some Online plotter capabilities

If at least one "online plotter" component is present in the simulation, an online plot will be displayed during the simulation. The online plotter offers several features that will help you analyze the simulation results while it is running and after it is done.

STOP/RESUME THE SIMULATION

You can interrupt / resume the simulation while it is running by right-clicking anywhere in the plot, by using the "F7" and "F8" keys, or using the "Calculation/Stop" and "Calculation/Resume" menu entries. The "Pause at…" command is also very useful when you want to diagnose some problems occurring at a given time in a simulation.

CHANGING SOME PLOT OPTIONS

When the simulation is stopped, you can use the "Plot options" menu to change the plot background or line thickness. You can also change the left and right Y-axis limits by clicking on the axes themselves, which will display a dialog box (see Figure 5.8.5–1). Please note that changes to those limits will be lost if you re-run the simulation. You should change the online plotter parameters in the input file or Studio project if you want changes to be permanent.
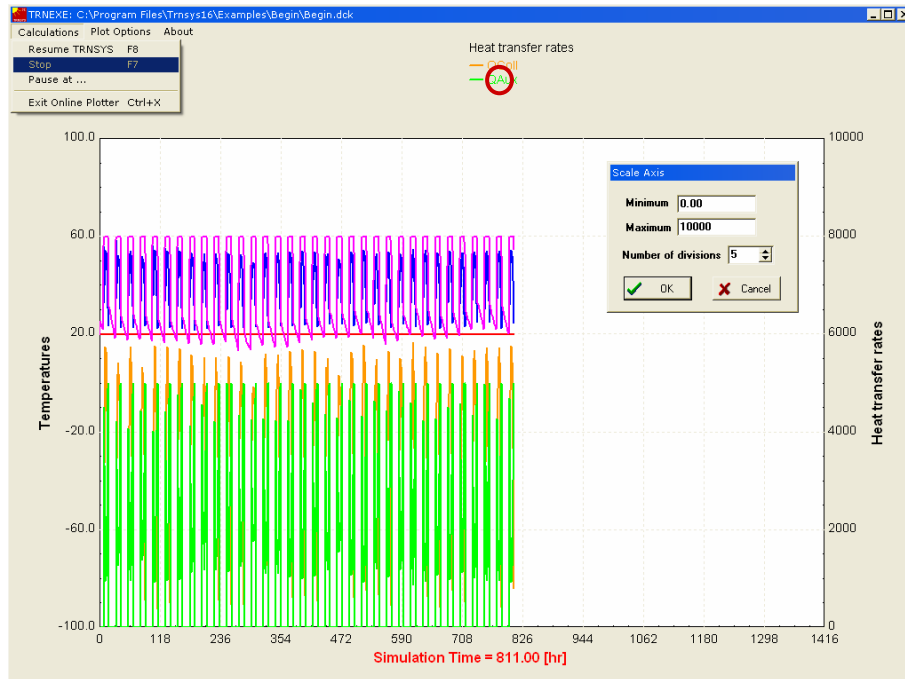
Figure 5.8.5–1: The online plotter window

You can hide or show any variable in the plot by clicking on its name in the legend fields. For example clicking in the red circle in Figure 5.8.5–1 would hide/show the QAux plot.

ANALYZING THE SIMULATION: ZOOMING AND DISPLAYING NUMERICAL VALUES

You can zoom on part of the plot to have a more detailed view of a shorter time interval. Just click on the upper-left corner of the area you want to zoom in and drag the mouse pointer to the lower-right corner, then release the mouse button. In the zoom window, you can adjust the Y-axis limits **but also the X-axis (time) limits** by clicking on the axes. This is very useful when you want to study such a short period of time that it is hard to zoom on that period right away.

You can display the numerical value of any variable at any point in time in both the "normal" and the "zoom" windows. Press the SHIFT key and mover the mouse over the graph. The variable labels will be replaced with their value (and "time" will be replaced with the simulation time). This is shown in Figure 5.8.5–2 for the zoom window.
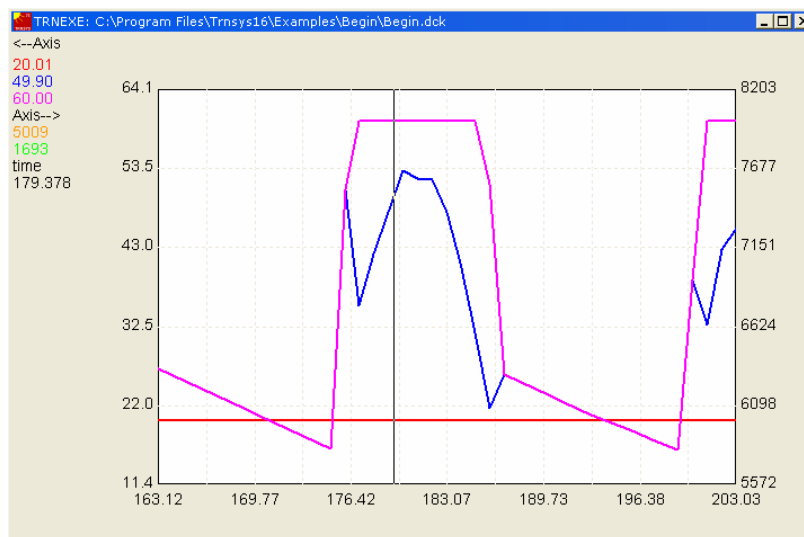
Figure 5.8.5–2: Displaying numerical values in the online plotter

> Note: By pressing SHIFT and moving the mouse over the plot, you will display the values plotted by the online plotter, which are interpolated between TRNSYS time steps. If you want to see only the actual simulation time steps, pres CTRL-SHIFT when moving the mouse. This can be useful to study control signal switching from 0 to 1, for example, since the online plotter will draw a continuous line between those 2 states and it will show interpolated values that do not correspond to any simulated values.

END OF THE SIMULATION

At the end of the simulation, TRNSYS will display a dialog box asking if you want to leave the online plotter open.
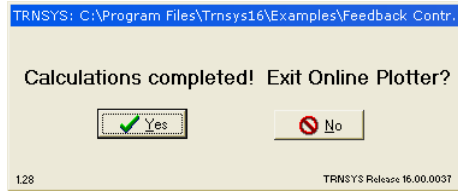
Figure 5.8.5–3: Dialog box at the end of the simulation

You can click "No" if you want to keep analyzing the simulation results. It is important to realize that if you do that, the TRNSYS simulation is actually not completed. The very last call (identified by INFO(8)=-1, see Volume 08 Programmer's Guide) only occurs after you close the online plotter. This means that some files might be locked (including the TRNSYS DLL, TRNDll.dll).

RUNNING TRNSYS IN BATCH MODE

You can run TRNSYS in batch mode by adding a "/n" switch to the command line, e.g. (on one line):

```
"C:\Program Files\Trnsys16\Exe\TRNExe.exe"
                 "C:\Program Files\Trnsys16\Examples\SDHW\SDHW.dck" /n
```

In TRNSYS 16, the behavior of the /n switch was changed so that it also skips the dialog box that informs you about errors in the simulation. Note that this is only true for actual TRNSYS errors, not for exceptions generated by the code such as floating point overflows, etc.

RUNNING TRNSYS IN HIDDEN MODE

You can run TRNSYS in hidden batch mode by adding a "/h" switch to the command line, e.g. (on one line):

```
"C:\Program Files\Trnsys16\Exe\TRNExe.exe"
                 "C:\Program Files\Trnsys16\Examples\SDHW\SDHW.dck" /h
```

The "/h" switch implies the "/n" switch and makes TRNSYS completely invisible (you can check that it is running by launching Windows' task manager and look for a process called TRNExe). **Please note that this switch is only applicable to simulations that do not use the online plotter or for which all online plotters are disabled** (by setting parameter 9 to -1).

5.9   *Physical Phenomena*

This section contains components that model physical phenomena rather than actual pieces of equipment. They are used in a similar way as the components found in the Utility category.

Type 16 (Radiation Processors) is a powerful component that handles all operations that are necessary to calculate the incident radiation on a tilted surface from the available solar radiation in a typical data file.

Type 30 (Collector Array Shading) is used to take into account the shading on collector rows by other collector rows in a large-size collector array.

Type 33 (Psychrometrics) is a flexible component that can be used to calculate different properties of humid air from 2 independent variables.

Type 54 (Weather Generator) is used to generate hourly weather data from monthly average values.

Type 58 (Refrigerant properties) calculates state properties of various refrigerants from two independent properties.

Type 68 (Shading Masks) models shading effects of obstructions on windows, walls, etc. It reads a file with the angular height of obstructions.

Type 69 (Effective Sky Temperature) calculates an effective sky temperature used to take into account long-wave radiation between walls, roofs, collectors, etc. and the sky.

Type 77 (Simple Ground Temperature Model) is used to obtain an approximation of the undisturbed ground temperature at different depths.

Type 80 (Convection Coefficient Calculation) calculates the natural convection coefficients for walls, ceilings and floors. This Type should not be used with Type 56 in TRNSYS 16, since its capabilities have been built into Type 56 itself (see Volume 06, Type 56 and TRNBuild, for more information).

5.9.1 Type 16: Solar Radiation Processor

Insolation data is generally recorded at one hour intervals and on a horizontal surface. In some TRNSYS simulations, estimates of radiation at time intervals other than one hour are required. This "component" interpolates radiation data, calculates several quantities related to the position of the sun, and estimates insolation on up to 8 surfaces of either fixed or variable orientation.

There are several possible methods of interpolating radiation data. One fairly simple method is to linearly interpolate hourly data to obtain estimates of radiation over shorter time intervals. This approach, which was used in TRNSYS prior to Version 10.1, has several drawbacks. The most readily apparent problem is that positive radiation values are produced before sunrise and after sunset. If sunrise is at 6:30 a.m., then an hourly radiation data file may have a value of zero at 6:00 and 40 watts/m^2 at 7:00. Linear interpolation will give 10 watts/m^2 at 6:15, fifteen minutes before sunrise. This problem is compounded by the fact that the ratio of beam radiation on a tilted surface to that on a horizontal, R_b, may become very large near sunrise and sunset. If the estimate of radiation on the horizontal is too large near sunrise, the calculated radiation on a tilted surface will be immense. Thus, the current radiation processor uses the curve for extraterrestrial radiation to interpolate radiation data. This seems to relieve the problems encountered with linear interpolation.

Total radiation on a tilted surface is usually required for solar energy system simulations. The models used in this subroutine to estimate the total tilted surface radiation require knowing the division of total horizontal radiation into its beam and diffuse components. If only total horizontal radiation is measured, correlations are provided to estimate the beam or diffuse radiation on a horizontal surface. The horizontal components are then projected onto the tilted surface. Type 16 has several options for calculating the horizontal radiation components as well as estimating the total radiation on a tilted surface.

Notes:

- With the release of TRNSYS 15, the Type 16 was not completely backwards compatible with versions distributed prior to TRNSYS 14.

- Radiation smoothing has been disabled in TRNSYS 16. Type 109 performs radiation smoothing if required.

5.9.1.1 Nomenclature

A_I	-	Anisotropy index
a/c		weighted circumsolar solid angle
E		Factor accounting for the eccentricity of the earth's orbit
f		Modulating factor for Reindl titlted surface model
F_1'		Reduced brightness coefficient (circumsolar)
F_2'		Reduced brightness coefficient (horizon brightening)
I_o		Extraterrestrial radiation
I_{on}		Extraterrestrial radiation at normal incidence
I_b		Beam radiation on horizontal surface
I_{bn}		Beam radiation at normal incidence
I_{bT}		Beam radiation on tilted surface
I_d		Diffuse radiation on horizontal surface
I_{dn}		Direct normal beam radiation
I_{dT}		Diffuse radiation on tilted surface

I	Total radiation on a horizontal surface
I_T	Total radiation on a tilted surface
I_{gT}	Ground reflected radiation on a tilted surface
k_T	Ratio of total radiation on a horizontal surface to extraterrestrial radiation
L_{loc}	Longitude of a given location
L_{st}	Standard meridian for time zone
n	Day of year of the start of the simulation
R_b	Ratio of beam radiation on tilted surface to beam on horizontal
R_d	Ratio of diffuse radiation on tilted surface to diffuse on horizontal
R_r	Ratio of reflected radiation on tilted surface to total radiation on horizontal
rh	relative humidity [%]
S_c	Solar constant
SHFT	Shift in solar time relative to the nominal time of data reading
T_a	Ambient temperature
t_1	Time of start of time step
t_2	Time of end of time step
t_{d1}	Time of last data reading
t_{d2}	Time of next data reading
α	Solar altitude angle (90 - qz)
β	Slope of surface, positive when tilted in the direction of the azimuth specification
β	Slope of tracking axis
δ	Solar declination angle
Δ	Sky brightness parameter
ϵ	Sky clearness parameter
γ	Azimuth angle of surface; angle between the projection of the normal to the surface into the horizontal plane and the local meridian. (facing equator = 0, west positive, east negative)
γ'	Azimuth angle of axis; angle between the projection of the axis line onto the horizontal plane and local meridian. (Same sign convention as for γ)
γ_s	Solar azimuth angle
θ	Angle of incidence of beam radiation on surface
θ_Z	Solar zenith angle
ρ_g	Ground reflectance
ϕ	Latitude
ω	Mean hour angle of time step (0 at noon, mornings negative)
ω_1	Hour angle at start of time step, or sunrise hour angle if sunrise occurs during time step
ω_2	Hour angle at end of time step, or sunset hour angle if sunset occurs during time step.
ω_{d1}	Hour angle at start of data
ω_{d2}	Hour angle at end of data

In practice, most radiation data are actually integrated totals of instantaneous measurements. The TYPE 9 data reader interpolates data linearly. This is not appropriate for radiation (see above): **TYPE 9 should be set up to not interpolate the radiation data**. The TYPE 16 Radiation Processor uses the total radiation between times t_{d1} and t_{d2} that is read in by the data reader. Then, by summing integrals if necessary, the total radiation between hour angles ω_{d1} and ω_{d2} is found. The hour angles ω_{d1} and ω_{d2} are chosen so that $\omega_{d1} \le \omega_1$ and $\omega_{d2} \ge \omega_2$. Here ω_1 is the angle of the start of the time step and ω_2 is the angle of the end of the time step. If sunrise or sunset occurs during the time step, then the portion of the time step when the sun is below the horizon is ignored.

The total extraterrestrial radiation between hour angles ω' and ω'' is found from:

$$I_0\big|_{\omega'}^{\omega''} = \int_{\omega'}^{\omega''} S_c\, E\, (\cos\phi\, \cos\delta\, \cos\omega + \sin\phi\, \sin\delta)\, d\omega$$

Eq. 5.9-1

Given $I\big|_{\omega d1}^{\omega d2}$, a reasonable estimate of the actual insolation over the time step is

$$I\big|_{\omega_1}^{\omega_2} = I\big|_{\omega d1}^{\omega d2} * \frac{I_0\big|_{\omega_1}^{\omega_2}}{I_0\big|_{\omega d1}^{\omega d2}}$$

Eq. 5.9-2

This calculation scales integrated radiation data using the ratio of extraterrestrial radiation over the time step to extraterrestrial radiation over the period which corresponds to the data. Since other TRNSYS routines require the rate of solar radiation, the integrated radiation is converted to the average rate over the time step.

HORIZONTAL RADIATION MODE

Type 16 has five methods for obtaining beam and diffuse radiation on a horizontal surface from total radiation on a horizontal surface data. Horizontal Radiation Modes 1 and 2 are based on the relationships developed by Reindl (9a). Both modes provide estimates of the diffuse fraction of the total horizontal radiation (I_d/I). Mode 1 is a reduced form of the full correlation given in Mode 2. Mode 1 uses the clearness index and the solar altitude angle to estimate the diffuse fraction. The correlation is given by the following equations:

Interval: $0 \le k_T \le 0.3$; Constraint: $I_d/I \le 1.0$

$$I_d/I = 1.020 - 0.254\ k_T + 0.0123\ \sin(\alpha)$$

Eq. 5.9-3

Interval: $0.3 < k_T < 0.78$; Constraint: $0.1 \le I_d/I \le 0.97$

$$I_d/I = 1.400 - 1.749\ k_T + 0.177\ \sin(\alpha)$$

Eq. 5.9-4

Interval: $0.78 < k_T$; Constraint: $0.1 \le I_d/I$

$$I_d/I = 0.486\ k_T - 0.182\ \sin(\alpha)$$

Eq. 5.9-5

Horizontal Radiation Mode 2 estimates the diffuse fraction as a function of the clearness index, solar altitude angle, ambient temperature, and relative humidity. The correlation is given by the following equations:

Interval: $0 \le k_T \le 0.3$; Constraint: $I_d/I \le 1.0$

$$I_d/I = 1.000 - 0.232\ k_T + 0.0239\ \sin(\alpha) - 0.000682\ T_a + 0.0195\ (rh/100)$$

Eq. 5.9-6

Interval: $0.3 < k_T < 0.78$; Constraint: $0.1 \le I_d/I \le 0.97$

$$I_d/I = 1.329 - 1.716\ k_T + 0.267\ \sin(\alpha) - 0.00357\ T_a + 0.106\ (rh/100)$$

Eq. 5.9-7

Interval: $0.78 < k_T$; Constraint: $0.1 \leq I_d/I$

$I_d/I = 0.426\ k_T - 0.256\ \sin(\alpha) + 0.00349\ T_a + 0.0734\ (rh/100)$ **Eq. 5.9-8**

Rather than constrain each variable in the above correlations, a subsequent constraint is placed on the overall estimate of the diffuse fraction. The constraints limit the diffuse fraction estimates to values that are physically possible.

For the above Horizontal Radiation Modes, beam radiation on a horizontal surface is calculated by the difference between the total radiation and the diffuse component,

$I_b = I - I_d$ **Eq. 5.9-9**

In Horizontal Radiation Mode 3, beam and diffuse radiation on a horizontal surface are Input directly. For Horizontal Radiation Mode 4, total horizontal and direct normal radiation are Inputs and Horizontal Radiation Mode 5 has Inputs of total and diffuse radiation on a horizontal surface.

If measurements of global horizontal and beam or diffuse radiation are available, then Horizontal Radiation Mode 3, 4 or 5 should be used. Horizontal Radiation Mode 4 can be used with SOLMET (4) data, since direct normal radiation values have been estimated for this data using the algorithm developed by Randall and Whitson (5). When beam and diffuse radiation measurements are not available, Horizontal Radiation Modes 1 or 2 must be used. If total radiation on a horizontal surface, ambient temperature, and relative humidity data are available, Horizontal Radiation Mode 2 is recommended. (Note that the temperature and relative humidity data *may* be interpolated by the Type 9 Data Reader. They *will not* be interpolated by TYPE 16.) If only total radiation is available, then it is recommended that Horizontal Radiation Mode 1 be used.

The above recommendations are based on evaluation of the existing correlations with several sets of measurements (9a).

POSITION OF SUN IN SKY

The position of the sun in the sky can be specified by giving the solar zenith and solar azimuth angles. The zenith angle is the angle between the vertical and the line of sight of the sun. This is 90 minus the angle between the sun and the horizontal (solar altitude angle). The solar azimuth angle is the angle between the local meridian and the projection of the line of sight of the sun onto the horizontal plane. Zero solar azimuth is facing the equator, west is positive, while east is negative. Both zenith and solar angles can be determined from trigonometric relationship given in Chapter 2 of Duffie and Beckman (6) or ASHRAE (7), or by Braun and Mitchell (8).

$$\cos\theta_Z = \sin\delta\sin\phi + \cos\phi\cos\delta\cos\omega$$ **Eq. 5.9-10**

$$\sin\gamma_s = \frac{\cos\delta\ \sin\omega}{\sin\theta_Z}$$ **Eq. 5.9-11**

SURFACE TRACKING MODE

Four Surface Tracking Modes are incorporated into TRNSYS for handling various surfaces for which determination of incident radiation is often needed. Tracking Mode 1 is for surfaces that do

not track to maximize incoming radiation. The slope and azimuth Inputs denote the position of the surface. These may vary with time as with any TRNSYS Inputs or may be constant. Tracking Modes 2-4 handle various kinds of optimally tracked surfaces. An optimally tracked collector will be maneuvered to maximize radiation at all times. In general, this amounts to maximizing beam radiation, or $\cos\theta$.

Tracking Mode 2 handles a tracking surface with a fixed surface slope and variable surface azimuth rotating about a vertical axis as denoted in Figure 5.9.1–1. For this case, beam radiation is maximized when $\gamma = \gamma_s$. The azimuth Input in this situation is ignored.
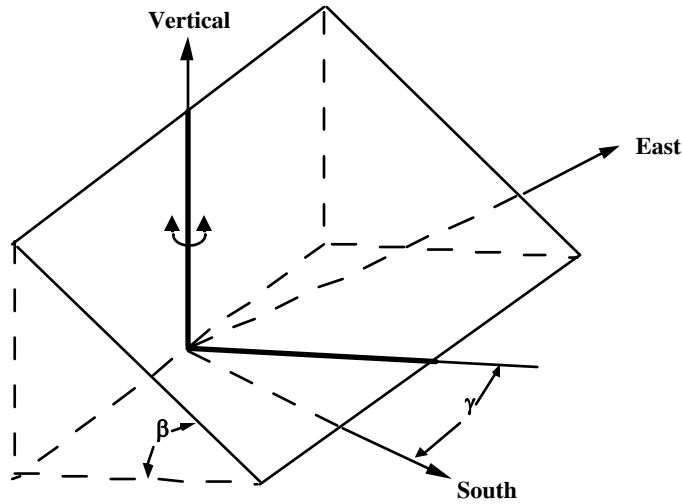
Figure 5.9.1–1: Tracking Mode 2 Surface

Tracking Mode 3 handles the general case of a surface rotating about a single axis that is always parallel to the surface. An illustration of this scheme is presented in Figure 5.9.1–2. For a horizontal axis, the surface slope at any instant is given by

$$\beta = \tan^{-1}\left(\tan\theta_Z \cos(\gamma_s - \gamma)\right)$$

Eq. 5.9-12

where the surface azimuth is given in terms of the axis azimuth as

$$\gamma = \gamma' + 90° \qquad \text{if } \gamma_s - \gamma' > 0$$

Eq. 5.9-13

$$\gamma = \gamma' - 90° \qquad \text{if } \gamma_s - \gamma' < 0$$

Eq. 5.9-14

If a surface tracks about a single axis that is always parallel to the surface, but is not vertical or horizontal, both azimuth and slope of the surface vary with time. In this case,

$$\gamma = \gamma' + \tan^{-1}\left(\frac{\sin\theta_Z \sin(\gamma_s - \gamma')}{\sin\beta' \cos\theta'}\right)$$

Eq. 5.9-15

$$\beta = \tan^{-1}\left(\frac{\tan\beta'}{\cos(\gamma-\gamma')}\right)$$

Eq. 5.9-16

where θ' is the incidence angle for a surface with slope and azimuth equal to those of the axis.

The slope and azimuth Inputs for Mode 3 refer to the position of the axis.
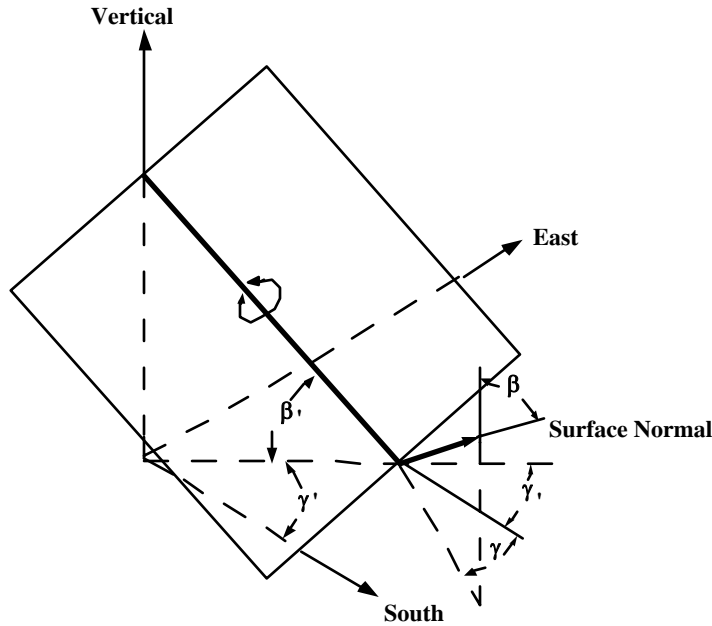
Figure 5.9.1–2: Tracking Mode 3 Surface

In Tracking Mode 4, two-axis tracking surfaces are considered. Beam radiation is maximized for a surface adjusted such that the sun's rays are always at normal incidence (i.e. $\cos\theta = 1$). This is accomplished when $\gamma = \gamma_s$ and $\beta = \theta_z$. Both slope and azimuth Inputs are ignored. The derivations of the trigonometric relationships for the class of tracking collectors presented here are given in Reference 8.

TILTED SURFACE RADIATION MODE

For most surfaces, an estimate of the total radiation incident on the surface is of interest. Type 16 provides four models for estimating the total radiation on a tilted surface. Each model requires knowledge of total and diffuse (or beam) radiation on a horizontal surface as well as the sun's position. In general the total tilted surface radiation is calculated by estimating and adding beam, diffuse and reflected radiation components on the tilted surface.

All tilted surface radiation models use the same techniques for projecting the beam and ground reflected radiation onto a tilted surface; they differ only in the estimate of diffuse radiation on a tilted surface. The contribution of beam radiation on a tilted surface (in short time intervals) can be calculated by using the geometric factor R_b (6):

$$R_b = \frac{\cos \theta}{\cos \theta_Z} \qquad\qquad \text{Eq. 5.9-17}$$

where

$$\cos\theta = \cos\theta_Z \cos\beta + \sin\theta_Z \cos(\gamma_s - \gamma) \sin\beta \qquad\qquad \text{Eq. 5.9-18}$$

In the above equation, β is the slope of the surface defined as the angle between the surface and the horizontal, while γ is the surface azimuth or the angle between the projection of the normal to

the surface into the horizontal plane and the local meridian. The sign convention for surface azimuth is identical to that for solar azimuth (zero facing equator, positive if west, negative if east). Slope is measured as a positive value when tilted in the direction of the azimuth specification.

Once R_b is found,

$$I_{bT} = I_b \cdot R_b$$ **Eq. 5.9-19**

The contribution of reflected radiation on a titled surface is calculated by assuming the ground acts as an isotropic reflector and defining R_r as the ratio of reflected radiation on a tilted surface to the total radiation on a horizontal surface is:

$$R_r = 0.5 \ (1 - \cos \beta) \ \rho_g$$ **Eq. 5.9-20**

$$I_{gT} = I \cdot R_r$$ **Eq. 5.9-21**

The contribution of diffuse radiation on a tilted surface is determined by using one of the four models provided in Type16's Tilted Surface Radiation Mode. Tilted Surface Radiation Mode 1 uses the isotropic sky model. This is the model that has been used by default in previous versions of TRNSYS. The isotropic sky model assumes that the diffuse radiation is uniformly distributed over the complete sky dome. A factor R_d, the ratio of diffuse radiation on a tilted surface to that on a horizontal, is given by:

$$R_d = 0.5 \ (1 + \cos \beta)$$ **Eq. 5.9-22**

Thus the diffuse radiation on a tilted surface assuming isotropic sky is:

$$I_{dT} = I_d \cdot R_d$$ **Eq. 5.9-23**

Tilted Surface Radiation Mode 2 uses a model developed by Hay and Davies (10). The Hay and Davies model accounts for both circumsolar and isotropic diffuse radiation. Under clear sky conditions, there is an increased intensity of diffuse radiation in the area around the sun (circumsolar diffuse). Hay and Davies weight the amount of circumsolar diffuse by using an anisotropy index, A_I The anisotropy index defines a portion of the diffuse radiation to be treated as circumsolar with the remaining portion of diffuse radiation considered isotropic. The Hay and Davies tilted surface diffuse radiation model is given by:

$$A_I = \frac{I_{bn}}{I_{on}}$$ **Eq. 5.9-24**

$$I_{dT} = I_d \left[0.5 \ (1 - A_I) \left(1 + \cos \ \beta \right) + A_I \ R_b \right]$$ **Eq. 5.9-25**

The first term in bracket represents the contribution of isotropic diffuse radiation while the second term represents the contribution of circumsolar diffuse radiation.

Tilted Surface Radiation Mode 3 uses a model developed by Reindl (9b) based on the work of several previous authors. This model adds a horizon brightening diffuse term to the Hay and Davies model. The horizon brightening is lumped with the isotropic diffuse term and its magnitude is controlled by a modulating factor, f.

The Reindl tilted surface diffuse radiation model is given by:

$$f = \sqrt{\frac{I_b}{I}}$$

Eq. 5.9-26

$$I_{dT} = I_d \left[0.5 \ (1 - A_I) \left(1 + \cos \beta \right) \left(1 + (f) \sin^3(\beta/2) \right) + A_I \ R_b \right]$$

Eq. 5.9-27

The first term in brackets represents the contribution of isotropic and horizon diffuse and the second term represents the contribution of circumsolar diffuse.

Tilted Surface Radiation Mode 4 uses a version of the tilted surface model developed Perez, et al (11). This model accounts for circumsolar, horizon brightening, and isotropic diffuse radiation by empirically derived "reduced brightness coefficients". The reduced brightness coefficients, F'_1, F'_2, are functions of sky clearness, e, and sky brightness, Δ, parameters.

$$\varepsilon \equiv \frac{\left[\frac{(I_d + I_{dn})}{I_d} + 1.041 \ \theta_Z^3 \right]}{\left[1 + 1.041 \theta_Z^3 \right]}$$

Eq. 5.9-28

Where θ_Z is in radians:

$$\Delta \equiv \frac{I_d \ m}{I_{on}} = \frac{I_d}{I_o}$$

Eq. 5.9-29

The sky clearness and sky brightness parameters are used to calculate the reduced brightness coefficients from the relationships and table given below.

$$F'_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon) \cdot \Delta \ + F_{13}(\varepsilon) \cdot \theta_Z$$

Eq. 5.9-30

$$F'_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon) \cdot \Delta \ + F_{23}(\varepsilon) \cdot \theta_Z$$

Eq. 5.9-31

The Perez coefficients (F_{11}, etc.) are given in the following table (11):

ε Bin	Upper Limit for ε	Cases (%)	F11	F12	F13	F21	F22	F21
1	1.065	13.60	-0.196	1.084	-0.006	-0.114	0.180	-0.019
2	1.230	5.60	0.236	0.519	-0.180	-0.011	0.020	-0.038
3	1.500	7.52	0.454	0.321	-0.255	0.072	-0.098	-0.046
4	1.950	8.87	0.866	-0.381	-0.375	0.203	-0.403	-0.049
5	2.800	13.17	1.026	-0.711	-0.426	0.273	-0.602	-0.061
6	4.500	21.45	0.978	-0.986	-0.350	0.280	-0.915	-0.024
7	6.200	16.06	0.748	-0.913	-0.236	0.173	-1.045	0.065
8	-	13.73	0.318	-0.757	0.103	0.062	-1.698	0.236

The magnitude of the reduced brightness coefficients weight the respective circumsolar, horizon brightening, and isotropic diffuse radiation components. The angular location of the circumsolar region is determined by the ratio a/c.

$$a/c = \frac{\max\left[0, \cos \theta \right]}{\max\left[\cos 85, \cos \theta_Z \right]}$$

Eq. 5.9-32

The tilted surface diffuse radiation can be estimated by the following

$$I_{dT} = I_d \left[0.5 \left(1\text{-}F'_1 \right) \left(1\text{+}\cos \beta \right) + F'_1 \left(\frac{a}{c} \right) + F'_2 \sin \beta \right]$$

Eq. 5.9-33

Thus the total radiation incident on a tilted flat surface for all tilted surface radiation modes is

$$I_T = I_{bT} + I_{dT} + I_{gT}$$

Eq. 5.9-34

In general, the anisotropic sky models (Hay and Davies, Reindl, and Perez, et al) provide comparable estimates of the total radiation on a tilted surface and are recommended for general use. The Hay and Davies and the Reindl models are computationally simple when compared to the Perez model. The isotropic sky model (mode 1) under predicts the total radiation on a tilted surface and is not recommended for general use; it is included to permit consistency with simulations performed with earlier versions of TRNSYS.

SOLAR TIME CALCULATION

Since many of the calculations made in transforming insolation on a horizontal surface depend on the time of day, it is important that the correct solar time be used. Several correction factors are used in computing solar time. Following the development in Chapter 2 of Duffie and Beckman,

solar time (hrs) = standard time + E + $(L_{st} - L_{loc})/15$

Eq. 5.9-35

Here E accounts for the eccentricity of the earth's orbit and varies between about -.24 hours and +.26 hours each year. L_{st} is the standard meridian for the local time zone and L_{loc} is the longitude of the location in question. Both standard and local meridians are measured in degrees 0 to ±180°. West of longitude 0 (Greenwich, England) is positive, east is negative. Standard meridians for continental U.S. time zones are Eastern 75° W, Central 90° W, Mountain l05° W, and Pacific l20°. Standard meridians for Europe are Western (Greenwich time) 0° and Central (MEZ time) -15°.

For processing the total radiation over a time step, the mean hour angle

$$\omega = 0.5 \left(\omega_1 + \omega_2 \right)$$

Eq. 5.9-36

is used. This is to ensure that the calculated position of the sun will be the average position for the time step.

The solar time that is used is

solar time = t + E + SHFT/15

Eq. 5.9-37

where t is the time in hours corresponding to ω. Comparing the two equations for solar time, one can see that SHFT should be set to $L_{st} - L_{loc}$. Also, simulation time should be set so that the first data line read in corresponds to the period (typically hour) <u>ending</u> at the simulation starting time. If data is supplied at even solar time intervals, then the factors E and SHFT should be omitted. This is accomplished by including a negative last parameter.

5.9.1.2   References

1. Liu, B. Y. H. and Jordan, R. C. "The Interrelationships and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation," <u>Solar Energy</u>, Vol. IV, July, (1960), pp. 1-19.

2. Boes, E. C. et al., "Distribution of Direct and Total Solar Radiation Availabilities for the U.S.A.," Sandia Report SAND76-0411, August, (1976).

3. Erbs, D. G., "Methods for Estimating the Diffuse Fraction of Hourly, Daily and Monthly Average Global Solar Radiation," Masters Thesis in Mechanical Engineering, University of Wisconsin-Madison, (1980).

4. SOLMET, Volume 2 – Final Report, "Hourly Solar Radiation Surface Metereological Observations," TD-9724, (1979).

5. Randall, C.M. and Whitson, M. E., Final Report, "Hourly Insolation and Metereological Data Bases Including Improved Direct Insolation Estimates," Aerospace Report No. ATR-78(7592)-1, (1977).

6. Duffie, J. A. and Beckman, W. A., Solar Energy Thermal Processes, Wiley, New York, (1974).

7. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigeration and Air-Conditioning Engineers, (1972).

8. Braun, J. E. and Mitchell, J.C., "Solar Geometry for Fixed and Tracking Surfaces," Solar Energy, Vol. 31, No. 5, October, (1983).

9. (a) Reindl, D.T., Beckman, W.A. and Duffie, J.A., "Diffuse Fraction Correlations", Solar Energy, Vol. 45, No. 1, (1990), pp.1-7.

   (b) Reindl, D.T., Beckman, W.A. and Duffie, J.A., "Evaluation of Hourly Tilted Surface Radiation Models", Solar Energy, Vol. 45, No. 1, (1990), pp. 9-17.

10. Hay, J.E., Davies, J.A., "Calculation of the Solar Radiation Incident on an Inclined Surface", Proceedings First Canadian Solar Radiation Workshop, (1980), pp. 59-72.

11. Perez, R., Stewart, R., Seals, R., and Guertin, T., "The Development and Verification of the Perez Diffuse Radiation Model", Sandia Report SAND88-7030, (1988).

5.9.2   Type 30: Collector Array Shading

This component determines incident radiation upon an array of collectors that shade one another. There are two possible modes. MODE 1 considers fixed flat plate collectors in a sloped field. Incident total, beam, and diffuse radiation are output. MODE 2 is for single axis tracking parabolic trough collectors that utilize beam radiation only.

5.9.2.1   Nomenclature

D_a	-	distance between tracking axes of single axis tracking collectors
D_R	-	distance between rows of flat plate collectors in a field
f_{bs}	-	fraction of total array area that is shaded from beam radiation
f'_{bs}	-	fraction of ground area between rows of collectors that is shaded from beam radiation
$(f_{bs})_1$	-	fraction of area of a single row of collectors that is shaded by an adjacent row
F_{gnd}	-	overall view factor from the collector array to the ground in front of the array
F_{g-s}	-	overall view factor from the ground between rows of collectors to the sky
F_{sky}	-	overall view factor from the collector array to the sky
F'_{gnd}	-	overall view factor from the collector array to the ground between rows
H_c	-	height of each collector row
I	-	total unshaded horizontal radiation per unit area
I_{bT}	-	unshaded incident beam radiation per unit area
I_{dT}	-	unshaded incident diffuse radiation per unit area
I_T	-	unshaded total incident radiation per unit area
I'_{bT}	-	unshaded incident beam radiation per unit area on the field slope on which collectors are mounted
I'_{dT}	-	unshaded incident diffuse radiation per unit area on the field of slope β_F on which collectors are mounted
$(I_{bT})_s$	-	incident beam radiation per unit area including shading effects
$(I_{dT})_s$	-	diffuse incident radiation per unit area including shading effects
$(I_T)_s$	-	total incident radiation per unit area including shading effects
N_R	-	number of rows of collectors
P	-	distance between planes that contain sun and each axis of a single axis tracking system
W_a	-	width of collector aperture
W_R	-	width of row of collectors
β	-	collector surface slope
β_a	-	slope of plane containing the tracking axes
β_F	-	slope of field on which collector array is situated
γ	-	azimuth of collector surface; angle between the projection of the normal into the horizontal plane and the local meridian. Zero azimuth facing the equator, west positive, east negative
γ_a	-	azimuth angle of the plane containing the tracking axes.
γ_s	-	solar azimuth; angle between the projection of the line of sight to the sun into the horizontal plan and the local meridian
ρ_g	-	ground reflectance to the plane
θ_p	-	angle between a plane containing the sun and an axis and a plane that is perpendicular containing all the collector axes
θ_z	-	solar zenith angle

5.9.2.2 Mathematical Description

MODE 1

This mode calculates incident radiation on a rectangular field of collectors that shade one another. The collector arrangement and pertinent dimensions are shown in Figure 5.9.2–1. The field on which the collectors are located is assumed to be sloped in the direction of the array azimuth.

The incident radiation for this array is

$$(IT)_S = (1 - f_{bs})\,I_{bT} + F_{sky}\,I_{dT} + r_g F_{gnd}I + r_g\,[(1 - f'_{bs})F'_{gnd}I'_{bT} + F_{g-s}F'_{gnd}I'_{dT}]$$

Eq. 5.9-38

The first term in Eq. 5.9-38 is the shaded incident beam radiation. I_{bT} is the incident beam radiation on an unshaded surface, while f_{bs} is the fraction of the collector array area that is shaded from direct beam radiation. The second and third terms in the above equation are the diffuse radiation that strikes the collector surface originating from the sky and the ground in front of the array. I_{dT} and I are the diffuse and total radiation on a horizontal surface. F_{sky} and F_{gnd} are the view factors from the collector to the sky and ground considering the obstructed view due to adjacent rows of collectors. The ground reflectance is ρ_g. The final term in Eq. 5.9-1 is the incident diffuse radiation resulting from beam and diffuse radiation striking the area between rows of collectors. I'_{bT} and I'_{dT} are the beam and diffuse radiation incident upon the sloped ground on which the array is located. F'_{bs} is the fraction of the area between rows that is shaded from beam radiation. F_{g-s} is the view factor from the ground between rows to the sky and F'_{gnd} is the view factor from the collector array to the ground between rows.
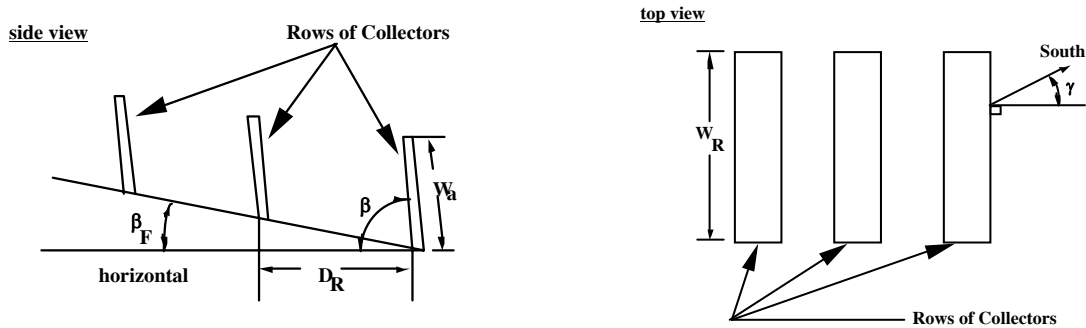
Figure 5.9.2–1: Flat Plate Collectors

MODE 2

Mode 2 determines the effect of shading on the incident beam radiation over surfaces that track about a single axis. For the case of parabolic collectors, where the main objective is to take advantage of the beam radiation, shading can be characterized by the fraction of the collector area that is blocked by a neighboring collector row in the direction of the sun. Figure 5.9.2–2 shows the geometrical parameters that are defined for two adjacent surfaces whose slope is set in order to track the position of the sun. In this figure, W_a is the width of the parabolic collector, D_a is the distance between axes, β is the slope of the collectors and β_{ap} is the slope of the plane that contains the collector axes. In order to maximize beam radiation, it is necessary that the sun be in a plane that is perpendicular to the collector aperture and that contain the receiver axes. For a

single row of collectors, the fraction of the aperture area shaded by an adjacent row of collectors neglecting edge effects, is given by

$$f_{bs,1} = \max\big((1 - P/W_a), 0\big),$$

Eq. 5.9-39

where P is the distance between the collector axes on a projection that is normal to a line from a collecto axis to the sun. If θ_p is the angle between a plane containing the sun and an axis and a plane that is perpendicular to the plane which contains the collector axes, P is found from

$$P = D_a \cos(\theta_p).$$

Eq. 5.9-40

From geometry, it is possible to derive the following expression to calculate the angle θ_p:

$$\theta_p = \beta - \beta_{ap}.$$
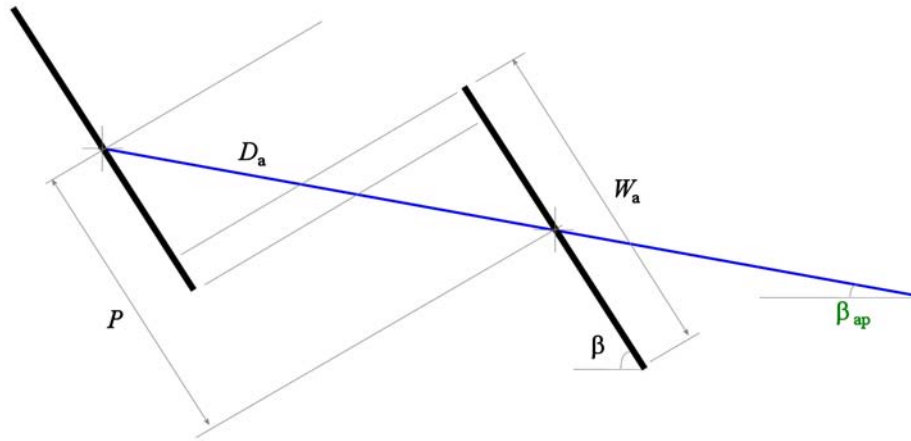
Eq. 5.9-41

Figure 5.9.2–2: Shading of incident beam radiation.

The overall fraction of array area that is shaded at any point in time is given in terms of the shaded fraction for a single row of collectors and the number of rows, N_R, as

$$f_{bs} = \frac{(N_R - 1)}{N_R} f_{bs,1}$$

Eq. 5.9-42

The incident beam radiation is then

$$I_{bT,s} = (1 - f_{bs}) I_{bT}.$$

Eq. 5.9-43

where I_{bT} is the incident beam radiation on an unshaded surface.

This geometry may be applied to two different arrangements of collector rows, as shown in Figure 5.9.2–3. The plane created by the collector axes may be characterized by its slope, β_{cf}, and azimuth angles, γ_{cf}. In Figure 5.9.2–3-a, the collector axes are inclined with an angle equal to the slope of the axes plane; therefore, in Eq. 5.9-41,

$$\beta_{ap} = \beta_{cf} \; .$$

<div align="right">**Eq. 5.9-44**</div>

When the collectors axes run horizontally, as shown in Figure 5.9.2–3-b, the angle $\beta_{ap} = 0$.
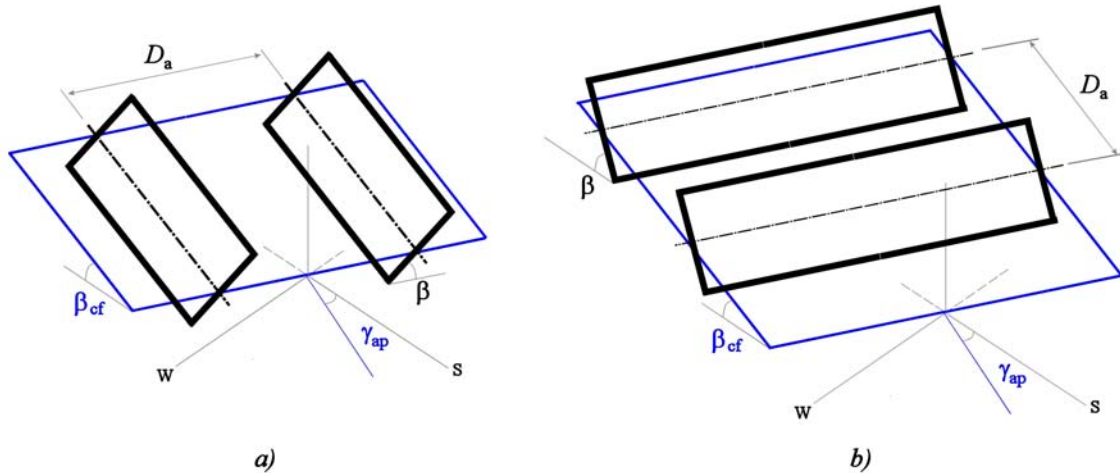
Figure 5.9.2–3: Geometrical definitions for collector arrays. a) Collector axes oriented N-S.   b) Collector axes oriented E-W-

In order to use this component, the unshaded radiation on the tracking surface must be calculated with a radiation processor that has the corresponding azimuth and tracking mode. If Type 16 is used as radiation processor, the tracking mode must be set to 3 (tracking about a single axis parallel to the collector surface). In this case, the input to Type16 labeled as 'Slope of the surface' corresponds to the axis slope (β_{ap}). For the case shown in Figure 5.9.2–3-a, the surface azimuth angle varies as the surfaces tracks the sun, but in Figure 5.9.2–3-b, the surface azimuth angle is the azimuth angle of the axes plane, γ_{ap}.

5.9.3   Type 33: Psychrometrics

This component is merely a wrapper for a call to the TRNSYS Psychrometrics utility subroutine. It takes as Input: 1) dry bulb temperature and one other property, depending on the mode: wet bulb temperature, relative humidity, dew point temperature, humidity ratio, or enthalpy; or 2) humidity ratio and enthalpy. It calls the Psychrometrics subroutine (see Manual 08:Programmer's Guide for additional information) to calculate humidity ratio, wet bulb temperature, enthalpy, density of the air-water mixture, density of dry air only, relative humidity (as percentage), dry bulb temperature and dew point temperature.

The model's first parameter determines the which two properties will be provided as Inputs to the model.

The second parameter determines whether the wet bulb temperature should or should not be calculated. The calculation of wet bulb temperature requires an iterative process that can be quite time consuming. If the wet bulb temperature is not needed, the second parameter should be set to 0. Please note also that in TRNSYS 15.x and below, the second parameter was the atmospheric pressure, not the wet bulb calculation mode. With the release of TRNSYS 16, atmospheric pressure was made a time dependent Input to the model.

The third parameter to Type 33 is the "error mode." If set to 1, only one warning per error condition will be reported. If set to 2, a warning will be printed at each iteration that an error condition occurs. The error conditions range from 1 to 14 and are listed below for reference.

Table 5.9.3–1: Type33 Error Codes

Error Code	Error Description
1	A total pressure greater than 5 atmospheres. Beware that the ideal gas relations used in the psychrometrics are not accurate at higher pressures.
2	An enthalpy less than possible for the given humidity ratio. The air was assumed to be saturated at the given humidity ratio and the enthalpy set for this condition
3	A humidity ratio less than 0.0. Dry air was assumed and the humidity ratio set to 0.0
4	A wet bulb temperature greater than the dry bulb temperature. Saturated air was assumed and the wet bulb temperature set to the dry bulb temperature.
5	A dew point temperature greater than the dry bulb temperature. The dew point was set equal to the dry bulb temperature.
6	A wet bulb temperature below that for dry air at the given dry bulb temperature. Dry air was assumed and a new wet bulb temperature found.
7	A relative humidity less than 0. The relative humidity was set to 0.0.
8	A relative humidity greater then 1.0. The relative humidity was set to 1.0.

9	A humidity ratio above the saturation humidity ratio for the given dry bulb temperature. The air was assumed saturated at the given dry bulb temperature and the humidity ratio set for this condition.
10	An enthalpy greater then that for saturated air at the given dry bulb temperature. The air was assumed saturated and the enthalpy set for this condition.
11	An enthalpy less then that for dry air at the given dry bulb temperature. Dry air was assumed and the enthalpy set for this condition.
12	Conditions outside the intended range of the water vapor saturation pressure correlation. The correlation, from the 1985 ASHRAE Fundamentals Handbook, is for temperature range of -100 C.
13	Conditions outside the intended range of the dew point temperature correlation. Then correlation from the 1981 ASHRAE Fundamentals Handbook is for the temperature range of -60 c to 70 C.
14	A humidity ratio less than possible for the given enthalpy. The air was assumed to be saturated at the given enthalpy and the humidity ratio set for this condition.

5.9.4 Type 54: Hourly Weather Data Generator

This component generates hourly weather data given the monthly average values of solar radiation, dry bulb temperature, humidity ratio, and wind speed (optional). The data are generated in a manner such that their associated statistics are approximately equal to the long-term statistics at the specified location. The purpose of this method is to generate a single year of typical data, similar to a Typical Meteorological Year. The model is based on algorithms developed by Knight et al. [1,2], Graham et al. [3,4], Degelman [5,6], and Gansler [10-12]. This component allows TRNSYS to be used for any location for which standard yearly average weather statistics are known. However, many of the correlations used in the model were developed from primarily temperate climate data. For other climates, e.g., tropical climates, the generated data are less accurate and the user may wish to make some modifications. For a more detailed discussion, see reference 1.

5.9.4.1 Nomenclature

k_t hourly clearness index (total radiation over extraterrestrial global radiation for an hour)

K_t daily clearness index (total radiation over extraterrestrial global radiation for a day)

$\overline{K_t}$ monthly clearness index (total radiation over extraterrestrial global radiation for a month) (or Kt(bar))

5.9.4.2 Mathematical Description

DATA BASE

The Type 54 component requires an external data file containing the monthly average radiation, humidity, and temperature. This data file, as described in Table 5.9.4–1, can contain data for many different locations.

The user can develop his or her own data file or use the example weather data file called "Type54-WeatherGenerator.dat", located in "%TRNSYS16%\Examples\Data Files". Additionally, the user can add data for specific locations to the end of that file. The file contains monthly average weather data for 329 locations. The data are taken from the publication Input Data for Solar Systems, by Cinquemani, Owenby, and Baldwin, published by the U.S. National Oceanic and Atmospheric Administration, Asheville, NC. Data for 96 Canadian locations is also included.

Table 5.9.4–1: Weather Data File Format

line 1: NLOC
line 2: LOCATION 1   LATITUDE
line 3: I1 I2 I3 . . . I12
line 4: w1*10000 w2*10000 w3*10000 . . . w12*10000
line 5: TEMP1 TEMP2 TEMP3 . . . TEMP12
line 6: LOCATION 2   LATITUDE
line 7: I1 I2 I3 . . . I12
ETC.

where:

NLOC   the number of locations in the data base

LOCATION   is the name of the location, maximum of 32 characters

LATITUDE   between -90.0° and 90.0° , number must start in column 33

I1-I12   Monthly average daily global horizontal solar radiation (kJ/m^2)

w1-w12   Monthly average humidity ratio times 10,000 (kg water/kg air)

TEMP1-TEMP12 is the monthly average temperature (°C)

From one to as many locations as desired can be entered into the data file. If locations are added to the end of wdata.dat; the first line, which contains NLOC, must be changed.

Additionally, the National Renewable Energy Lab has created a new set of monthly average weather data for the same 239 US sites listed in wdata.dat. The National Renewable Energy Laboratory (NREL) is in the process of creating new TMY data. The new TMY data is yet to be released however they have already released new monthly average data in the National Solar Radiation Data Base (NSRDB). This data was first included with TRNSYS 14.1 in a file called NREL.DAT. These data should be more accurate and more current than the data in wdata.dat. It is based on 30 years during the period 1961 through 1990. We suggest that you use the new data from NREL.DAT.

ALGORITHMS

The following is a brief description of the weather data generation model; a more detailed description can be found in Knight et al. [1,2].

Radiation is often described in a dimensionless form called the clearness index, which is simply the ratio of the total radiation on a horizontal surface to the extraterrestrial global solar radiation on a horizontal surface at the same time. The instantaneous values can be integrated over any time period; commonly used quantities are hourly (k_t)), daily (K_t)), and monthly ($K_{t(bar)}$) clearness indices.

K_t values for each day of the month are calculated in TYPE 54 from the daily clearness index cumulative distribution function. A correlation is used to approximate the distribution as a function of $K_{t(bar)}$. To determine the order in which the days should occur, a "sequence" is used. Specifically, the integers 1 to 31 are assigned to the 31 K_t values obtained from the distribution, with 1 corresponding to the smallest K_t value and 31 to the largest. The "sequence" consists of the integers 1 to 31, ordered such that when the K_t values corresponding to the integers are placed in that order, the approximate lag one daily K_t autocorrelation is reproduced. A similar process is used for the other weather variables, and likewise, there are "sequences" for the other variables [5,6].

The long-term mean k_t value for each hour (k_{tm}) is estimated from a correlation. The deviations from this long-term average value are generated from a first order autoregressive model (which introduces some randomness); the autoregressive model parameter is a function of K_t [1, 2, 3, 4]. Diffuse radiation values are computed from the diffuse fraction correlation of Erbs et al. [7].

When the hourly radiation values are summed, the daily total of the generated radiation is not necessarily equal to the original 'target' daily radiation value. Over a month, these discrepancies tend to average out; as an alternative, TYPE 54 can scale the hourly values (by multiplying them by the ratio of the 'target' K_t value to the generated Kt value) such that the 'target' K_t values are matched exactly. The effect of this correction on the diurnal variation is insignificant, however, the hourly lag one autocorrelation <u>is</u> affected. For systems sensitive to the hourly autocorrelation of radiation, no correction to the radiation values should be made, i.e., PAR. 5 = 2. For systems in which the daily autocorrelation has more of an effect (most systems), the radiation correction should be made, i.e., PAR. 5 = 1.

There are two models for dry bulb temperature; the first is a stochastic model (PAR. 4 = 1) in which the hourly values are determined from a second order autoregressive model (some randomness is introduced); the second is a deterministic hourly model (PAR. 4 = 2).

In the stochastic hourly temperature model (PAR. 4 = 1), 24 hourly monthly-average dry bulb temperature values are computed, and the hourly deviations from these average values are then calculated with a second order autoregressive (AR2) model. The coefficients in the AR2 model have constant values determined from data for Albuquerque, NM, Madison, WI, and Miami, FL. To ensure the correct monthly-average dry bulb temperature value, the entire month's hourly values are generated on the first hour of the month. A monthly-average value is computed from the hourly values and compared to the Input monthly-average value; the hourly values are then adjusted by adding the difference to each hourly temperature [1,2].

The deterministic hourly dry bulb temperature model (PAR. 4 = 2) is similar to the radiation model. Daily average values and daily maximum values are obtained from normal distributions where the means and standard deviations are either Input or estimated from correlations [8]; the daily average and daily maximum dry bulb temperatures are then each ordered with a "sequence". The daily average temperature value is assumed to be both the mean and the median value; the time at which the minimum and maximum temperatures occur are taken to be sunrise and 3 p.m., respectively. Hourly values are calculated by a cosine interpolation between the daily minimums and maximums [5, 6].

The stochastic model (PAR. 4 = 1) better represents the hourly autocorrelation structure of the dry bulb temperatures, however, it does not always generate temperature data with the correct daily autocorrelation and daily distribution. The deterministic model (PAR. 4 = 2) consistently reproduces the daily structure but neglects the variation and autocorrelation of the hourly sequence. Studies by Hollands et al. [9] indicate that for some systems, the error in solar fraction when neglecting the random component of the hourly temperatures is very small (on the order of 1%). The user should decide whether the hourly or daily structure would have a greater effect upon the simulation and select the appropriate model; often the deterministic model (PAR. 4 = 2) will be more appropriate.

The relative humidity model is actually a dewpoint temperature model. The Input humidity ratios are converted to monthly-average dewpoint temperatures. Daily-average dewpoint temperatures are obtained from a normal distribution (with the mean equal to the monthly-average dewpoint temperature and the standard deviation equal to the standard deviation of the daily maximum dry bulb temperature) and ordered according to a "sequence". An algorithm is used to determine the dewpoint depressions at the hours corresponding to the maximum and minimum dry bulb temperature each day. Hourly dewpoint depressions are computed by linearly interpolating between the dewpoint depressions at the minimum and maximum dry bulb temperatures. Dewpoint temperatures and relative humidities are calculated from the dewpoint depressions [8, 5, 6].

The monthly-average windspeed is assumed equal to 9 mph (4 m/s) unless other values are Input by the user. Daily values are computed from a normal distribution with the mean equal to the monthly-average value and the standard deviation equal to 0.31 times the mean; the daily values are then ordered by a "sequence". Hourly values are randomly selected from a normal distribution with the mean equal to the daily-average value and the standard deviation equal to 0.35 times the mean [5, 6].

Cross-correlations are not directly reproduced by TYPE 54; this is perhaps the most serious shortcoming, and further research in this area is necessary. For comparison of the generated data with 22 years of recorded data and Typical Meteorological Year data, see Knight et al. [1, 2].

Some features of Type 54 are listed here below:

- Users may start the simulation at any hour of the year.

- The weather variables for a specified day remain unchanged as the simulation start time is changed.

- New algorithms eliminate zero radiation hours during the day and provide better match of long term clearness indices.

With the release of TRNSYS 16, other features were added to Type54 in order to increase its flexibility, especially when used in a TRNSED simulation.

- Location latitude may now be entered as a PARAMETER to the model (following the TRNSYS 15 PARAMETERS). If provided, this value supercedes that read from the data file.

- Monthly average values of integrated daily solar radiation values, monthly average humidity ratios, and monthly average dry bulb temperatures may be entered as PARAMETERS to the model.

5.9.4.3   References

1. Knight, K.M., Klein, S.A., and Duffie, J.A., "A Methodology for the Synthesis of Hourly Weather Data," to be published in Solar Energy, (1991).

2. Knight , K.M., "Development and Validation of a Weather Data Generation Model," M.S. Thesis, 1988, University of Wisconsin - Madison, Solar Energy Laboratory.

3. Graham, V.A., "Stochastic Synthesis of the Solar Atmospheric Transmittance," Ph.D. Thesis in Mechanical Engineering, University of Waterloo (1985).

4. Graham, V.A., Hollands, K.G.T., and Unny, T.E., "Stochastic Variation of Hourly Solar Radiation Over the Day," Advances in Solar Energy Technology, Vol. 4, ISES Proceedings, Hamburg, Germany, September 13-18, (1987).

5. Degelman , L.O., "A Weather Simulation Model for Building Energy Analysis," ASHRAE Transactions, Symposium on Weather Data, Seattle, WA, Annual Meeting, June 1976, pp. 435-447.

6. Degelman, L.O., "Monte Carlo Simulation of Solar Radiation and Dry Bulb Temperatures for Air Conditioning Purposes," Report No. 70-9, sponsored by the National Science Foundation under Grant No. GK-2204, Department of Architectural Engineering, The Pennsylvania State University, September, (1970).

7. Erbs, D.G., Klein, S.A., and Duffie, J.A., "Estimation of the Diffuse Radiation Fraction of Hourly, Daily, and Monthly-Average Global Radiation," Solar Energy, Vol. 28, pp. 293-302, (1982).

8. Erbs, D.G., "Models and Applications for Weather Statistics Related to Building Heating and Cooling Loads," Ph.D. Thesis, University of Wisconsin-Madison, (1984).

9. Hollands, K.G.T., D'Andrea, L.T., and Morrison, I.D., "Effect of Random Fluctuations in Ambient Air Temperature on Solar System Performance," Solar Energy, Vol. 42, pp. 335-338, (1989).

10. Gansler, R.A., "Assessment of Generated Meterological Data for Use in Solar Energy Simulations", M.S. Thesis, 1993, University of Wisconsin - Madison, Solar Energy Laboratory

11. Gansler, R.A., Klein S.A., "Assessment of the Accuracy of Generated Meteorological Data for Use in Solar Energy Simulation Studies", Proceedings of the 1993 ASME International Solar Energy Conference, April 1993, Washington D.C., pp. 59-66

12. Gansler, R.A., Klein S. A., Beckman W. A., " Investigation of Minute Solar Radiation Data", Proceedings of the 1994 Annual Conference of the American Solar Energy Society, June 1994, San Jose CA, pp. 344-348

5.9.5   Type 58: Refrigerant Properties

This component takes as Input two unique independent state properties of a refrigerant and calculates the remaining state properties. It calls the FLUID_PROPS subroutine and the STEAM_PROPS subroutine (see Volume 08: Programmer's Guide) to calculate the thermodynamic properties.

The available refrigerants for this routine are: R-11, R-12, R-13, R-14, R-22, R-114A, R-134A, R-500, R-502, ammonia (R-717) and steam (R-718).

5.9.5.1   Special Considerations

1. The required number of PARAMETERS is equal to the number of INPUTS supplied multiplied by three.

2. The number of OUTPUTS is equal to seven times the number of INPUTS.

3. A maximum of 10 states per unit can be calculated by TYPE 58.

4. Be careful when specifying state properties of saturated refrigerants temperature and pressure are not independent properties in the saturated region.

5. Subcooled properties are not calculated by the TYPE 58 routine. If subcooled propertied are supplied, saturated liquid values will be computed and returned by the TYPE 58 routine.

6. The reference state for ammonia and R134A is: enthalpy = 0 kJ/kg at -40°C.

7. Reference states for all other fluids is: enthalpy = 0 kJ/kg at 0°C.

5.9.6   Type 59: Lumped capacitance model

Type 59 represents the dynamic thermal behavior of a body using the lumped capacitance model.

5.9.6.1   Mathematical description

Type 59 solves the ordinary differential equation that represents the thermal behaviour of a body whose temperature is assumed to be uniform, given by

$$\rho C \forall \frac{dT}{dt} = \dot{E}_{in} - hA\left(T - T_{\infty}\right)$$

<div align="right">Eq. 5.9-45</div>

where ρ is the density of the body with volume $\forall$, area A and specific heat C. The energy balance represented this equation takes into account an energy input and convective heat transfer to the surroundings, at a temperature T_{∞} with a heat transfer coefficient h. The energy input may be used to represent radiation on the surface or thermal energy generation within the body.

The solution of the differential equation uses the routine DIFFERENTIAL_EQN.

5.9.6.2   References

1. Incropera, F.P., and DeWitt, D.P., "*Fundamentals of Heat and Mass Transfer*". John Wiley and Sons, 5th ed., 2002.

5.9.7 Type63: Thermodynamic properties of substances with NASA CEA2

Type 63 calculates the thermodynamic properties of different substances, using the subroutines defined by the program NASA CEA2. For more information on the program CEA2, please go to http://www.grc.nasa.gov/WWW/CEAWeb/

"The NASA Computer program CEA (Chemical Equilibrium with Applications) calculates chemical equilibrium compositions and properties of complex mixtures. Applications include assigned thermodynamic states, theoretical rocket performance, Chapman-Jouguet detonations, and shock-tube parameters for incident and reflected shocks." [1] The subroutines that calculate the thermodynamic properties of substances are used by Type63.

The program NASA CEA2 allows for creating sets of different substances to be included in the calculation of their thermodynamic properties. The thermodynamic properties are stored in a binary data file. Type 63 requires this data file and the name of the substance. The list of substances that are available can be found on the appendix B of reference [2].

5.9.7.1 References

1. NASA. Chemical Equilibrium. http://www.grc.nasa.gov/WWW/CEAWeb/ Last accessed on December 20, 2006.

2. McBride, B.J., and Gordon, S. "*Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II. User's Manual and Program Description.*" NASA R.P.1311, 1993. (http://www.grc.nasa.gov/WWW/CEAWeb/RP-1311P2.htm). Last accessed on December 20, 2006.

5.9.8   Type 64: Shading By External Object with Single Shading Mask

Type 64 is a special case of Type67, where all of the defined orientations use the same information of angular heights of obstructions. It reads a data file containing the angular heights of obstructions seen from a location and outputs numbers that describe the time dependent shading for all defined orientations. Please refer to to Section 5.9.9 for a complete mathematical description of this component.

5.9.8.1   External Data File

Type64 reads the information of the angular heights (θ) of obstructions stored in a data file, and uses it for calculating the shading on all of the defined orientations. This is the fundamental difference with Type67, which requires individual angular heights for each of the orientations. Therefore, the data file for Type64 does not contain information about the orientation of the openings.

The Type makes use of a call to the TRNSYS Data Reading subroutine and therefore there are certain restrictions placed on the Type. The maximum number of characters on a single line that can be read by TRNSYS in either the Input file or an external file is set in the TrnsysConstants.f90 file located in the TRNSYS Source Code Kernel directory. The default line length is 1000 characters. Modification of this value necessitates that the TRNDll.dll file be recompiled and relinked.

A few notes on file format may help avoid problems:

- The surface angles for which angular obstruction heights (θ) are provided correspond to absolute azimuths.

- Surface angles in the data file MUST cover the entire range of possible surface angles. In other words, the first surface angle should always be –180. Surface angles must also have an equal step size between them; it is not possible to add more precision to part of the surface angle range.

The file format should be as follows:

```
Alpha1 Alpha2 alpha3 … AlphaN    (equally spaced, must cover whole range)
θ for OPEN_ID1 at α = Alpha1     (Alpha 1 is ALWAYS -180)
θ for OPEN_ID1 at α = Alpha2
…
θ for OPEN_ID1 at α = AlphaN     (AlphaN is ALWAYS 180-step where step is the
θ for OPEN_ID2 at α = Alpha1      increment used between Alpha values)
θ for OPEN_ID2 at α = Alpha2
…
θ for OPEN_ID2 at α = AlphaN
…
θ for OPEN_IDn at α = Alpha1
θ for OPEN_IDn at α = Alpha2
…
θ for OPEN_IDn at α = AlphaN
```

EXAMPLE

See the files in Examples\Data Files\Type64*.* for a data file example.

```
-180.0 -157.5 -135.0 … -22.5 0.0 22.5 … 112.5 135.0 157.5 ! View angles - ALWAYS (-180:step:180-step)
10.000    ! Obstruction height for opening 1, view angle  1 (i.e. between -180   and -157.5)
30.000    ! Obstruction height for opening 1, view angle  2 (i.e. between -157.5 and -135  )
20.000    ! Obstruction height for opening 1, view angle  3 (i.e. between -135   and -112.5)
…
50.000    ! Obstruction height for opening 1, view angle 15 (i.e. between  135   and  157.5)
10.000    ! Obstruction height for opening 1, view angle 16 (i.e. between  157.5 and  180  )
10.000    ! Obstruction height for opening 2, view angle  1 (i.e. between -180   and -157.5)
60.000    ! Obstruction height for opening 2, view angle  2 (i.e. between -157.5 and -135  )
…
30.000    ! Obstruction height for opening 2, view angle 15 (i.e. between  135   and  157.5)
20.000    ! Obstruction height for opening 2, view angle 16 (i.e. between  157.5 and  180  )
```

5.9.9   Type 67: Shading By External Object

Type67 reads a data file containing the angular heights of obstructions seen from an arbitrary opening and outputs numbers that describe the time dependent shading of the opening.

Among the outputs is a 0 or a 1 corresponding to whether beam radiation is blocked or visible and a number between 0 and 1 which gives the fraction of diffuse radiation visible from the opening. A 0 indicates that no diffuse radiation is visible and a 1 indicates that all the diffuse radiation normally visible by the window is indeed visible.

The beam radiation calculation is made simply by deciding whether the sun is obstructed by an object at any given time. The diffuse fraction calculation is made by integrating the shading effects seen by the window and dividing by the view from the opening were there no shading objects present. With these dimensionless numbers, the radiation normally incident on the opening can be adjusted to account for shading.

Type67 also takes unshaded radiation values and internally multiplies these values by the calculated shading factors, outputting not only the shading factors described above but also the shaded radiation values.

For each opening, Type67 calculates the shaded beam and diffuse radiation on a horizontal surface affected by the corresponding shading. Having these values on a horizontal surface makes it easier to calculate the shading effect of external objects (Type67) and wingwalls and overhangs (Type34).

5.9.9.1   Nomenclature

Underlined letters indicate a vector. Vectors appearing in equations have an arrow over their letter representation.

α	-	Surface angle measured in TRNSYS coordinates (for the northern hemisphere South = 0, East = -90, West = 90, North = ±180)
β	-	the slope of the plane containing an opening
θ	-	The angular height of an obstruction
$\underline{i}, \underline{j}, \underline{k}$	-	Unit normal vectors in x, y and z respectively
S	-	The plane of an opening
$\underline{n}$S	-	The unit normal vector for S
$\underline{v}$	-	A vector representation of a surface angle
$\underline{p}$	-	The projection of a surface angle vector in the plane S
σ	-	The angle between $\underline{n}$S and $\underline{p}$
h1	-	The height of a spherical zone
h2	-	The height of a spherical cap

S1   -   The surface area of a segment of the spherical zone defined by the plane of
                          the diameter, a height h1 and an angle α

S2   -   The surface area of a segment of the spherical cap defined by a height h2
                          and an angle α

5.9.9.2   Mathematical Description

For any given opening (described by a slope and an azimuth) it is necessary to calculate two numbers. The first is a 0 or a 1 corresponding to whether beam radiation is blocked or visible. The second is a number between 0 and 1 which gives the fraction of diffuse radiation visible from the opening. A 0 indicates that no diffuse radiation is visible and a 1 indicates that all the diffuse radiation normally visible by the window is indeed visible. The fraction is fairly easy to calculate for a vertical or horizontal openings but becomes quite difficult if sloped openings are allowed. A vertical opening has a viewing angle of 180 degrees and a horizontal opening has a view angle of 360 degrees. It is less evident what the viewing angle for an arbitrarily sloped opening is. Consequently, it was decided that all openings would be defined as having a 360 degree view angle and that the plane containing the opening would be considered an obstruction shading the opening.

Obstructions are defined by an angular height as viewed from the opening. Surface angles (α) are defined in an absolute co-ordinate system (as opposed to relative to the opening) and for each one, an angular obstruction height θ is required Figure 5.9.9–1.
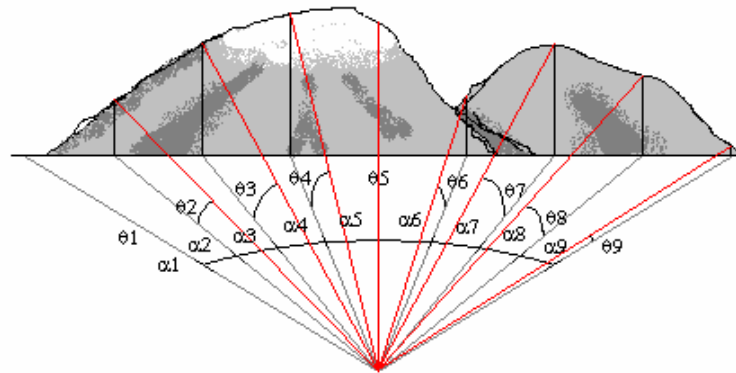
Figure 5.9.9–1: Definition of surface angles (α) and obstruction height angles (θ)

For the case of a vertical opening, the plane containing the opening forms θ angles of 90° for all a angles departing to the rear of the window. In the case of a sloped plane, the θ angles departing toward the rear of the opening are not always 90° but follow a the function described by Eq. 5.9-57. The angle departing directly behind the window forms an angle equal to the slope of the opening (Figure 5.9.9–2)
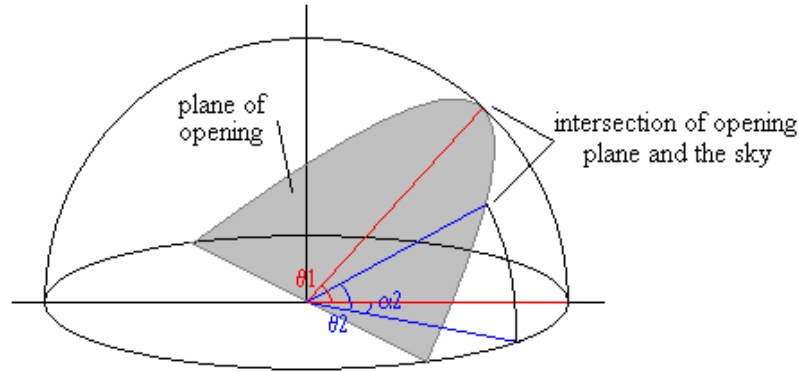
Figure 5.9.9–2: Apparent Obstruction Angles Created by the Plane of a Sloped Opening

CALCULATION OF VISIBLE DIFFUSE RADIATION FRACTION

The overall goal of this calculation is to come up with the fraction of diffuse radiation normally visible from the opening that is still visible, given the effects of shading objects. The numerator of the fraction is the amount of sky visible with shading objects. It is found using a call to the TRNSYS Data Reading subroutine. For each opening identification number and for each direction (α), an angular obstruction height (β) is provided. The format of the data file and an example can be found at the end of the mathematical description.

The denominator of the fraction is the amount of sky normally visible from the opening. A horizontal opening sees the entire sky. A vertical opening sees half the sky, and a tilted opening sees some fraction in between. Instead of trying to calculate how much of the sky is visible, a series of apparent obstruction angles representing the plane of the opening are computed.

For a wall tilted at an angle β, find an expression for the angle between wall and ground for a given surface angle α.

For simplicity sake, we will pretend for now that the plane of the wall faces due south. It can therefore be described by the equation $0X + \tan \beta\ Y + Z = 1$. We will call the plane, as shown in Figure 5.9.9–3, S.
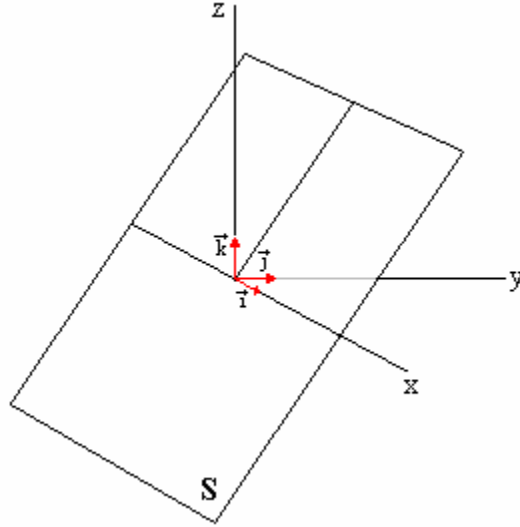
Figure 5.9.9–3: Coordinate System for the Plane Containing an Opening

The normal vector for plane S has the direction nS{0,tanβ,1}

The length of the normal vector is given by the determinant of the vector nS as:

$$\left| \vec{n}S \right| = \sqrt{0^2 + \left(\tan \beta \right)^2 + 1^2} = \sqrt{1 + \left(\tan \beta \right)^2}$$

<div align="right">Eq. 5.9-46</div>

The unit normal vector to S is thus:

$$\vec{n}S = \frac{1}{\sqrt{1 + \left(\tan \beta \right)^2}} \left(\tan \beta \vec{j} + \vec{k} \right)$$

<div align="right">Eq. 5.9-47</div>

A vector v representing each surface angle α is projected onto plane S by the following formula in which p is the resulting vector in S and in which k is a constant.

$$\vec{p} = \vec{v} - k\vec{n}S$$

<div align="right">Eq. 5.9-48</div>

To find k, we dot both sides of the equation with nS. Since p and nS are perpendicular, their dot product is 0. nS dotted with itself is unity. Consequently, the formula for k is:

$$k = \vec{v} \bullet \vec{n}S$$

<div align="right">Eq. 5.9-49</div>

The vector v exists in the plane of the horizontal so it only has x and y components. The formula for v comes directly from the definition of the tangent in a right triangle

$$\vec{v} = \left(\tan \alpha \vec{i} + \vec{j} \right)$$

<div align="right">Eq. 5.9-50</div>

solving for k gives:

$$k = (\tan \alpha)(0) + (1)\left(\frac{\tan \beta}{\sqrt{1 + (\tan \beta)^2}} \right) + (0)(1) = \frac{\tan \beta}{\sqrt{1 + (\tan \beta)^2}}$$

Eq. 5.9-51

Now we can write and simplify a vector for p

$$\vec{p} = (\tan \alpha \vec{i} + \vec{j}) - \left(\frac{\tan \beta}{\sqrt{1 + (\tan \beta)^2}} \right)\left(\frac{1}{\sqrt{1 + (\tan \beta)^2}} \right)(\tan \beta \vec{j} + \vec{k})$$

Eq. 5.9-52

$$\vec{p} = (\tan \alpha \vec{i} + \vec{j}) - \left(\frac{\tan \beta}{1 + (\tan \beta)^2} \right)(\tan \beta \vec{j} + \vec{k})$$

Eq. 5.9-53

$$\vec{p} = \tan \alpha \vec{i} + \left(1 - \frac{(\tan \beta)^2}{1 + (\tan \beta)^2} \right)\vec{j} + \frac{\tan \beta}{1 + (\tan \beta)^2} \vec{k}$$

Eq. 5.9-54

The next step is to find the angle that the projection vector p makes with the plane of the horizontal. The angle is found by taking the dot product of p and the unit normal of the horizontal plane.

The unit normal vector to the horizontal is {0,0,1}

$$\vec{n}H \bullet \vec{p} = |\vec{n}H||\vec{p}|\cos \sigma$$

Eq. 5.9-55

expanding gives:

$$\{0,0,1\} \bullet \left\{ \tan \alpha, 1 - \frac{(\tan \beta)^2}{1 + (\tan \beta)^2}, \frac{\tan \beta}{1 + (\tan \beta)^2} \right\}$$

$$= \sqrt{0^2 + 0^2 + 1^2} \sqrt{(\tan \alpha)^2 + \left(1 - \frac{(\tan \beta)^2}{1 + (\tan \beta)^2} \right)^2 + \left(\frac{\tan \beta}{1 + (\tan \beta)^2} \right)^2} \cos \sigma$$

Eq. 5.9-56

which can be simplified to

$$\frac{\tan \beta}{1 + (\tan \beta)^2} = \sqrt{(\tan \alpha)^2 + \left(1 - \frac{(\tan \beta)^2}{1 + (\tan \beta)^2} \right)^2 + \left(\frac{\tan \beta}{1 + (\tan \beta)^2} \right)^2} \cos \sigma$$

Eq. 5.9-57

Eq. 5.9-57 can be solved for the angle between the projection of a surface angle α in S and a vertical line (the normal to the horizontal plane). The angle σ is subtracted from 90 to arrive at the angle that the projection makes with the horizontal plane. The result is called θ. At this stage, we

have a set of apparent obstruction height angles for the plane of the opening. This set is compared with the data provided in the file for each surface angle α.

There is of course one more complication. Simply comparing two obstruction heights and dividing them to find the fraction of sky that remains visible for that surface angle does not take into account the fact that each surface angle in reality represents a wedge of sky; an obstruction angle height of $\theta = 45°$ does not mean that for the given α, half the sky is visible. Instead, we need to compare the two surface areas S1 and S2 as shown in Figure 5.9.9–4.
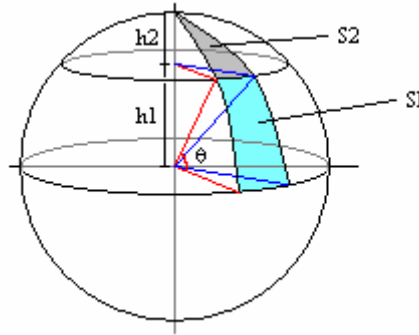
Figure 5.9.9–4: Segment Areas

The fraction of sky visible for a given a is

$$f = \frac{S2}{S2 + S1}$$

Eq. 5.9-58

Because we are working with a sphere, we can write that

$$h1 + h2 = r$$

Eq. 5.9-59

Furthermore, a right triangle is formed by the vertical axis of the sphere, a radius and the plane containing the base of the segment S2. Consequently, it can be written that

$$h1 = r\cos(2\pi - \theta)$$

Eq. 5.9-60

in which θ is in radians.

The areas S1 (a segment of a spherical zone) and S2 (a segment of a spherical cap) both have the same basic formula. γ is measured in radians.

$$S1 = \gamma r h1$$
$$S2 = \gamma r h2$$

Eq. 5.9-61

Using the results of equations Eq. 5.9-59, Eq. 5.9-60 and Eq. 5.9-61, Eq. 5.9-58 can be rewritten as

$$f = 1 - \cos(2\pi - \theta)$$

Eq. 5.9-62

θ is again in radians

Now that all the math is in place, two θ sums over the set of surface angles (α) are made and divided. The numerator contains the set θ angles from the data file as applied to equation Eq. 5.9-62. The denominator contains the set of θ angles found using Eq. 5.9-57 as applied to equation Eq. 5.9-62.

$$f = \frac{\sum\limits_{\alpha=-\pi}^{\pi} 1 - \cos(2\pi - \theta_{shaded})_\alpha}{\sum\limits_{\alpha=-\pi}^{\pi} 1 - \cos(2\pi - \theta_{unshaded})_\alpha}$$

Eq. 5.9-63

CALCULATION OF VISIBLE BEAM RADIATION

To detect whether the beam radiation is behind an obstruction, Type67 takes the sun's position (solar azimuth angle and solar altitude angle), and compares them to the information in the data file. If, for a given a, the solar altitude angle is less than the corresponding obstruction height angle, beam radiation is said to be blocked.

5.9.9.3   *External Data File*

Type67 centers around a data file that contains the angular heights (θ) of obstructions seen from an opening. The Type makes use of a call to the TRNSYS Data Reading subroutine and therefore there are certain restrictions placed on the Type; the entire list of opening ID numbers, the entire list of opening slopes, the entire list of opening azimuths, and the entire list of surface angles must each fit on its own line in the external data file.

The maximum number of characters on a single line that can be read by TRNSYS in either the Input file or an external file is set in the TrnsysConstants.f90 file located in the TRNSYS Source Code Kernel directory. The default line length is 1000 characters. Modification of this value necessitates that the TRNDll.dll file be recompiled and relinked.

A few notes on file format may help avoid problems:

- The surface angles for which angular obstruction heights (θ) are provided correspond to absolute azimuths; they are NOT specified relative to the azimuth of the opening.

- Surface angles in the data file MUST cover the entire range of possible surface angles. In other words, the first surface angle should always be –180. Surface angles must also have an equal step size between them; it is not possible to add more precision to part of the surface angle range.

- Opening ID numbers should be in increasing order.

The file format should be as follows:

```
OPEN_ID1 OPEN_ID2 … OPEN_Idn
SLP1  SLP2 … SLPn
AZ1  AZ2  … Azn
Alpha1 Alpha2 alpha3 … AlphaN   (equally spaced, must cover whole range)
θ for OPEN_ID1 at α = Alpha1    (Alpha 1 is ALWAYS -180)
θ for OPEN_ID1 at α = Alpha2
…
θ for OPEN_ID1 at α = AlphaN    (AlphaN is ALWAYS 180-step where step is the
θ for OPEN_ID2 at α = Alpha1     increment used between Alpha values)
θ for OPEN_ID2 at α = Alpha2
…
θ for OPEN_ID2 at α = AlphaN
…
θ for OPEN_IDn at α = Alpha1
θ for OPEN_IDn at α = Alpha2
…
θ for OPEN_IDn at α = AlphaN
```

EXAMPLE

See the files in Examples\Data Files\Type67*.* for full examples with more openings (or orientations).

In the example here below line 4 is shortened by replacing a few actual values with "…" In the real file all values need to be specified

```
   001    002    ! Opening (or "orientation") unique ID
   090    045    ! Opening slope
   0.0   -45.0   ! Opening azimuth (0 = facing Equator, East is negative)
-180.0 -157.5 -135.0 … -22.5 0.0 22.5 … 112.5 135.0 157.5 ! View angles - ALWAYS (-180:step:180-step)
10.000    ! Obstruction height for opening 1, view angle  1 (i.e. between -180   and -157.5)
30.000    ! Obstruction height for opening 1, view angle  2 (i.e. between -157.5 and -135  )
20.000    ! Obstruction height for opening 1, view angle  3 (i.e. between -135   and -112.5)
…
50.000    ! Obstruction height for opening 1, view angle 15 (i.e. between  135   and  157.5)
10.000    ! Obstruction height for opening 1, view angle 16 (i.e. between  157.5 and  180  )
10.000    ! Obstruction height for opening 2, view angle  1 (i.e. between -180   and -157.5)
60.000    ! Obstruction height for opening 2, view angle  2 (i.e. between -157.5 and -135  )
…
30.000    ! Obstruction height for opening 2, view angle 15 (i.e. between  135   and  157.5)
20.000    ! Obstruction height for opening 2, view angle 16 (i.e. between  157.5 and  180  )
```

5.9.10 Type 68: Shading By External Object

Until TRNSYS 16.1, Type68 was the component used for calculating shading by external objects. It was improved for easier interaction with shading from wingwalls and overhangs (Type34). Type68 was kept for backwards compatibility. Please refer to Section 5.9.9 for the mathematical description of this component.

5.9.11 Type 69: Effective Sky Temperature

This components determines a effective sky temperature. With this effective sky temperature, the long-wave radiation exchange from external surfaces of a building to the atmosphere can be calculated.

5.9.11.1 Nomenclature

C_{Cover}	[0..1]	cloudiness factor of the sky
E_{Dif}	[kJ/hr.m2]	diffuse radiation on the horizontal
E_{Dir}	[kJ/hr.m2]	beam radiation on the horizontal
$E_{Glob,h}$	[kJ/hr.m2]	total radiation on the horizontal
g	[m/s2]	gravitational acceleration
h	[m]	elevation above sea level
p_{atm}	[atm]	atmospheric pressure
p_0	[atm]	atmospheric pressure at the height ho
ρ_0	[kg/m3]	air density at the height ho
ε_0	[0..1]	emittance of the clear sky
T_{amb}	[°C]	ambient temperature
T_{sat}	[°C]	dew point temperature at ambient conditions
T_{sky}	[°C]	sky temperature

5.9.11.2 Mathematical Description

An effective sky temperature is used for calculating the long-wave radiation exchange from external surfaces to the atmosphere. For this calculation, the sky is assumed to be an ideal black surface. The actual emittance of the clear and the clouded sky must be known. Thus, the effective sky temperature is a function of the ambient temperature, air humidity, cloudiness factor of the sky, and the local air pressure

If the weather data do not include the cloudiness factor of the sky, the cloudiness factor can be determined according to the following equation [2]:

$$C_{Cover} = \left(1.4286 \, \frac{E_{Dif}}{E_{Glob,H}} - 0.3 \right)^{0.5}$$

Eq 5.9.11-1

For the night cloudiness factor, an averaged factor over the afternoon is used.

The atmospheric pressure is determined according the barometric height formula for the location in question:

$$p_{atm} = p_0 \, e^{\frac{g \rho_0 h}{p_0}}$$ **Eq 5.9.11-2**

The emittance of the clear sky can be derived by the T_{sat} corresponding the ambient conditions (temperature and air humidity) [1]:

$$\varepsilon_0 = 0.711 + 0.005\, T_{sat} + 7.3x10^{-5}\, T_{sat}^2 + 0.013 \cos\left[2\pi \frac{time}{24}\right] + 12x10^{-5}\left(p_{atm} - p_o\right)$$ **Eq 5.9.11-3**

where the variable *time* corresponds to the hour of the day.

The effective sky temperature can then be determined by [1]:

$$T_{sky} = T_{amb}\left(\varepsilon_0 + 0.8\left(1 - \varepsilon_0\right)C_{Cover}\right)^{0.25} \qquad [K]$$ **Eq 5.9.11-4**

5.9.11.3   References

[1] M. Martin, P. Berdahl, *Characteristics of Infrared Sky Radiation in the United States,* Lawrence Berkeley Laboratory, University of California - Berkeley, Solar Energy Vol. 33, No. 3/4, pp. 321-336, 1984.

[2] Kasten Czeplak, Solar Energy Vol. 24, S. 177 - 189, Pergamon Press Ltd.

5.9.12   Type 77: Simple Ground Temperature Profile

This subroutine models the vertical temperature distribution of the ground given the mean ground surface temperature for the year, the amplitude of the ground surface temperature for the year, the time difference between the beginning of the calendar year and the occurrence of the minimum surface temperature, and the thermal diffusivity of the soil. These values may be found in a variety of sources including the ASHRAE Handbooks (refer to soil temperature) [1].

5.9.12.1   Nomenclature

T	[ºC]	Temperature
T_{mean}	[ºC]	Mean surface temperature (average air temperature)
T_{amp}	[ºC]	Amplitude of surface temperature (maximum air temperature minus minimum air temperature)
Depth	[m]	Depth below surface
α	[m²/day]	Thermal diffusivity of the ground (soil)
t_{now}	[day]	Current day of the year
t_{shift}	[day	Day of the year corresponding to the minimum surface temperature
$T_{initial}$	[C]	initial temperature

5.9.12.2   Mathematical Description

Kasuda [2] found that the temperature of the undisturbed ground is a function of the time of year and the depth below the surface and could be described by the following correlation:

$$T = T_{mean} - T_{amp} * \exp\left[-depth * \left(\frac{\pi}{365\,\alpha}\right)^{0.5}\right] * \cos\left\{\frac{2\pi}{365} * \left[t_{now} - t_{shift} - \frac{depth}{2} * \left(\frac{365}{\pi\,\alpha}\right)^{0.5}\right]\right\} \qquad \textbf{Eq 5.9.12-1}$$

In absence of a measured value, T_{mean} (the mean surface temperature) may be taken as the average annual air temperature.

The Kasuda equation results in a distribution of temperature with respect to time for different values of soil depth and for a given climate as shown in Figure 5.9.12–1.
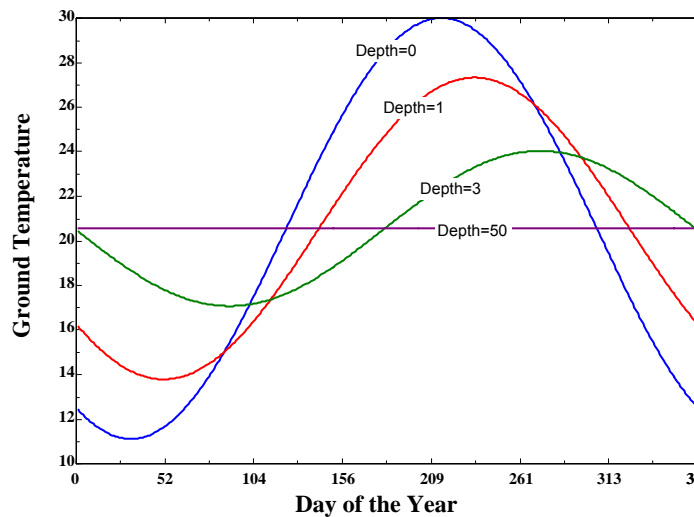
Figure 5.9.12–1: Temperature Profiles as a Function of Depth

The range of temperatures generated by this equation are shown in Figure 5.9.12–2. Line WI shows one extreme that the temperature profile assumes during the winter season. Line SU shows the other extreme that the temperature profile assumes during the summer. In between the summer and winter extremes, the ground temperature profile will lie between the two extremes. In the shoulder seasons (spring (SP) and fall (FA)), the surface is heated and cooled more quickly than the lower depths; resulting in the 'humped' distributions shown in Figure 5.9.12–2
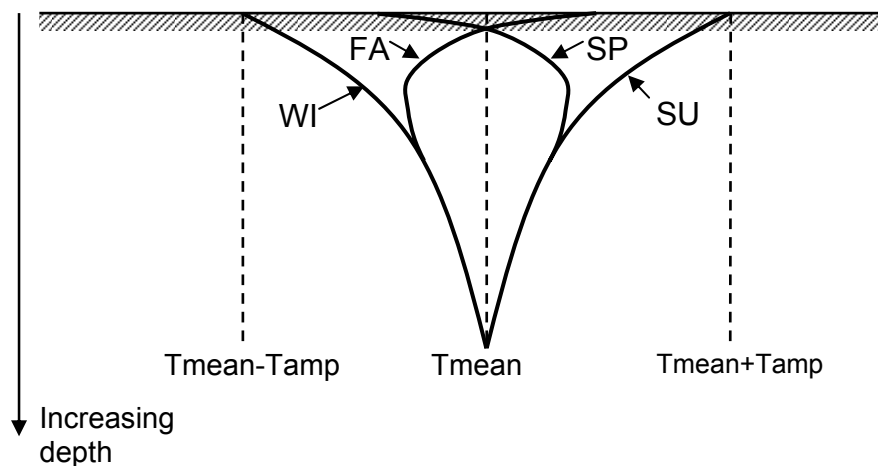
Figure 5.9.12–2: Seasonal Temperature Distributions as a Function of Depth

5.9.12.3   References

[1] ASHRAE. Chapter 31- Geothermal Energy. In: ASHRAE Handbook: Heating, Ventilating and Air-Conditioning APPLICATIONS. 1999.

[2] Kasuda, T., and Archenbach, P.R. "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States", ASHRAE Transactions, Vol. 71, Part 1, 1965

5.9.13 Type 80: Calculation of Convective Heat Transfer Coefficients

This routine calculates the convective heat transfer coefficient for up to 10 surfaces. The surfaces may be either horizontal or vertical. Type80 is of particular use for cases where the surface temperature is likely to vary beyond the usual range for which constant coefficients are acceptable, e.g. floor heating or radiant cooling/heating in general. Multiple units of Type 80 may be used.

> In TRNSYS 16, Type 56 (the multi-zone building model) includes an option to automatically calculate the inside convection coefficients. That function essentially performs the same calculations as Type 80. It is a more user-friendly solution, since you will not have to configure the convection coefficients as Inputs and connect them to Type 80. Please check Volume 06 for more information on Type 56 radiant cooling/heating options and on the automatic calculation of convection coefficients.
>
> Type 80 is available for backwards compatibility reasons and for use with other building (or slab) models than Type 56.

5.9.13.1 Nomenclature

α_{conv} convective heat transfer coefficient

Tsurf   surface temperature

Tair   air temperature

K   correlation coefficient

e   correlation exponent

5.9.13.2 Mathematical Description

For horizontal surfaces, the convective heat transfer coefficient due to the difference between the surface temperature and the temperature of the air right near the surface is calculated by Eq. 5.9-64:

$$\alpha_{conv} = 2.11 \, (Tsurf - Tair)^{0.31} \qquad \text{Eq. 5.9-64}$$

The above relationship is valid assuming that the surface temperature is higher than the surrounding air temperature. If this is not the case, then the relationship given by Eq. 5.9-65

$$\alpha_{conv} = 1.87 \, (Tsurf - Tair)^{0.25} \qquad \text{Eq. 5.9-65}$$

There are, of course, many alternative correlations possible to calculate the heat transfer coefficients. The user can choose any alternative by setting PARAMETER 1 to –1. In this case, eight additional PARAMETERS are needed in order to define Eq. 5.9-66

$$\alpha_{conv} = K_1 \, (Tsurf - Tair)^{e1} \qquad \text{Eq. 5.9-66}$$

Again, if the temperature difference is negative, Eq. 5.9-67 will be used

$$\alpha_{conv} = K_2 \, (Tsurf - Tair)^{e2} \qquad\qquad \textbf{Eq. 5.9-67}$$

For vertical surfaces the routine uses the following default equation:

$$\alpha_{conv,vertical} = 1.5 \, (Tsurf_{vertical} - Tair_{vertical})^{0.25} \qquad\qquad \textbf{Eq. 5.9-68}$$

If, however, PAR(1) is set to –2, 2 additional PARAMETERS have to be defined, resulting in Eq. 5.9-69:

$$\alpha_{conv,vertical} = K_{v1} \, (Tsurf_{vertical} - Tair_{vertical})^{ev1} \qquad\qquad \textbf{Eq. 5.9-69}$$

The user is able to use coefficients that can be found in literature or by measurements.

5.10   Solar Thermal Collectors

The components in this section allow to model different types of solar collectors:

Type 1 models a quadratic efficiency equation that is a generalization from the well-known Hottel-Whillier equation. Different Optical Modes can be used, which correspond to different models of the Incidence Angle Modifiers. Type 1 is recommended when collector test reports according to ASHRAE or European standards (and any similar standards) are available.

Type 45 is different from other models in this category because it models a thermosyphon collector with integral storage. Capacitance effects in other collector types are generally negligible and they are typically used with forced flow.

Type 71 models evacuated tube collectors. It is very similar to Type 1 but only offers one optical mode corresponding to asymmetrical (biaxial) Incidence Angle Modifiers.

Type 72 is a performance map collector. The collector efficiency must be provided for different combinations of solar radiation, ambient temperature and wind speed. It adds wind dependency to Type 1 and also allows to model a more general dependency on $\Delta T/I_T$. Type 72 offers different optical modes similar to the ones in Type 1.

Type 73 models the performance of a theoretical flat-plate collector. The steady-state Hottel-Whillier analysis is used. Collector design data are entered as parameters.

Type 74 models a Compound Parabolic Concentrating (CPC) Collector. The thermal performance model is similar to the one in other models in this section, but the optical model takes into account the special characteristics of CPC's.

5.10.1   Type 1:   Flat-plate collector (Quadratic efficiency)

This component models the thermal performance of a variety of collector types using theory. The total collector array may consist of collectors connected in series and in parallel. The thermal performance

of the total collector array is determined by the number of modules in series and the characteristics of each module. The user must provide results from standard tests of efficiency versus a ratio of fluid temperature minus ambient temperature to radiation ($\Delta T/I_T$). The fluid temperature may be an inlet, average, or outlet temperature. The model assumes that the efficiency vs. $\Delta T/I_T$ curve can be modeled as a quadratic equation. Corrections are applied to the slope, intercept, and curvature parameters to account for the presence of a heat exchanger, identical collectors in series, and flow rates other than those at test conditions.

There are four possibilities for considering the effects of off-normal solar incidence. Optical modes 2 and 3 require test data for single-axis incidence angle modifiers. Optical mode 4 determines modifiers from properties of the covers. In the fifth optical mode, the user must enter bi-axial incidence angle modifier data. This is useful for considering non-optically symmetric collectors such as evacuated tubes, etc. If the optical mode is set to 1, no off-normal incidence effects are considered.

5.10.1.1   Nomenclature

A	[m²]	Total collector array aperture or gross area (consistent with $F_R(\tau\alpha)$, $F_R U_L$, $F_R U_{L/T}$ and G_{test})
A_a	[m²]	Aperture area of a single collector module
A_r	[m²]	Absorber area of a single collector module
a_0	[-]	Intercept (maximum) of the collector efficiency (Eq 5.10.1-3)
a_1	[kJ/h-m²-K]	Negative of the first-order coefficient in collector efficiency equation
a_2	[kJ/h-m²-K²]	Negative of the second-order coefficient in collector efficiency equation
b_0	[-]	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation (Eq 5.10.1-13)
b_1	[-]	Negative of the 2nd-order coefficient in the IAM curve fit equation
C_{pf}	[kJ/kg-K]	Specific heat of collector fluid
C_{min}	[kJ/h-K]	Minimum capacitance rate (mass flow times specific heat) of heat exchanger flow streams
F_R	[-]	Overall collector heat removal efficiency factor
F_{av}	[-]	Modified value of F_R when the efficiency is given in terms of T_{av}, not T_i
F_o	[-]	Modified value of F_R when the efficiency is given in terms of T_o, not T_i
I	[kJ/h-m²]	Global (total) horizontal radiation
I_d	[kJ/h-m²]	Diffuse horizontal radiation
I_T	[kJ/h-m²]	Global radiation incident on the solar collector (Tilted surface)

I_{bT}	[kJ/h-m²]	Beam radiation incident on the solar collector
$\dot{m}$	[kg/h]	Flowrate at use conditions
$\dot{m}_{test}$	[kg/h]	Flowrate in test conditions
N_S	[-]	Number of identical collectors in series
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i	[°C]	Inlet temperature of fluid to collector
T_o	[°C]	Outlet temperature of fluid from collector
U_L	[kJ/h-m²-K]	Overall thermal loss coefficient of the collector per unit area
$U_{L/T}$	[kJ/h-m²-K²]	Thermal loss coefficient dependency on T (see Eq 5.10.1-5)
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above thehorizontal plane
θ	[°]	Incidence angle for beam radiation
ρ_g	[-]	Ground reflectance
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation

5.10.1.2   Mathematical Description

A general equation for solar thermal collector efficiency can be obtained from the Hottel-Whillier equation (Duffie and Beckman, 1991) as:

$$\eta = \frac{Q_u}{A\,I_T} = \frac{\dot{m}\,C_{pf}\left(T_o - T_i\right)}{A\,I_T} = F_R\left(\tau\alpha\right)_n - F_R\,U_L\,\frac{\left(T_i - T_a\right)}{I_T}$$

Eq 5.10.1-1

The loss coefficient U_L is not exactly constant, so a better expression is obtained by taking into account a linear dependency of U_L versus $(T_i\text{-}T_a)$:

$$\eta = \frac{Q_u}{A\,I_T} = F_R\left(\tau\alpha\right)_n - F_R\,U_L\,\frac{\left(T_i - T_a\right)}{I_T} - F_R\,U_{L/T}\,\frac{\left(T_i - T_a\right)^2}{I_T}$$

Eq 5.10.1-2

Eq 5.10.1-2 can be rewritten as:

$$\eta = a_0 - a_1\,\frac{\left(\Delta T\right)}{I_T} - a_2\,\frac{\left(\Delta T\right)^2}{I_T}$$

Eq 5.10.1-3

Which is the general solar collector thermal efficiency equation used in Type 1. The thermal efficiency is defined by 3 parameters: a_0, a_1 and a_2. Those 3 parameters are available for collectors tested according to ASHRAE standards and rated by SRCC (ASHRAE, 2003; SRCC, 1995), as well as for collectors tested according to the recent European Standards on solar collectors (CEN, 2001). Many examples of collector parameters can be found on the internet (e.g. SPF, 2004).

> Note: It is important to make sure that collector area entered as a parameter match the area used when determining the values of a_0, a_1 and a_2. Typically, efficiency curves are provided for gross area in the US and aperture area in Europe

In Eq 5.10.1-3, ΔT is equal to $(T_i - T_a)$. Collector test reports sometimes provide the efficiency curve using a different temperature difference:

$$\Delta T = \begin{cases} \Delta T_i = T_i - T_a \\ \Delta T_{av} = T_{av} - T_a \\ \Delta T_o = T_o - T_a \end{cases}$$

Eq 5.10.1-4

The 1st formulation is usually preferred in the US, while the 2nd one is used in most European documents. Eq 5.10.1-2 can use any of those definitions of the temperature difference and the user can specify the a_0, a_1 and a_2 coefficients using any of the definitions. If the coefficients are given in terms of the average or the outlet temperature, correction factors are applied. Those correction factors have been derived for linear efficiency curves (Eq 5.10.1-1), so Eq 5.10.1-2 must first be converted to that form by performing some manipulations. A modified first-order collector efficiency coefficient is defined:

$$U_L' = U_L + U_{L/T}\left(T_i - T_a\right)$$

Eq 5.10.1-5

Which gives

$$\eta = \frac{Q_u}{A\,I_T} = F_R(\tau\alpha)_n - F_R\,U_L'\,\frac{(T_i - T_a)}{I_T}$$

Eq 5.10.1-6

The correction factors are then given by (Duffie and Beckman, 1991):

$$\begin{cases} F_R(\tau\alpha) = F_{av}(\tau\alpha)_n \left(\dfrac{\dot{m}_{test}\,C_{pf}}{\dot{m}_{test}\,C_{pf} + \dfrac{F_{av}U_L'}{2}} \right) \\[2em] F_R\,U_L' = F_{av}\,U_L'\left(\dfrac{\dot{m}_{test}\,C_{pf}}{\dot{m}_{test}\,C_{pf} + \dfrac{F_{av}U_L'}{2}} \right) \end{cases}$$

Eq 5.10.1-7

$$\begin{cases} F_R(\tau\alpha) = F_o(\tau\alpha)_n \left(\dfrac{\dot{m}_{test}\,C_{pf}}{\dot{m}_{test}\,C_{pf} + F_o U_L'} \right) \\[1.5em] F_R\,U_L' = F_o\,U_L'\left(\dfrac{\dot{m}_{test}\,C_{pf}}{\dot{m}_{test}\,C_{pf} + F_o U_L'} \right) \end{cases}$$

Eq 5.10.1-8

5.10.1.3   Corrections to the ideal efficiency curve

Analytical corrections are applied to the collector parameters to account for:

- Operation at flow rates other than the value at test conditions
- N_S identical collectors mounted in series
- Non-normal solar incidence

These modifications are outlined in (Duffie and Beckman, 1991) and summarized as follows.

FLOW RATE CORRECTION

In order to account for conditions when the collector is operated at a flow rate other than the value at which it was tested, both $F_R (\tau\alpha)_n$ and $F_R U_L{}'$ are corrected to account for changes in F_R. The ratio, r_1, by which they are corrected is given by:

$$r_1 = \frac{F_R U'_L \big|_{use}}{F_R U'_L \big|_{test}} = \frac{F_R (\tau\alpha)_n \big|_{use}}{F_R (\tau\alpha)_n \big|_{test}} = \frac{\dfrac{\dot{m}\, C_{pf}}{A\, F'\, U_L}\left(1 - e^{-A F' U_L / \dot{m} C_{pf}}\right)\Big|_{use}}{\dfrac{\dot{m}_{test}\, C_{pf}}{A\, F'\, U_L}\left(1 - e^{-A F' U_L / \dot{m}_{test} C_{pf}}\right)\Big|_{test}}$$

Eq 5.10.1-9

To use this equation, it is necessary to estimate $F'U_L$. That quantity can be calculated from the test conditions:

$$F'\, U_L = -\frac{\dot{m}\, C_{pf}}{A}\, \ln\left(1 - \frac{F_R U'_L A}{\dot{m}\, C_{pf}}\right)$$

Eq 5.10.1-10

For liquid collectors, $F'U_L$ calculated from the test conditions is approximately equal to $F'U_L$ at use conditions and can be used in both the numerator and denominator of Eq 5.10.1-9.

SERIES COLLECTORS

Both $F_R (\tau\alpha)_n$ and $F_R U_L{}'$ are analytically modified to account for identical collectors mounted in series. The ratio, r_2, by which they are corrected is:

$$r_2 = \frac{1 - \left(1 - \dfrac{A\, F_R\, U'_L}{\dot{m}\, C_{pf}}\right)^{N_S}}{N_S\, \dfrac{A\, F_R\, U'_L}{\dot{m}\, C_{pf}}}$$

Eq 5.10.1-11

INCIDENCE ANGLE MODIFIER (IAM)

Collector tests are generally performed on clear days at normal incidence so that the transmittance - absorptance product $(\tau\alpha)$ is nearly the normal incidence value for beam radiation, $(\tau\alpha)_n$. The intercept efficiency, $F_R(\tau\alpha)_n$, is corrected for non-normal solar incidence by the factor $(\tau\alpha)/(\tau\alpha)_n$. By definition, $(\tau\alpha)$ is the ratio of the total absorbed radiation to the incident radiation. Thus, a general expression for $(\tau\alpha)/(\tau\alpha)_n$ is:

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{I_{bT}\frac{(\tau\alpha)_b}{(\tau\alpha)_n} + I_d\left(\frac{1+\cos\beta}{2}\right)\frac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho_g\, I\left(\frac{1-\cos\beta}{2}\right)\frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{I_T}$$

Eq 5.10.1-12

For flat-plate collectors, $(\tau\alpha)_b/(\tau\alpha)_n$ can be approximated from ASHRAE test results (ASHRAE, 2003) as:

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) - b_1\left(\frac{1}{\cos\theta} - 1\right)^2$$

Eq 5.10.1-13

Note: Some collector tests only provide the IAM value at one incidence angle, typically 50°. In such case, it is recommended to use Optical Mode 2, assume that $b_1 = 0$ and calculate b_0 using Eq 5.10.1-3.

TYPE 1 OPTICAL MODES

5 optical modes can be selected to Input the IAM data:

- Optical mode 1: perfect IAM $(\tau\alpha)/(\tau\alpha)_n$=1 for any incidence angle

- Optical mode 2: the user specifies the values of b_0 and b_1 in Eq 5.10.1-13.

- Optical mode 3: values of $(\tau\alpha)_b/(\tau\alpha)_n$ versus θ are supplied in an external data file but the collector is assumed to be symmetrical so only one direction is provided in the data file (see here below).

- Optical mode 4: the function routine TAU_ALPHA (see Volume 08, Programmer's guide) is used to estimate incidence angle modifiers for beam radiation in terms of incidence angle and cover properties.

- Optical mode 5: values of $(\tau\alpha)_b/(\tau\alpha)_n$ versus θ are supplied in an external data file for both the longitudinal and transversal directions (see here below). Note that this mode is usually used to simulate evacuated collectors, for which it is recommended to use Type 71.

The incidence angle modifiers for both sky, $(\tau\alpha)_s/(\tau\alpha)_n$, and ground diffuse, $(\tau\alpha)_g/(\tau\alpha)_n$, are determined in modes 2-4 by defining equivalent incidence angles for beam radiation that give the same transmittance as for diffuse radiation (Duffie and Beckman, 1991). The effective incidence angles for sky diffuse and ground reflected radiation are:

θ_{sky} = 59.68 - 0.1388 β + 0.001497 β^2 (in degrees)   Eq 5.10.1-14

θ_{gnd} = 90.00 - 0.5788 β + 0.002693 β^2 (in degrees)   Eq 5.10.1-15

5.10.1.4   External data files

Type 1 can optionally read the incidence angle modifier (IAM) data from an external data file. These data are read and interpolated by subroutine DYNAMICDATA (See Volume 08, Programmer's Guide). The data consists of between 2 and 10 values of incidence angles and modifiers. This section will only describe the data file used in Optical Mode 3. Optical Mode 5 (bidirectional IAM's) is typically used for evacuated tube collectors, for which it is recommended to use Type 71. The data file used in Optical Mode 5 is the same as the data file used by Type 71, and is described in section 5.10.3.4, page 5–348.

DATA FILE FOR OPTICAL MODE 3

Type 1 optionally reads the IAM values from a data file. An example is provided in "Examples\Data Files". The data file format is as follows ($2 \le N_a \le 10$):

```
<Incidence angle 1> <Incidence angle 2> etc.          Na values [0;90]
<IAM 1>                                               IAM for angle  1
<IAM 2>                                               IAM for angle  1
...
<IAM Na>                                              IAM for angle  Na
```

The principle of the data file is that the first line gives the values of the independent variable (incident angle) that will be used in the "IAM map". Then the dependent variable (IAM) is provided for all values of the independent variable. Data are read in free format.

Example

```
   0   10   20   30   40   50   60   70   80   90    ! Angle values
1.000    ! IAM for incident angle  1 ( 0)
0.997    ! IAM for incident angle  2 (10)
0.988    ! IAM for incident angle  3 (20)
...
0.644    ! IAM for incident angle  8 (70)
0.120    ! IAM for incident angle  9 (80)
0.000    ! IAM for incident angle 10 (90)
```

5.10.1.5   References

ASHRAE, 2003 - Standard 93-2003: Methods of testing to determine the performance of solar collectors, ASHRAE, Atlanta

CEN, 2001. EN 12975-2:2001. Thermal solar systems and components – Solar collectors – Part 2: Test methods. European Committee for Standardization, Brussels, Belgium. (www.cenorm.be)

Duffie J.A. and Beckman W.A., 1991. Solar Engineering of Thermal Processes – Second Edition, Wiley-Interscience, New York

Solar Rating and Certification Corporation, 1995. SRCC Standard 100. Test Methods and Minimum Standards for ertifying Solar Collectors. Available on www.solar-ratings.org

SPF, 2004 - Institut für Solartechnik SPF, online collector test reports on www.spf.ch

5.10.2 Type 45: Thermosyphon collector with integral collector storage

This component models the thermosyphon system depicted in Figure 5.10.2–1. The system consists of a flat-plate solar collector, a stratified storage tank (either vertical or horizontal cylinder), a check valve to prevent reverse flow, and water as the working fluid. Flow in the loop is assumed to be steady-state. The system is analyzed by dividing the thermosyphon loop into a number of segments normal to the flow direction and applying Bernoulli's equation for incompressible flow to each segment. The flow rate is obtained by numerical solution of the resulting set of equations. The stratification in the storage tank is modeled using the Type 38 Algebraic tank component. The advantage of the Type 38 model over fixed node models (Type 4) is that large simulation time steps can be used. A time step of 1 hour in the Type 38 tank model is sufficient for many stratified tank systems, whereas simulation time steps of a few minutes are necessary in a Type 4 model with a large number of fixed nodes
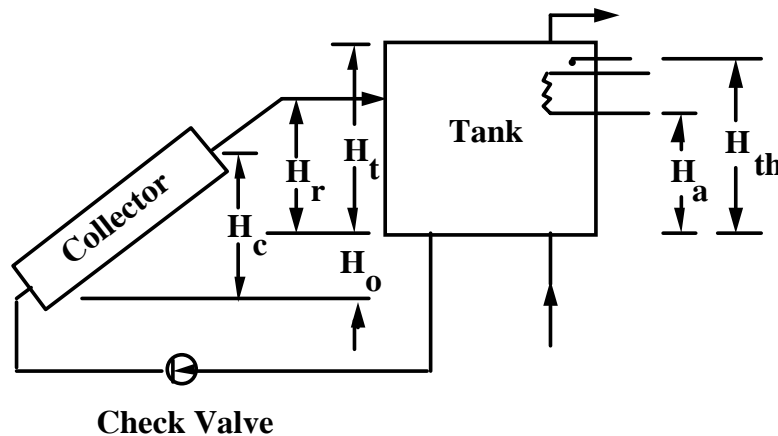
Figure 5.10.2–1: Thermo syphon System Schematic

5.10.2.1 Nomenclature

A	-	Collector area
b_o	-	Incidence angle modifier constant from ASHRAE 93-77 test result
C_p	-	Specific heat of working fluid
d_i, d_o	-	Diameter of collector inlet and outlet pipes
d_H	-	Diameter of collector headers
d_R	-	Diameter of collector risers
f	-	Friction factor for flow in pipes
$F'U_L$	-	Product of the collector efficiency factor, F', and heat loss coefficient, U_L
FRU_L	-	Slope of the collector efficiency versus $(T_{ci} - T_a)/IT$ curve
$F_R(\tau\alpha)_n$	-	Intercept of the collector efficiency versus $(T_{ci} - T_a)/IT$ curve
$F_R(\tau\alpha)$	-	Intercept efficiency corrected for non-normal incidence
g	-	Gravitational constant
G	-	Collector flowrate per unit area
G_{test}	-	Collector flowrate per unit area at test conditions at which F_RU_L and $F_R(\tau\alpha)_n$ were determined

H_c	-	Vertical distance between outlet and inlet of collectors
H_a	-	Height of auxiliary heating element above bottom of tank
H_o	-	Vertical distance between outlet of tank and inlet to collector
H_R	-	Height of collector return above bottom of tank
H_t	-	Height of tank
H_{th}	-	Height of auxiliary thermostat above bottom of tank
h_{Li}	-	Frictional head loss in the piping
I	-	Horizontal total radiation per unit area
I_{bT}	-	Beam radiation per unit area
I_d	-	Horizontal diffuse radiation per unit area
I_g	-	Diffuse reflected ground radiation per unit area
I_T	-	Total incident radiation per unit area
k_w	-	Effective thermal conductivity of water and tank
k_i, k_o	-	Number of velocity heads lost by flow in bends, tees, and restrictions of inlet and outlet piping
L_i, L_o	-	Length of inlet and outlet piping
L_h	-	Length of collector headers
LU	-	Fortran logical unit containing collector frictional head loss data
$\dot{m}$	-	Thermosyphon flowrate
$\dot{m}_L$	-	Load flowrate
N_{B1}, N_{B2}		Number of equivalent right angle bends in inlet and outlet connecting pipes
NDATA	-	Number of lines of data in LU
N_R	-	Number of parallel collector risers
N_x	-	Number of equal sized collector nodes
$\dot{Q}_{AUX}$	-	Rate of auxiliary energy Input to tank
$\dot{Q}_{env}$	-	Rate of energy loss from tank
$\dot{Q}_{in}$	-	Rate of energy Input to tank by solar
$\dot{Q}_{sup}$	-	Rate of energy supply to load by tank
$\dot{Q}_{he}$	-	Maximum rate at which auxiliary heater can supply energy
$\dot{Q}_u$	-	Rate of useful energy collection
ri	-	Ratio of insulation thickness (see Parameter 33 description)
r	-	Ratio of collector heat removal efficiency factor, FR, to the value at test conditions
Re	-	Reynolds number for flow in pipes
T_a	-	Ambient temperature
T_{env}	-	Environmental temperature for losses from storage
T_{ci}	-	Collector inlet temperature
T_{ck}	-	Temperature of kth node in collector
T_{co}	-	Collector outlet temperature
T_h	-	Temperature of hot fluid entering tank
T_i	-	Temperature of ith tank segment
$\overline{T}_p$	-	Average temperature of fluid in a pipe
T_{pi}	-	Temperature of inlet fluid to pipe
T_{po}	-	Pipe outlet fluid temperature
T_L	-	Temperature of load flowstream entering tank
T_{set}	-	Set temperature for tank auxiliary heater thermostat
U_i, U_o	-	Loss coefficients for inlet and outlet pipes (based on pipe surface area)
UA	-	Overall UA value for tank

$(UA)_f$	-	Conductance for heat loss from tank to auxiliary heater flue
$(UA)_p$	-	Conductance for heat loss from pipes
v	-	Velocity of fluid in pipes
V_h	-	Velocity of fluid at entry to inlet header and at exit of outlet header
V_t	-	Volume of storage medium
Δh_i	-	Height of the ith node
ΔT_{db}	-	Thermostat temperature deadband
ΔP_h	-	Pressure change across collector inlet and outlet headers
ΔP_i	-	Change in pressure across the ith node
ΔE	-	Change in internal energy of storage since beginning of simulation
β	-	Collector slope measured from horizontal
γ_{htr}	-	Control signal for auxiliary heater (0 or 1) that disables or enables auxiliary heater
ρ_i	-	Density of ith node
ρ_g	-	Ground reflectance
ρ_s	-	Density of working fluid at standard conditions
θ	-	Solar incidence angle
$\dfrac{(\tau\alpha)}{(\tau\alpha)_n}, \dfrac{(\tau\alpha)_b}{(\tau\alpha)_n}, \dfrac{(\tau\alpha)_s}{(\tau\alpha)_n}, \dfrac{(\tau\alpha)_g}{(\tau\alpha)_n}$		
	-	incidence angle modifiers for total, beam, sky diffuse and ground diffuse radiation

5.10.2.2 Mathematical Description

Application of Bernoulli's equation to any node, i, in the thermosyphon loop results in the following expression for pressure drop:

$$\Delta P_i = \rho_i g \Delta h_i + \rho_i g h_{Li} \qquad\qquad \textbf{Eq 5.10.2-1}$$

at any instant of the time, the sum of the pressure changes around the loop is zero:

$$\sum_{i=1}^{i=N} \rho_i\, \Delta h_i = \sum_{i=1}^{i=N} \rho_i\, h_{Li} \qquad\qquad \textbf{Eq 5.10.2-2}$$

The thermosiphon model involves the numerical solution for the flow rate that satisfies the above equation. The density of the fluid is evaluated at the local temperature using a correlation for water. Temperatures and frictional head losses in each node of the collector and pipes are determined as described below.

The collector inlet and outlet pipes are each considered to be single nodes, with negligible thermal capacitance.

A first law analysis yields the following expressions for average and outlet temperatures of these pipes:

$$\overline{T}_p = T_a + (T_{pi} - T_a) \cdot \frac{\dot{m}C_p}{(UA)_p} \cdot \left(1 - \exp\left(-\frac{(UA)_p}{\dot{m}C_p}\right)\right) \qquad\qquad \textbf{Eq 5.10.2-3}$$

$$T_{po} = T_a + (T_{pi} - T_a) \cdot \exp\left(-\frac{(UA)_p}{\dot{m}C_p}\right) \qquad\qquad \textbf{Eq 5.10.2-4}$$

FRICTION HEAD LOSS

Frictional head loss in either pipe is given as:

$$H_p = \frac{fLv^2}{2d} + \frac{kv^2}{2}$$

Eq 5.10.2-5

where the friction factor, f, is

$f = 64/ Re$ for $Re < 2000$

$f = 0.032$ for $Re > 2000$

A correction is also applied to allow for the additional friction due to developing flow in the connecting pipes (Morrison and Ranatunga, 1980).

The program can evaluate the collector pressure drop or pressure drop versus flow rate for the collector (and a check value etc.) can be entered as a data file. Friction pressure drop versus flow rate data entered by the user is not adjusted to allow for the variation of water viscosity with temperature. The friction head in each section of the thermosyphon loop is evaluated as follows.

1. Entry from tank to connecting pipe to collector
   k = .5

2. Developing flow in the connecting pipes (and collector risers if collector pressure drop versus flow rate data is not specified) (Morrison and Ranatunga, 1980).
   $f = f[1 + .038/(L/Re/d)^{.964}]$

3. Losses due to bends in connecting pipes
   a. right angle bend
      equivalent length of pipe increased by 30 d for $Re \leq 2000$
      or k = 1.0 for $Re \geq 2000$
   b. 45° bend
      equivalent length at pipe increased by 20 d for $Re \leq 2000$
      or k = 0.6 for $Re > 2000$

4. Cross section change at junction of connecting pipes and header (and riser entry and exit to header if collector friction data is not specified)
   a. Sudden Expansion
      $k = .667 (D_1/D_2)^4 - 2.667 (D_1/D_2)^2 + 2.0$
   b. Sudden Contraction
      $k = -.3259 (D_2/D_1)^4 -.1784 (D_2/D_1)^2 + 0.5$
      where D_1 = inlet diameter, D_2 = outlet diameter

5. Collector header pressure drop (if collector friction data is not specified) - average of pressure change along inlet and outlet headers for equal mass flow in each riser:

$$S_1 = \sum_{i=1}^{N_R} \frac{N_R - i + 1}{N_R^2}$$

Eq 5.10.2-6

$$S_2 = \sum_{i=1}^{N_R} \frac{N_R - i + 1}{N_R^2}$$

Eq 5.10.2-7

$$A_{11} = \frac{f L_h V_h^2}{2 d_h}$$

Eq 5.10.2-8

where f = 64/Re with Re based on inlet header velocity and temperature

$$A_{12} = A_{11} \quad \text{with f = 64/Re}$$

Eq 5.10.2-9

Based on outlet header, velocity and temperature;

$$A_2 = \frac{\rho V_h^2}{2}$$

Eq 5.10.2-10

$$P_h = (-S_1 A_{11} + 2 (S_2 A_2) + S_1 A_{12})/2$$

Eq 5.10.2-11

6. Loss at entry of flow into tank
   k = 1

Friction head loss in the tank is neglected. If pressure drop versus flow rate data for the collector (and check value etc.) is entered via an external file, the program only evaluates friction loss in the connecting pipes, connections to the tank and bends.

If pressure drop versus flow rate data are supplied, they are read and interpolated by subroutine DYNAMICDATA (See Volume 08, Programmer's Guide). The data consist of between 2 and 10 values of flow rate and head loss (meters of water). All values of flow rate are listed first, in increasing order, followed by values of pressure drop (free format) loss in meters of water. For numerical stability, the first data line should correspond to zero head loss at zero flow rate.

THERMOSIPHON HEAD

The net weight of fluid in the collector is found by dividing the collector into Nx (user specified) equally sized nodes. The thermal performance is modeled according to the Hottel-Whillier equation (Morrison and Ranatunga, 1980). The temperature at the midpoint of any collector node, k, is:

$$T_{ck} = T_a + \frac{I_T F_R(\tau\alpha)}{F_R U_L} + \left(T_{ci} - T_a - \frac{I_T F_R(\tau\alpha)}{F_R U_L}\right) \cdot \exp\left[\frac{F'U_L}{G \cdot C_p} \cdot \frac{(k - 1/2)}{N_x}\right]$$

Eq 5.10.2-12

The collector parameter $F'U_L$ is calculated from the value of $F_R U_L$ and G at test conditions:

$$F'U_L = -G_{test} \cdot C_p \ln\left(1 - \frac{F_R U_L}{G_{test} C_p}\right)$$

Eq 5.10.2-13

This procedure neglects changes in F' and U_L due to changes in the fluid heat transfer coefficient. The parameter $F_R(\tau\alpha)$ is determined from the intercept efficiency at normal incidence $F_R(\tau\alpha)_n$, using an incidence angle modifier, $(\tau\alpha)/(\tau\alpha)_n$. In general,

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{I_{bT}\dfrac{(\tau\alpha)_b}{(\tau\alpha)_n} + I_d\dfrac{1+\cos\beta}{2}\dfrac{(\tau\alpha)_s}{(\tau\alpha)_n} + I_g\dfrac{1-\cos\beta}{2}\dfrac{(\tau\alpha)_g}{(\tau\alpha)_n}}{I_T}$$

Eq 5.10.2-14

The incidence angle modifier for beam radiation is given in terms of incidence angle and a user specified constant, b_o, (ASHRAE 93 test result) as:

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_o\left(\frac{1}{\cos\theta} - 1\right)$$

Eq 5.10.2-15

For sky and ground diffuse radiation, the incidence angle modifiers are also determined using the above relation but at effective incidence angles as defined by Brandemuehl (2).

The overall useful energy collection is:

$$Q_u = r\,A_c\,(F_R(\tau\alpha)\,I_T - F_R U_L\,(T_{ci} - T_a))$$

Eq 5.10.2-16

Where:

$$r = \frac{F_R\big|\,\text{use}}{F_R\big|\,\text{test}} = \frac{G\left(1-\exp\left(-\dfrac{F'U_L}{GC_p}\right)\right)}{G_{test}\left(1-\exp\left(-\dfrac{F'U_L}{G_{test}C_p}\right)\right)}$$

Eq 5.10.2-17

From a simple energy balance, the collector outlet temperature is:

$$T_{co} = Q_u/\dot{m}C_p + T_{ci}$$

Eq 5.10.2-18

Thermal stratification in the storage tank is modeled using the Type 38 Algebraic Tank component.

5.10.3   Type71: Evacuated tube solar collector

Type 71 models an evacuated tube solar collector using a quadratic efficiency curve and a biaxial Incidence Angle Modifiers (IAM).

The thermal model is identical to the one used in Type 1, and the reader is invited to refer to section 5.10.1 (page 5–333) for more details on the thermal efficiency model.

The optical model is described here below.

5.10.3.1   Nomenclature

a_0	[-]	Intercept (maximum) of the collector efficiency (Eq 5.10.1-3)
a_1	[kJ/h-m²-K]	Negative of the first-order coefficient in collector efficiency equation
a_2	[kJ/h-m²-K²]	Negative of the second-order coefficient in collector efficiency equation
b_0	[-]	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation (Eq 5.10.1-13)
b_1	[-]	Negative of the 2nd-order coefficient in the IAM curve fit equation
I	[kJ/h-m²]	Global (total) horizontal radiation
I_d	[kJ/h-m²]	Diffuse horizontal radiation
I_T	[kJ/h-m²]	Global radiation incident on the solar collector (Tilted surface)
I_{bT}	[kJ/h-m²]	Beam radiation incident on the solar collector
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i	[°C]	Inlet temperature of fluid to collector
T_o	[°C]	Outlet temperature of fluid from collector
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above thehorizontal plane
θ	[°]	Incidence angle for beam radiation
θ_l	[°]	Incidence angle in the longitudinal direction (see Figure 5.10.3–1)
θ_t	[°]	Incidence angle in the transversal direction (see Figure 5.10.3–1)
ρ_g	[-]	Ground reflectance
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation

5.10.3.2 Mathematical description

The thermal efficiency of the collector is given by:

$$\eta = a_0 - a_1 \frac{(\Delta T)}{I_T} - a_2 \frac{(\Delta T)^2}{I_T}$$

Eq 5.10.3-1

Which is the general solar collector thermal efficiency equation used in Type 1.

The thermal efficiency is defined by 3 parameters: a_0, a_1 and a_2. Those 3 parameters are available for collectors tested according to ASHRAE standards and rated by SRCC (ASHRAE, 2003; SRCC, 1995), as well as for collectors tested according to the recent European Standards on solar collectors (CEN, 2001).

Many examples of collector parameters can be found on the internet (e.g. SPF, 2004).

> Note: It is important to make sure that the collector area entered as a parameter matches the area used when fitting the values of $a_0..a_2$. Efficiency curves are typically provided for gross area in the US and aperture area in Europe

In the equation here above, ΔT is equal to (T_i-T_a). Collector test reports sometimes provide the efficiency curve using a different temperature difference:

$$\Delta T = \begin{cases} \Delta T_i = T_i - T_a \\ \Delta T_{av} = T_{av} - T_a \\ \Delta T_o = T_o - T_a \end{cases}$$

Eq 5.10.3-2

The 1st formulation is usually preferred in the US, while the 2nd one is used in most European documents. Type 71 will apply correction factor depending on the Efficiency Mode that is selected (see section 5.10.1).

5.10.3.3 Optical properties: Incidence Angle Modifier (IAM)

Collector tests are generally performed on clear days at normal incidence so that the transmittance - absorptance product $(\tau\alpha)$ is nearly the normal incidence value for beam radiation, $(\tau\alpha)_n$. The intercept efficiency, $F_R (\tau\alpha)_n$, is corrected for non-normal solar incidence by the factor $(\tau\alpha)/(\tau\alpha)_n$. By definition, $(\tau\alpha)$ is the ratio of the total absorbed radiation to the incident radiation. Thus, a general expression for $(\tau\alpha)/(\tau\alpha)_n$ is:

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{I_{bT}\frac{(\tau\alpha)_b}{(\tau\alpha)_n} + I_d\left(\frac{1+\cos\beta}{2}\right)\frac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho_g I\left(\frac{1-\cos\beta}{2}\right)\frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{I_T}$$

Eq 5.10.3-3

IAM FOR BEAM RADIATION

Evacuated tube collectors are optically non-symmetric. Type 71 requires biaxial Incidence Angle Modifiers $(\tau\alpha)_b/(\tau\alpha)_n$ to be provided in an external data file, which is described in section 5.10.3.4.

Figure 5.10.3–1 shows a graphical representation of the longitudinal and transversal directions:

- The longitudinal incidence angle is measured in a plane that is perpendicular to the collector plane and contains the collector azimuth. The corresponding IAM is referred to as the longitudinal IAM, or altitude modifier.

- The transversal incidence angle is measured in a plane that is perpendicular to both the collector aperture and the longitudinal plane. The corresponding IAM is referred to as the transversal IAM, or azimuthal modifier.
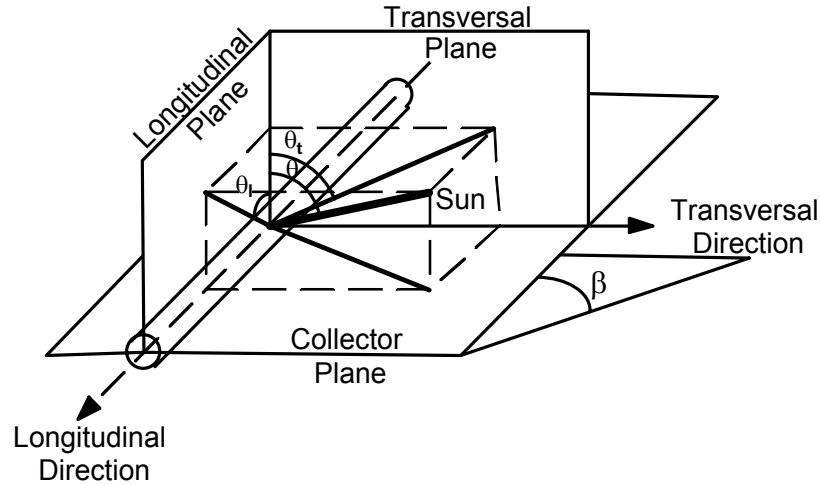
Figure 5.10.3–1: Transversal and longitudinal directions

Note: The collector tube represented in Figure 5.10.3–1 is in the most common orientation, along a North-South axis (assuming the collector faces due South). If the collector was tested in a different configuration or if it is mounted with the tubes along an East-West axis, the IAM data obtained from a collector test may have to be adapted (by switching the longitudinal and transversal directions). In TRNSYS, "longitudinal" and "transversal" always refer to the plane of the collector and the sun as described here below, not to the tubes.

In most cases, collector test reports provide the transversal IAM for different transversal incidence angle values (and longitudinal angle = 0) and longitudinal IAM for different longitudinal incident angles (and transversal angle = 0). The data file requires the IAM for non-zero longitudinal **and** transversal angles. The IAM for any θ_l and θ_t can be approximated by multiplying $IAM(\theta_l,0)$ and $IAM(0, \theta_t)$, as discussed in (McIntire, 1982) and (Theunissen and Beckman, 1985).

IAM FOR DIFFUSE RADIATION

The IAM for diffuse radiation is calculated by evaluating the ratio of absorbed diffuse radiation over to incident diffuse radiation over the sky dome for a horizontal collector, assuming isotropic diffuse radiation. In general:

$$\frac{(\tau\alpha)_d}{(\tau\alpha)_n} = \frac{4}{\pi} \int_0^{\pi/2} \int_0^{\pi/2} \frac{(\tau\alpha)_b}{(\tau\alpha)_n} (\theta, \gamma_s) \cos(\theta) \sin(\theta) \, d\theta \, d\gamma_s \qquad \text{Eq 5.10.3-4}$$

This integration is performed numerically, once at the start of the simulation, with the user-supplied IAM data for $(\tau\alpha)_b/(\tau\alpha)_n$.

5.10.3.4   External data file

Type 71 reads the biaxial incidence angle modifier (IAM) data from an external data file. These data are read and interpolated by subroutine DYNAMICDATA (See Volume 08, Programmer's Guide). The data consists of between 2 and 10 values of incidence angles (in both directions) and modifiers. An example is provided in "Examples\Data Files".

The data file format is as follows ($2 \leq Nt \leq 10$ and $2 \leq Nl \leq 10$):

```
<Transversal angle 1> <Transversal angle 2> etc.        Nt values [0;90]
<Longitudinal angle 1> <Longitudinal angle 1> etc.      Nl values [0;90]
<IAM  1  1>                            IAM for transv. angle  1, long. angle  1
<IAM  1  2>                            IAM for transv. Angle  1, long. angle  2
...
<IAM  1 Nl>                            IAM for transv. angle  1, long. angle Nl
<IAM  2  1>                            IAM for transv. angle  2, long. angle  1
<IAM  2  2>                            IAM for transv. angle  2, long. angle  2
...
<IAM  2 Nl>                            IAM for transv. angle  2, long. angle Nl
<IAM  3  1>                            IAM for transv. angle  3, long. angle  1
...
<IAM Nt Nl>                            IAM for transv. angle Nt, long. angle Nl
```

The principle of the data file is that the first line gives the values of the 2 independent variables (Transversal and longitudinal incident angles) that will be used in the "IAM map". Then the dependent variable (IAM) is provided for all values of the independent variables. The values of the last independent variable (Longitudinal angle) are first cycled through, then the 1st independent variable (Transversal angle). Data are read in free format.

Notes:

- Typical test data give the IAM for transversal angle i and longitudinal angle =0 on one hand, and the IAM for transversal angle = 0 and longitudinal angle j on the other hand. As discussed here above, IAM (i,j) can be approximated by IAM (i,0) * IAM (0,j)

- In case only one value of IAM is provided in one direction, it is recommended to fit a b_0 value as explained in section 5.10.1.3 and then enter the IAM for a few incidence angles

- The data are interpolated by the generic DYNAMICDATA routine, which does not have any knowledge about IAM's. It is recommended to include values for angle = 0 (IAM=1) and angle = 90° (IAM=0) in the data.

EXAMPLE

This file includes IAM data for a hypothetical collector for which the following data is available:

```
Direction        |  0° |  15° |  30° |  45° |  60° |  75° |  90° |
------------------------------------------------------------------
Transversal  IAM | 1.00 | 1.01 | 1.03 | 1.05 | 1.04 | 1.02 | 0.00 |
Longitudinal IAM | 1.00 | 1.00 | 0.98 | 0.96 | 0.90 | 0.71 | 0.00 |
```

The value for both incidence angles different from zero are obtained by multiplication, as explained here above. The file contents are:

```
   0    15    30    45    60    75    90    ! 7 Incidence angle values (transversal)
   0    15    30    45    60    75    90    ! 7 Incidence angle values (longitudinal)
1.00    ! IAM for ThetaT 1, ThetaL 1
1.00    ! IAM for ThetaT 1, ThetaL 2
0.98    ! IAM for ThetaT 1, ThetaL 3 ( 1.00 * 0.98 = 0.98)
...
0.00    ! IAM for ThetaT 1, ThetaL 7 ( 1.00 * 0.00 = 0.00)
```

```
1.01    ! IAM for ThetaT 2, ThetaL 1 ( 1.01 * 1.00 = 1.01)
1.01    ! IAM for ThetaT 2, ThetaL 2 ( 1.01 * 1.00 = 1.01)
0.99    ! IAM for ThetaT 2, ThetaL 3 ( 1.01 * 0.98 = 0.99)
...
0.00    ! IAM for ThetaT 2, ThetaL 7 ( 1.01 * 0.00 = 0.00)
1.03    ! IAM for ThetaT 3, ThetaL 1 ( 1.03 * 1.00 = 0.00)
...
0.00    ! IAM for ThetaT 7, ThetaL 1 ( 0.00 * 1.00 = 0.00)
0.00    ! IAM for ThetaT 7, ThetaL 2 ( 0.00 * 1.00 = 0.00)
...
0.00    ! IAM for ThetaT 7, ThetaL 7 ( 0.00 * 0.00 = 0.00)
```

5.10.3.5   References

McIntire W.R., 1982. Factored approximations for biaxial incidence angle modifier. Solar Energy, 24 (4), pp. 315

Theunissen P.H. and Beckman W.A., 1985. Solar transmittance characteristics of evacuated tubular collectors with diffuse back reflectors. Solar Energy, 35 (4), pp. 311-320

5.10.4 Type 72: Performance Map Solar Collector

This component models the thermal performance of a solar collector using performance data. The total collector array may consist of collectors connected in series and in parallel. The thermal performance of the total collector array is determined by the number of modules in series and the characteristics of each module. The user must enter a performance map of collector efficiency as a function of $\Delta T/I_T$, radiation, and wind speed. This is useful for collectors with non-linear efficiency vs. $\Delta T/I_T$ relationships, concentrating collectors whose performance may depend strongly upon the level of radiation, or coverless collectors that are sensitive to wind speed. If imaging collectors, which use only beam radiation, are considered then only beam radiation should be provided as an Input to this component.

There are four possibilities for considering the effects of off-normal solar incidence. Optical mode 1 assumes there to be no incidence angle modifiers. Optical modes 2 and 3 require test data for single-axis incidence angle modifiers. Optical mode 4 determines modifiers from properties of the covers. In the fifth optical mode, the user must enter bi-axial incidence angle modifier data. This is useful for considering non-optically symmetric collectors such as evacuated tubes, etc. If the optical mode is set to 0, no off-normal incidence effects are considered.

5.10.4.1 Nomenclature

A	[m²]	Total collector array aperture or gross area (consistent with $F_R(\tau\alpha)$, $F_R U_L$, $F_R U_{L/T}$ and G_{test})
A_a	[m²]	Aperture area of a single collector module
A_r	[m²]	Absorber area of a single collector module
a_0	[-]	Intercept (maximum) of the collector efficiency (Eq 5.10.1-3)
a_1	[kJ/h-m²-K]	Negative of the first-order coefficient in collector efficiency equation
a_2	[kJ/h-m²-K²]	Negative of the second-order coefficient in collector efficiency equation
b_0	[-]	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation (Eq 5.10.1-13)
b_1	[-]	Negative of the 2nd-order coefficient in the IAM curve fit equation
C_{pf}	[kJ/kg-K]	Specific heat of collector fluid
C_{min}	[kJ/h-K]	Minimum capacitance rate (mass flow times specific heat) of heat exchanger flow streams
F_R	[-]	Overall collector heat removal efficiency factor
F_{av}	[-]	Modified value of F_R when the efficiency is given in terms of T_{av}, not T_i
F_o	[-]	Modified value of F_R when the efficiency is given in terms of T_o, not T_i
I	[kJ/h-m²]	Global (total) horizontal radiation
I_d	[kJ/h-m²]	Diffuse horizontal radiation
I_T	[kJ/h-m²]	Global radiation incident on the solar collector (Tilted surface)
I_{bT}	[kJ/h-m²]	Beam radiation incident on the solar collector
$\dot{m}$	[kg/h]	Flowrate at use conditions

$\dot{m}_{test}$	[kg/h]	Flowrate in test conditions
N_S	[-]	Number of identical collectors in series
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i	[°C]	Inlet temperature of fluid to collector
T_o	[°C]	Outlet temperature of fluid from collector
U_L	[kJ/h-m²-K]	Overall thermal loss coefficient of the collector per unit area
$U_{L/T}$	[kJ/h-m²-K²]	Thermal loss coefficient dependency on T (see Eq 5.10.1-5)
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above thehorizontal plane
η	[-]	Collector thermal efficiency for entire array
η_j	[-]	Collector thermal efficiency for module j
η_n	[-]	Collector thermal efficiency at normal incidence
η_0	[-]	Collector thermal efficiency when $\Delta T/I_T = 0$
θ	[°]	Incidence angle for beam radiation
ρ_g	[-]	Ground reflectance
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation

5.10.4.2   Mathematical description

The energy collection for N_S collector modules mounted in series is modeled as:

$$\dot{Q}_u = \frac{AI_T}{N_S} \sum_{j=1}^{N_S} \eta_j \qquad\qquad \textbf{Eq 5.10.4-1}$$

The efficiency of an individual module (or set of collectors in parallel) is determined from user supplied data and a correction for off-normal incidence as follows:

$$\eta_j = \eta_{j,n} - \eta_{j,n,0}\left(1 - \frac{(\tau\alpha)}{(\tau\alpha)_n}\right) \qquad\qquad \textbf{Eq 5.10.4-2}$$

$\eta_{j,n}$ is the efficiency at normal incidence at the current meteorological conditions and fluid temperature. $\eta_{j,n,o}$ is the efficiency at normal incidence for $\Delta T/I_T$ equal 0. The second term in the above equation represents the difference between the efficiency at normal incidence and that at off-normal incidence.

As with Type 1, there are four possibilities for determining the incidence modifier, $(\tau\alpha)/(\tau\alpha)_n$. Please see section 5.10.1.3, page 5–336 for more information.

In order to evaluate the efficiency for each module, the outlet temperature of one module is used as the inlet to the next. In general:

$$T_{o,j} = \frac{A\ I_T\ \eta_j}{N_s\ \dot{m}_c\ C_{pf}}$$
<div align="right">**Eq 5.10.4-3**</div>

If the efficiency data is based upon average or outlet temperature, an iterative solution for the fluid temperature is required.

A complete thermal performance map of the collector consists of efficiency versus $\Delta T/I_T$ data for different levels of radiation and wind speed (See section 5.10.4.3). Explanations for data Input for three possible cases follows for convenience.

> Note: In the following, ΔT refers to one of the 3 definitions described in the Type 1 description (see section 5.10.1.2). Be careful to select the Efficiency Mode that matches the performance map. This is also true for the collector area (which can be gross, aperture or absorber area).

EFFICIENCY VERSUS $\Delta T/I_T$ ONLY

In this case NI_T and NW should be set to 1 in the parameter list. Performance will be a function of $\Delta T/I_T$ only. The first $N\Delta T$ numbers in the data file should be increasing values of $\Delta T/I_T$. The second $N\Delta T$ numbers are efficiencies corresponding to the values of $\Delta T/I_T$. Note that it is recommended to use Type 1 if possible.

DEPENDENCE ON I_T OR W

In this situation, efficiency vs. $\Delta T/I_T$ data is to be provided for different levels of radiation or wind speed, but not both. Either NI_T or NW should be set to l in the parameter list. The first set of NI_T or NW (whichever is greater than 1) numbers in the data file should be the levels of radiation or wind speed for which efficiency vs. $\Delta T/I_T$ data is provided. The second $N\Delta T$ numbers should be increasing values of $\Delta T/I_T$. For each value of radiation or wind speed $N\Delta T$ values of efficiency at the corresponding $\Delta T/I_T$ must follow.

DEPENDENCE ON BOTH I_T AND W

This means both NI_T and NW are greater than one and efficiency vs. $\Delta T/I_T$ data must be provided for each combination of radiation and wind speed. In all $N\Delta T * NI_T * NW$ efficiency points are required. The first NW values are wind speeds in increasing order. This is followed by NI_T increasing levels of radiation and $N\Delta T$ values of $\Delta T/I_T$ in increasing order. The next $N\Delta T$ values are efficiencies as a function of $\Delta T/I_T$ for the lowest I_T and W specified. The next $N\Delta T$ numbers are for the second level of radiation, but lowest wind speed. NI_T sets of $N\Delta T$ efficiencies are required for each wind speed.

5.10.4.3   External data files

Type 72 reads both the collector thermal performance and the Incidence Angle Modifier data from external files. The Optical Modes and IAM data files for Type 72 are identical to those for Type 1 and will not be discussed here (see section 5.10.1.4, page 5–338).

COLLECTOR THERMAL PERFORMANCE

This section presents the data file required to model a collector for which values of the efficiency versus $\Delta T/I_T$ are available for different values of I_T and different wind speeds, which is the most general case. In practice Type 72 is most often used to simulate unglazed collectors for which the wind speed dependency is important, but only one value of I_T is generally required. An example file is provided in "Examples\Data Files".

The data are read and interpolated by subroutine DYNAMICDATA (See Volume 08, Programmer's Guide). The data consists of between 2 and 10 values of incidence angles (in both directions) and modifiers. An example is provided in "Examples\Data Files".

The data file format is as follows ($2 \leq NW \leq 5$, $2 \leq NIT \leq 5$ and $2 \leq NDT/IT \leq 10$):

```
<Wind speed 1> <Wind speed 2> etc.        NW values
<Sol rad 1> <Sol Rad 2> etc.              NIT values
<DT/IT 1> <DT/IT 2> <DT/IT 3> etc.        NDT/IT values
<Efficiency 1 1 1>          Efficiency for Wind speed 1, IT 1, DT/IT 1
<Efficiency 1 1 2>          Efficiency for Wind speed 1, IT 1, DT/IT 2
...
<Efficiency 1 1 NDT/IT>     Efficiency for Wind speed 1, IT 1, last DT/IT
<Efficiency 1 2 1>          Efficiency for Wind speed 1, IT 2, DT/IT 1
<Efficiency 1 2 2>          Efficiency for Wind speed 1, IT 2, DT/IT 2
...
<Efficiency 1 2 NDT/IT>     Efficiency for Wind speed 1, IT 2, last DT/IT
...
<Efficiency 1 NIT 1>        Efficiency for Wind speed 1, last IT, DT/IT 1
...
<Efficiency 1 NIT NDT/IT>   Efficiency for Wind speed 1, last IT, last DT/IT
...
<Efficiency 2 1 1>   Efficiency for Wind speed 2, IT 1, DT/IT 1
...
...
<Efficiency NW NIT NDT/IT> Efficiency for last Wind speed, last IT, last DT/IT
```

The principle of the data file is that the first lines give the values of the 3 independent variables that will be used in the performance map. Then the dependent variable (Efficiency) is provided for all values of the independent variables. The values of the last independent variable ($\Delta T/I_T$) are first cycled through, then the 2nd independent variable (I_T) and finally the values of the 1st independent variable (Wind speed). Data are read in free format.

EXAMPLE

```
   0.0      3.0    ! 2 Wind speed values, [m/s]
2880.0    3600.0   ! 2 Solar radiation values, [kJ/h-m²]
0.000  0.005  0.010  0.015  0.016  0.020  0.025  0.030    ! 8 dT/IT [K-h-m²/kJ]
0.959    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 1
0.799    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 2
0.638    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 3
0.478    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 4
0.446    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 5
0.317    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 6
```

```
0.157    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 7
0.000    ! Efficiency for Wind Speed 1, Radiation 1, dT/IT 8
0.959    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 1
0.799    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 2
0.638    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 3
0.478    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 4
0.446    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 5
0.317    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 6
0.157    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 7
0.000    ! Efficiency for Wind Speed 1, Radiation 2, dT/IT 8
0.937    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 1
0.655    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 2
0.374    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 3
0.092    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 4
0.000    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 5
0.000    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 6
0.000    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 7
0.000    ! Efficiency for Wind Speed 2, Radiation 1, dT/IT 8
0.937    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 1
0.655    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 2
0.374    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 3
0.092    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 4
0.000    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 5
0.000    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 6
0.000    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 7
0.000    ! Efficiency for Wind Speed 2, Radiation 2, dT/IT 8
```

5.10.5 Type 73: Theoretical flat-plate collector

This component models the thermal performance of a theoretical flat plate collector. The total collector array may consist of collectors connected in series and in parallel. The thermal performance of the total collector array is determined by the number of modules in series and the characteristics of each module. This model provides for the theoretical analyses of a flat plate. The Hottel-Whillier steady-state model is used for evaluating the thermal performance.

5.10.5.1 Nomenclature

A	[m²]	Total collector array aperture or gross area (consistent with $F_R(\tau\alpha)$, $F_R U_L$, $F_R U_{L/T}$ and G_{test})
A_a	[m²]	Aperture area of a single collector module
A_r	[m²]	Absorber area of a single collector module
a_0	[-]	Intercept (maximum) of the collector efficiency (Eq 5.10.1-3)
a_1	[kJ/h-m²-K]	Negative of the first-order coefficient in collector efficiency equation
a_2	[kJ/h-m²-K²]	Negative of the second-order coefficient in collector efficiency equation
b_0	[-]	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation (Eq 5.10.1-13)
b_1	[-]	Negative of the 2nd-order coefficient in the IAM curve fit equation
C_{pf}	[kJ/kg-K]	Specific heat of collector fluid
C_{min}	[kJ/h-K]	Minimum capacitance rate (mass flow times specific heat) of heat exchanger flow streams
F_R	[-]	Overall collector heat removal efficiency factor
F_{av}	[-]	Modified value of F_R when the efficiency is given in terms of T_{av}, not T_i
F_o	[-]	Modified value of F_R when the efficiency is given in terms of T_o, not T_i
I	[kJ/h-m²]	Global (total) horizontal radiation
I_d	[kJ/h-m²]	Diffuse horizontal radiation
I_T	[kJ/h-m²]	Global radiation incident on the solar collector (Tilted surface)
I_{bT}	[kJ/h-m²]	Beam radiation incident on the solar collector
$\dot{m}$	[kg/h]	Flowrate at use conditions
$\dot{m}_{test}$	[kg/h]	Flowrate in test conditions
N_S	[-]	Number of identical collectors in series
$\dot{Q}_u$	[kJ/h]	Useful energy gain
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i	[°C]	Inlet temperature of fluid to collector
T_o	[°C]	Outlet temperature of fluid from collector

U_L	[kJ/h-m²-K]	Overall thermal loss coefficient of the collector per unit area
$U_{L/T}$	[kJ/h-m²-K²]	Thermal loss coefficient dependency on T (see Eq 5.10.1-5)
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above thehorizontal plane
θ	[°]	Incidence angle for beam radiation
ρ_g	[-]	Ground reflectance
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation

5.10.5.2   Mathematical Description

The energy collection of each module in an array of N_S modules in series is modeled according to the Hottel-Whillier equation such that (j is the module number):

$$\dot{Q}_u = \frac{A}{N_s} \sum_{j=1}^{N_s} F_{R,j}\left(I_T\left(\tau\alpha\right) - U_{L,j}\left(T_{i,j} - T_a\right)\right)$$

Eq 5.10.5-1

Where:

$$F_{R,j} = \frac{N_s \dot{m}_c C_{pc}}{A\, U_{L,j}}\left(1 - \exp\left(-\frac{F'U_{L,j}A}{N_s \dot{m}_c C_{pc}}\right)\right)$$

Eq 5.10.5-2

The collector fin efficiency factor, F', can be determined in a manner given in reference 2. The overall loss coefficient is a complicated function of the collector construction and its operating conditions. The following expression, developed by (Klein, 1975), is used to approximate $U_{L,j}$ in kJ/h-m²-K:

$$U_{L,j} = \frac{3.6}{\dfrac{N_G}{\dfrac{C}{T_{P,j}}\left[\dfrac{(T_{av,j} - T_a)}{N_G + f}\right]^{.33} + \dfrac{1}{h_w}}} + \frac{3.6\,\sigma\left(T_{av,j}^2 + T_a^2\right)(T_{av,j} + T_a)}{\dfrac{1}{\varepsilon_p + .05\,N_G(1 - \varepsilon_p)} + \dfrac{2N_G + f - 1}{\varepsilon_g} - N_G} + U_{be}$$

Eq 5.10.5-3

Where:

$$h_w = 5.7 + 3.8\ W\ (W/m^2\text{-}K)$$

$$f = (1 - 0.04\ hw + 0.0005\ hw^2)(1 + 0.091 N_G)$$

$$c = 365.9\ (1 - 0.00883\ \beta + 0.0001298\ \beta^2)$$

The overall transmittance-absorptance product is determined as:

$$(\tau\alpha) = \frac{I_{bT}(\tau\alpha)_b + I_d\left(\dfrac{1+\cos}{2}\right)(\tau\alpha)_s + \rho I\left(\dfrac{1-\cos\beta}{2}\right)(\tau\alpha)_g}{I_T}$$

Eq 5.10.5-4

The transmittance-absorptance products for beam, sky diffuse, and ground diffuse radiation are determined with function routine TALF (Section 3.4.3). Effective incidence angles for sky diffuse and ground reflected radiation are as defined in the mode I collector description. The outlet temperature of one module is used as the inlet to the next and is given as:

$$T_{o,j} = \frac{A F_{R,j}\ (I_T(\tau\alpha) - U_{L,j}\ (T_{i,j} - T_a))}{N_s \dot{m}_c C_{pc}} + T_i$$

Eq 5.10.5-5

If the collector flow is zero, the collector stagnation temperature is:

$$T_p = \frac{I_T(\tau\alpha)}{U_L} + T_a$$

Eq 5.10.5-6

5.10.5.3   References

Klein S.A., 1975. Calculation of flat-plate collector loss coefficients. Solar Energy, 17 (1). Pp. 79-80

5.10.6 Type 74: Compound Parabolic Concentrating Collector

This component models the thermal performance of a CPC collector. The total collector array may consist of collectors connected in series and in parallel. The thermal performance of the total collector array is determined by the number of modules in series and the characteristics of each module. The model provides for the theoretical analysis of compound parabolic concentrators (CPC). The Hottel-Whillier steady-state model is used for evaluating the thermal performance.

5.10.6.1 Nomenclature

A	[m²]	Total collector array aperture or gross area (consistent with $F_R(\tau\alpha)$, $F_R U_L$, $F_R U_{L/T}$ and G_{test})
A_a	[m²]	Aperture area of a single collector module
A_r	[m²]	Absorber area of a single collector module
A_s	[m²]	Receiver area of a single collector module
a_0	[-]	Intercept (maximum) of the collector efficiency (Eq 5.10.1-3)
a_1	[kJ/h-m²-K]	Negative of the first-order coefficient in collector efficiency equation
a_2	[kJ/h-m²-K²]	Negative of the second-order coefficient in collector efficiency equation
b_0	[-]	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation (Eq 5.10.1-13)
b_1	[-]	Negative of the 2nd-order coefficient in the IAM curve fit equation
C_{pf}	[kJ/kg-K]	Specific heat of collector fluid
C_{min}	[kJ/h-K]	Minimum capacitance rate (mass flow times specific heat) of heat exchanger flow streams
CR	[-]	Concentration ratio
F_R	[-]	Overall collector heat removal efficiency factor
F_{av}	[-]	Modified value of F_R when the efficiency is given in terms of T_{av}, not T_i
F_o	[-]	Modified value of F_R when the efficiency is given in terms of T_o, not T_i
F_{sky}	[-]	View factor to the sky
F_{gnd}	[-]	View factor to the ground
h	m	Height of full CPC with half acceptance angle θ_c
$\overline{h}$	m	Truncated height of CPC
I	[kJ/h-m²]	Global (total) horizontal radiation
I_d	[kJ/h-m²]	Diffuse horizontal radiation
I_T	[kJ/h-m²]	Global radiation incident on the solar collector (Tilted surface)
I_{bT}	[kJ/h-m²]	Beam radiation incident on the solar collector

$\dot{m}$	[kg/h]	Flowrate at use conditions
$\dot{m}_{test}$	[kg/h]	Flowrate in test conditions
N_S	[-]	Number of identical collectors in series
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i	[°C]	Inlet temperature of fluid to collector
T_o	[°C]	Outlet temperature of fluid from collector
U_L	[kJ/h-m²-K]	Overall thermal loss coefficient of the collector per unit area
$U_{L/T}$	[kJ/h-m²-K²]	Thermal loss coefficient dependency on T (see Eq 5.10.1-5)
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above thehorizontal plane
γ	[°]	Collector azimuth angle
γ_s	[°]	Solar azimuth angle
θ	[°]	Incidence angle for beam radiation
θ_c	[°]	Half-acceptance angle
θ_l	[°]	Longitudinal acceptance angle
θ_t	[°]	Transversal acceptance angle
ρ_g	[-]	Ground reflectance
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation

5.10.6.2   *Mathematical description*

A compound parabolic concentrating (CPC) collector consists of a concentrating reflector and an absorber. The walls of a 2-dimensional (trough-like) CPC are parabolic in shape. The focus of each parabola coincides with the intersection of the absorber and the opposite wall (see Figure 5.10.6–1). The CPC collects both beam and diffuse radiation, which approach the aperture within a critical angle θ_C, called the half-acceptance angle. A full CPC is one in which the walls extend upward to a height h which gives an aperture area of $l/\sin\theta_C$ times the absorber area. Optimal concentration is achieved in a full CPC, but a very large reflector area is required. In practice, most CPC's are truncated to a height $\bar{h} < h$. A CPC collector can be modeled in three steps. First, the total beam and diffuse radiation within the acceptance angle are determined. Next, reflector concentration and reflective loss are considered and the effective radiation striking the absorber is calculated. This effective radiation is then used to find the energy transferred to the collector flowstream and the resulting outlet temperature.

There are two possible orientations considered for a CPC receiver. First of all, the CPC axis may be located in a vertical plane that contains the surface azimuth. This is termed the longitudinal plane (see Figure 5.10.6–1). Beam radiation enters the CPC whenever $\theta_l \le \theta_c$ where:

$$\theta_1 = \left| \tan^{-1}\left(\tan\theta_z \cos(\gamma - \gamma_s) \right) - \beta \right|$$

<div align="right">Eq 5.10.6-1</div>

Alternatively, the CPC receiver may be located in a transverse plane 90° from the longitudinal orientation (see Figure 4.2.6.1). In this case, beam radiation enters the CPC when $\theta_t \le \theta_c$ where:

$$\theta_t = \tan^{-1}\left(\frac{\sin\theta_z \sin(\gamma - \gamma_s)}{\cos\theta} \right)$$

<div align="right">Eq 5.10.6-2</div>

Diffuse radiation entering the aperture is estimated using view factors to the sky and ground. For the longitudinal receiver orientation:

$$F_{sky} = \frac{1 + \cos\beta}{2CR}$$

<div align="right">Eq 5.10.6-3</div>

$$F_{gnd} = \frac{1 - \cos\beta}{2CR}$$

<div align="right">Eq 5.10.6-4</div>

and for the transverse receiver orientation:

$$F_{sky} = \frac{1/CR + \min(1/CR, \cos\beta)}{2}$$

<div align="right">Eq 5.10.6-5</div>

$$F_{gnd} = \frac{\max(1/CR, \cos\beta) - \cos\beta}{2}$$

<div align="right">Eq 5.10.6-6</div>
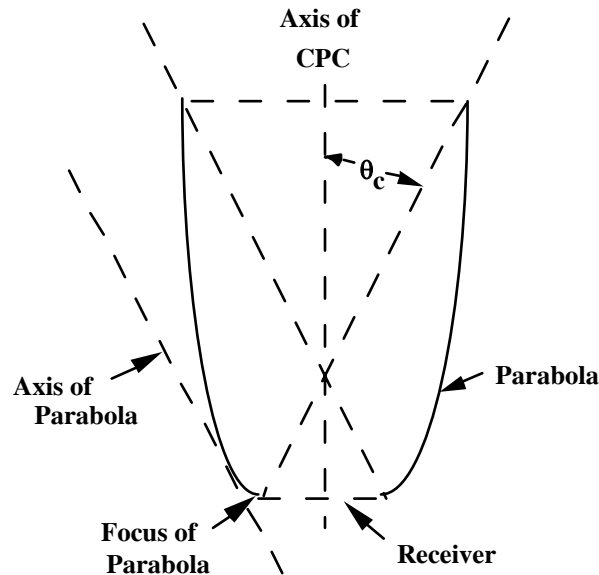
Figure 5.10.6–1: Cross-Section of a Non-Truncated CPC

The total radiation entering the reflector aperture within the acceptance angle is:

$$I_{in} = F_b I_{bT} + F_{sky} I_d + F_{gnd} \rho_g I \qquad \text{Eq 5.10.6-7}$$

where $F_b = I$ if the sun is within the acceptance angle, and $F_b = 0$ otherwise.

In discussing the reflector characteristics, it is helpful to use the coordinate system of Rabl shown in Figure 4.2.6.2. As given by Rabl, a branch of the CPC satisfies:

$$y = \frac{x^2}{2s \, (1 + \sin\theta_c)} \qquad \text{Eq 5.10.6-8}$$

and the x-coordinates of its endpoints are:

$$x_s = s \cos\theta_c \qquad \text{Eq 5.10.6-9}$$

and:

$$\bar{x} = s \left[\frac{1 + \sin\theta_c}{\cos\theta_c} \right] \left[-\sin\theta_c + \left(1 + \frac{\bar{h}}{h} \cot^2\theta_c \right)^{1/2} \right] \qquad \text{Eq 5.10.6-10}$$
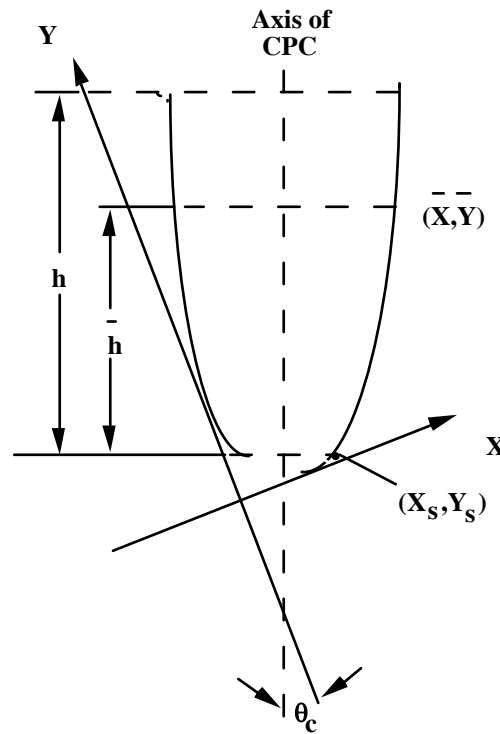
Figure 5.10.6–2: Geometry for Truncated CPC

The total radiation entering the collector aperture is $I_{in} \cdot A_a$. The total radiation incident on the absorber, ignoring reflective loss, may be written $I_R \cdot A_s$. Therefore, in passing from the aperture to the absorber, the radiation per unit area is increased by the concentration ratio:

$$CR = \frac{A_a}{A_s} = 2\left(\frac{\overline{x}}{s}\right)\cos\theta_c - \left(\frac{\overline{x}}{s}\right)^2 \frac{\sin\theta_c}{\sin\theta_c + 1} + \sin\theta_c - \cos^2\theta_c$$

Eq 5.10.6-11

For full CPC's, i.e. when $\overline{h}/h = l$, the concentration ratio is $l/\sin\theta_c$. The concentration ratio falls off from $l/\sin\theta_c$ as $\overline{h}/h$ decreases.

As radiation travels from the aperture to the absorber, some of it is reflected by the walls of the trough. If the walls are not perfect reflectors, there is some loss of radiation. To account for this reflective loss, one may define the effective reflectance of the reflector system as:

$$\rho_{eff} = \frac{I_R}{I_{in} \cdot CR}$$

Eq 5.10.6-12

As in the analysis of Rabl,

$$\rho_{eff} \approx \rho_R{}^n$$

Eq 5.10.6-13

where ρ_R is the wall reflectance and n is the average number of internal reflections.

The average number of internal reflections can be expressed as:

$$n = \frac{A_r}{A_s}\left(\frac{1}{2} - \frac{\overline{x} - x_s{}^2}{2A_r s \,(1 + \sin\theta_c)}\right)$$

Eq 5.10.6-14

with:

$$\frac{A_r}{A_s} = \left(1 + \sin\theta_c\right)\log\left[\frac{(\overline{x}/s) + \sqrt{\left(1 + \sin\theta_c\right)^2 + (\overline{x}/s)^2}}{\cos\theta_c + \sqrt{2\left((1 + \sin\theta_c\right)}}\right] + \left(\frac{\overline{x}}{s}\right)\sqrt{1 + \left(\frac{\overline{x}}{s(1 + \sin\theta_c)}\right)^2}$$

$$- \frac{\cos\theta_c\sqrt{2}}{\sqrt{1 + \sin\theta_c}}$$

Eq 5.10.6-15

It is interesting to note that both n and CR are independent of the absorber width s.

The CPC absorber is modeled using the Hottel-Whillier collector equation such that:

$$\dot{Q}_u = \frac{A\,F_R}{N_s}\sum_{j=1}^{N_s}\left(I_{in}\left(\tau\alpha\right) - U_{L,j}\left(T_{i,j} - T_a\right)\right)$$

Eq 5.10.6-16

where F_R is determined as in mode 3. The overall transmittance-absorbtance products is calculated as:

$$\left(\tau\alpha\right) = \frac{I_{bT}(\tau\alpha)_b + I_{dT}(\tau\alpha)_d}{I_T}$$

Eq 5.10.6-17

The transmittance-absorbtance products for beam and diffuse radiation are determined with function routine TALF using an effective absorbtance of $\rho_{eff} \cdot \alpha$. An equivalent incidence angle is defined for diffuse radiation as:

$$\theta_d = 44.86 - 0.0716\,\theta_c + 0.00512\,\theta_c^2 = 0.00002798\,\theta_c^3 \qquad \textbf{Eq 5.10.6-18}$$

Outlet and stagnation temperatures are calculated as in Type 73 (see section 5.10.5.2).

5.11   *Thermal Storage*

This section contains the following thermal storage components:

Type 4 (Stratified Storage Tank) models a stratified fluid storage tank (multi-node) with 2 optional internal auxiliary heaters. It is a robust model that provides a very good accuracy while keeping the parameter complexity and the computational effort reasonable. This is the most frequently used tank model in the standard library.

Type 60 (Detailed Fluid Storage Tank) is a more detailed model for stratified fluid storage tanks. In addition to the features of Type 4, It includes optional internal heat exchangers, which makes it suitable to model many commercially available Domestic Hot Water tanks for solar applications. It uses a detailed model that runs at an internal time steps and includes different iterative loops (for heat exchanger coefficients, node energy balance and internal heater control), which makes it more computationally intensive and less robust than Type 4. This component has been modified in TRNSYS 16 to take into account the most frequently reported problems in TRNSYS 15.

Type 10 (Rock Bed Storage) models a stratified (multi-node) rock bed storage. The storage is charged and discarged by blowing air respectively down and up the storage volume.

Type 38 (Plug-Flow Tank) models a stratified storage tank with a different approach from Type 4 and 60. It uses variable segments of fluid, which allows the model to simulate a particular zone of the tank using small segments without reauiring a large total number of nodes or small time steps.

Type 39 (Variable Volume Tank) models a fully mixed tank with constant cross-sectional area and a variable quantity of fluid.

5.11.1 Type 4: Stratified Fluid Storage Tank

The thermal performance of a fluid-filled sensible energy storage tank, subject to thermal stratification, can be modeled by assuming that the tank consists of N (N $\leq$ 15) fully-mixed equal volume segments, as shown in Figure 5.11.1–1. The degree of stratification is determined by the value of N. If N is equal to 1, the storage tank is modeled as a fully-mixed tank and no stratification effects are possible. Options of fixed or variable inlets, unequal size nodes, temperature deadband on heater thermostats, incremental loss coefficients, and losses to gas flue of auxiliary heater are all available.
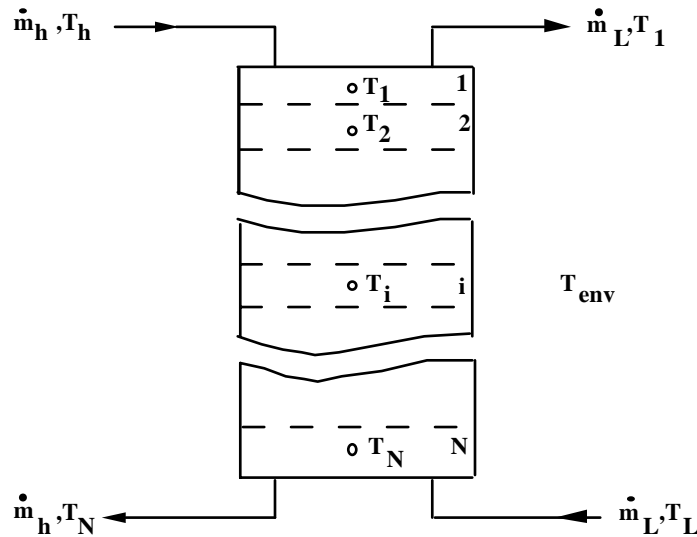
Figure 5.11.1–1: Stratified Fluid Storage Tank

5.11.1.1 Nomenclature

A_i surface area of the ith tank segment

C_{pf} specific heat of the tank fluid

H_i height of ith segment

i   tank segment with the top (hottest) segment having i = 1

I_1 number of the tank segment in which the first heater is located $1 \leq I \leq N$

I_2 number of the tank segment in which the second heater is located $1 \leq I \leq N$

IN_1 node position of entering flow from heat source $1 \leq I_T \leq N$

IN_2 node position of return flow from load $1 \leq I_T \leq N$

$I_{T,1}$ number of the tank segment in which the thermostat of the first heater is located $1 \leq I_{T,1} \leq N$

$I_{T,2}$ number of the tank segment in which the second heater thermostat is located $1 \leq I_{T,2} \leq N$

M_i mass of fluid in the ith section

$\dot{m}_L$ fluid mass flow rate to the load and/or of the makeup fluid

$\dot{m}_h$ fluid mass flow rate to tank from the heat source

N   number of fully mixed (uniform temperature) tank segments (N $\leq$ 15)

$\dot{Q}_{aux}$	total rate of energy input by the heater
$\dot{Q}_{aux,1}$	rate of energy input by the first auxiliary heater
$\dot{Q}_{aux,2}$	rate of energy input by the second auxiliary heater
$\dot{Q}_{env}$	rate of energy loss from the tank to the surroundings, including boiling effects if applicable
$\dot{Q}_{HE,1}$	maximum rate of energy input by the first heater
$\dot{Q}_{HE,2}$	maximum rate of energy input by the second heater
$\dot{Q}_i$	rate of energy input by the heating element to the ith segment
$\dot{Q}_{in}$	rate of energy input to tank from hot fluid stream
$\dot{Q}_{rec}$	the rate of energy input by the heater necessary for all segments $i \leq I$ to be raised to the set temperature
$\dot{Q}_s$	rate at which sensible energy is removed from the tank to supply the load
S_h	number of the tank segment to which the fluid from the heat source enters $1 \leq S_h \leq N$
S_L	number of the tank segment to which the fluid replacing that extracted to supply the load enters $1 \leq S_L \leq N$
t	time
$\overline{T}$	average storage temperature
T_{env}	temperature of the environment surrounding the tank
Ti	temperature of the ith tank segment
T_f	average temperature of exhaust flue when heater is not operating
T_h	temperature of the fluid entering the storage tank from the heat source
T_L	temperature of the fluid replacing that extracted to supply the load
$T_{set,1}$	set temperature of the first heater thermostat
$T_{set,2}$	set temperature of the second heater thermostat
U_t	loss coefficient between the tank and its environment (per unit area)
ΔU_i	incremental loss coefficient between the ith tank node and its environment (per unit area)
$(UA)_f$	total conductance for heat loss to gas flue when auxiliary heater is not operating
$(UA)_{f,i}$	conductance for heat loss to gas flue for node i
V_t	tank volume
ΔE	internal energy change of the tank
$\Delta T_{db,1}$	first thermostat temperature deadband. Heater turns on when $T_{IT1} = (T_{set,1} - \Delta T_{db,1})$ and stays on until $T_{IT1} = T_{set,1}$
$\Delta T_{db,2}$	second thermostat temperature deadband. Heater turns on when $T_{IT2} = (T_{set,2} - \Delta T_{db,2})$ and stays on until $T_{IT2} = T_{set,2}$
α_I	a control function defined by $\alpha_i = 1$ if $i = S_h$; 0 otherwise
β_i	a control function defined by $\beta_i = 1$ if $i = S_L$; 0 otherwise
γ_i	a control function defined by $\gamma_i = \dot{m}_h \sum\limits_{j=1}^{i-1} \alpha_j - \dot{m}_L \sum\limits_{j=i+1}^{N} \beta_j$

γ_f a control function that defines if the auxiliary heater is off or on. 1 is off, 0 is on

γ_{htr} an optional control function input (0 or 1) that disables or enables the internal auxiliary heater

ρ_f fluid density

5.11.1.2   Mathematical description

OPERATION MODES

In **mode 1**, flow streams enter the tank at fixed positions. The load flow enters at the bottom of the tank and the hot source stream enters just below the auxiliary, if present, or at the top of the tank if no auxiliary is specified. At the end of each time interval, any temperature inversions that exist are eliminated by total mixing of the appropriate adjacent nodes.

In **mode 2**, the flowstream enters the node that is closest to it in temperature. With sufficient nodes, this permits a maximum degree of stratification.

In **mode 3**, the user must specify the nodes containing the load flow and source flow inlet locations.

The user may specify the height of each node using parameters 6 through 5+N. Optionally, equal size nodes may be specified most simply by setting parameter 6 to a negative number such that the total tank height is the absolute value of parameter 6. In this case, no additional node size specifications are required.

INTERNAL AUXILIARY HEATERS

The model optionally includes two electric resistance heating elements, subject to temperature and/or time control. The control option allows the addition of electrical energy to the tank during selected periods of each day (e.g., off-peak hours). The electric resistance heaters may operate in one of two modes. The first mode, a master/slave relationship, allows the bottom heating element to be enabled only when the top element is satisfied. In this control mode, it is impossible for both electric heaters to be on simultaneously. However, it is possible for both heaters to be on during the same timestep (upper heater may be on during first half of the timestep and lower heater may be on during the second half of the timestep). Mode 1 is common to most domestic hot water applications. In mode 2, both heaters may be on simultaneously. This allows for quicker heating of the storage tank, but at a significantly higher electric demand. If no electric heating elements are present in the tank to be modeled, set the maximum auxiliary heating rate to zero (do not set the node locations to zero).

The auxiliary heaters employ a temperature deadband. The heater is enabled if the temperature of the node containing the thermostat is less than ($T_{set} - \Delta T_{db}$) or if it was on for the previous interval and the thermostat temperature is less than T_{set}. If the lower heater meets these criteria and the master/slave relationship is employed, a check will be made to see if the upper electric heater is on before enabling the second heating element.

THERMAL LOSSES

In many circumstances, the tank may not be uniformly insulated or users may wish to account for pipe entrances on the storage tank. With version 14, it became possible for users to incrementally insulate certain nodes of stratified storage tanks by the specification of additional parameters. To utilize the incremental loss coefficients, users must set the fifth parameter less than zero and specify the incremental loss coefficients. The loss coefficient for the ith node is then:

$$U_i = |PAR\ 5| + \Delta U_i$$

A pressure relief valve has been added to the storage tank to account for boiling effects. The user must specify the boiling temperature of the fluid; venting will release sufficient energy to keep the tank at the boiling temperature. The loss of mass due to venting has been neglected.

The model allows for losses to the exhaust flue of an in-tank gas auxiliary heater. The overall loss from any node above and including the auxiliary heater occurs from the exterior and interior of the tank. The user specifies the overall conductance for heat loss to the flue when the heater is not operating, $(UA)_f$, based upon an environmental temperature of T_{env}. This conductance is divided among the nodes above and including the heater.

FLOW STREAMS

An assumption, employed in this model, is to assume that the fluid streams flowing up and down from each node are fully mixed before they enter each segment. In terms of Figure 5.11.1–2, this implies that $\dot{m}_1$ is added to $\dot{m}_4$, $\dot{m}_2$ is added to $\dot{m}_3$, and a resultant flow, either up or down, is determined. An energy balance on the ith segment (neglecting losses) is then:

$$M_i C_{pf} \frac{dT_i}{dt} = \begin{cases} (\dot{m}_1 - \dot{m}_3)\, C_{pf}\,(T_{i-1} - T_i) & \dot{m}_1 \geq \dot{m}_3 \\ (\dot{m}_3 - \dot{m}_1)\, C_{pf}\,(T_{i+1} - T_i) & \dot{m}_1 < \dot{m}_3 \end{cases} \qquad \textbf{Eq 5.11.1-1}$$

It has been found that this latter assumption generally permits a higher degree of stratification than the former and yields results that agree well with experimental measurements (1).
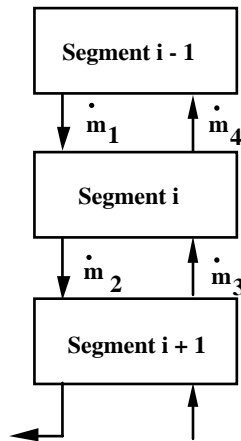
Figure 5.11.1–2: Flowstreams between Segments

The auxiliary heater is off if $\gamma_{htr} = 0$ or if it was previously off and $T_{IT} \geq (T_{set} - \Delta T_{db})$ or if $T_{IT} \geq T_{set}$. Otherwise, the rate of energy delivered to the tank from the heater is $\dot{Q}_{aux} = \min(\dot{Q}_{reg}, \dot{Q}_{max})$. If a master/slave relationship is specified between the two auxiliary heaters, the lower auxiliary heater is also off if the first auxiliary heater is on. The model assumes that energy supplied to the tank from the heater is placed in the tank segment containing the heater, until the temperature of that segment is equal to that of the segment above. Then, energy is added equally to both segments until they reach the temperature of the segment above them, etc. If both heating elements are allowed to be on simultaneously, the upper element effects are calculated first, followed by the lower element.

An energy balance written about the ith tank segment is expressed:

$$M_i C_{pf} \frac{dT_i}{dt} = \alpha_i \dot{m}_h C_{pf}(T_h - T_i) + \beta_i \dot{m}_L C_{pf}(T_L - T_i) + UA_i(T_{env} - T_i)$$

$$+\gamma_i(T_{i-1} - T_i)C_{pf} \qquad \text{if } g_i > 0$$

Eq 5.11.1-2

$$+\gamma_i(T_i - T_{i+1})C_{pf} \qquad \text{if } g_i < 0$$

$$+\dot{Q}_i \qquad \text{for } i = 1,N$$

The temperatures of each of the N tank segments are determined by the integration of their time derivatives expressed in the above equation as outlined in Section 1.10. At the end of each timestep, temperature inversions are eliminated by mixing appropriate adjacent nodes.

Energy flows and change in internal energy are calculated as follows:

$$\dot{Q}_{env} = \sum_{i=1}^{N} UA_i(T_i - T_{env}) + \gamma_f \sum_{i=1}^{i=l} (UA)_{f,i}(T_i - T_f) \qquad \text{**Eq 5.11.1-3**}$$

$$\dot{Q}_s = \dot{m}_L C_{pf}(T_1 - T_L) \qquad \text{**Eq 5.11.1-4**}$$

$$\dot{Q}_{in} = \dot{m}_h C_{pf}(T_h - T_N) \qquad \text{**Eq 5.11.1-5**}$$

$$\Delta E = \frac{V \rho_f C_{pf} \left[\sum_{i=1}^{N} T_i - \sum_{i=1}^{N} T_i \Big|_{t=TIME0} \right]}{N} \qquad \text{**Eq 5.11.1-6**}$$

5.11.1.3   References

1. Klein, S.A., "A Design Procedure for Solar Heating Systems", Ph.D. Thesis, Department of Chemical Engineering, University of Wisconsin-Madison, (1976)

5.11.2 Type 10: Rock bed storage

This component models a packed bed of graded pebbles (rocks). Hot air, the usual working fluid, enters the rock bed at the top and transfers heat to the pebbles. The storage can then be discharged by running cold air from the bottom to the top of the bed.

> The model does not allow airflows in both directions at the same time.

5.11.2.1 Nomenclature

A	cross-sectional area of the rock pile
C_p	specific heat of air
C_r	specific heat of rock
h_v	volumetric heat transfer coefficient between air and rocks
k	effective thermal conductivity of the rock bed in the axial direction
L	length of the rock bed in the flow direction
$\dot{m}$	air mass flow rate
P	perimeter of rock bed wall
$\dot{Q}_{env}$	rate of energy loss from rock bed to surroundings
$\dot{Q}_s$	rate at which energy is removed from the rock bed to meet the load
$\overline{T}$	average rock bed temperature
T	air temperature
T_{env}	temperature of surroundings
T_{in}	temperature of air entering the rock bed
T_r	rock temperature
T_i	temperature of air and rock in segment i
t	time
U	loss coefficient from the rock bed to the environment
V	volume of rock bed = AL
ΔE	change in internal energy of the rock bed
ε	$\dfrac{h_v V}{\dot{m}C_p}$ = NTU of the rock bed
ρ_r	apparent rock density (accounting for voids)
t	$\dfrac{V\rho_r C_r}{\dot{m}C_p}$

5.11.2.2   *Mathematical Description*

EQUATIONS WITHOUT AXIAL CONDUCTION

Rock bed thermal storage can be described by the relations governing heat transfer for fluid flow in packed beds. Neglecting temperature gradients within the rocks, axial conduction and assuming a uniform flow distribution of air through the bed, the following two partial differential equations describe the air and rock temperatures as a function of bed position and time.

$$\frac{\partial T_r}{\partial t} = \frac{\varepsilon}{\tau}(T - T_r)$$ (Eq 5.12.2.1)

$$\frac{\partial T}{\partial (X/L)} = \varepsilon(T_r - T) - \left(\frac{UPL}{\dot{m}C_p}\right)(T - T_{env})$$ (Eq 5.12.2.2)

These equations can be solved by finite difference methods. However, small time steps and many nodes are required to maintain accuracy. As a result, the use of this model in simulations for extended periods (e.g., a heating season or a year) becomes expensive in terms of computing costs.

The results of many simulations of air heating systems in which (Eq 5.12.2.1) and (Eq 5.12.2.2) have been used to describe the rock bed behavior, have shown that the system performance has an asymptotic dependence upon ε. For values of e greater than ~10, (which is generally much lower than the values encountered in most practical designs) the system performance is independent of ε (l); ε may be increased without bound without affecting system performance significantly.

This observation indicates that a rock bed model in which $\varepsilon \rightarrow \infty$ may be applicable in most cases. The equations describing the air and rock temperatures for $\varepsilon \rightarrow \infty$ are given in (Eq 5.12.2.3) and (Eq 5.12.2.4).

$$-A\rho_r C_r \frac{\partial T}{\partial t} = \dot{m}C_p \frac{\partial T}{\partial X} + UP(T - T_{env})$$ (Eq 5.12.2.3)

$$T_r = T$$ (Eq 5.12.2.4)

(Eq 5.12.2.3) and (Eq 5.12.2.4) can be solved with significantly less computational effort than (Eq 5.12.2.1) and (Eq 5.12.2.2).

For rock bed designs in which $\varepsilon > 10$, the solution of (Eq 5.12.2.3) and (Eq 5.12.2.4) is nearly identical to that of (Eq 5.12.2.1) and (Eq 5.12.2.2). In addition, it is possible to include axial conduction, since this situation is easily handled as shown in the next section.

EQUATIONS WITH AXIAL CONDUCTION

The partial differential equation describing both air and rock temperatures (considering axial conduction and losses to the surroundings) is given in (Eq 5.12.2.5)

$$- A\rho_r C_r \frac{\partial T}{\partial t} = \dot{m}C_p \frac{\partial T}{\partial x} + UP(T - T_{env}) - kA \frac{\partial^2 T}{\partial x^2} \qquad \text{(Eq 5.12.2.5)}$$

In order to solve this equation, the rock bed is divided into segments, as shown in Figure 5.11.2–1, in a manner analogous to that used for the thermally stratified fluid storage tank (Type 4). An ordinary differential equation can then be written for each segment, using finite difference methods.
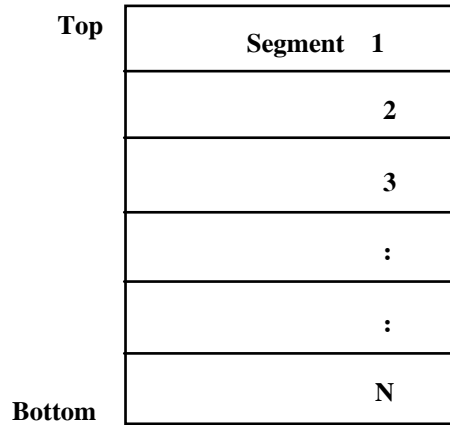
Figure 5.11.2–1: Rockbed segmentation

The N differential equations can be expressed:

For Air Flow Downwards (i.e., from segment 1 towards segment N)

for i = 1:

$$\frac{V}{N}\rho_r C_r \frac{dT_1}{dt} = \dot{m}C_p(T_{in} - T_1) - \frac{UPL}{N}(T_1 - T_{env}) - \frac{kA}{L/N}(T_1 - T_2) \qquad \text{(Eq 5.12.2.6)}$$

for i = 2, N - 1:

$$\frac{V}{N}\rho_r C_r \frac{dT_i}{dt} = \dot{m}C_p(T_{i-1} - T_i) - \frac{UPL}{N}(T_i - T_{env}) - \frac{kA}{L/N}(T_{i-1} - T_i) - \frac{kA}{L/N}(T_i - T_{i+1}) \qquad \text{(Eq 5.12.2.7)}$$

for i = N:

$$\frac{V}{N}\rho_r C_r \frac{dT_N}{dt} = \dot{m}C_p(T_{N-1} - T_N) - \frac{UPL}{N}(T_N - T_{env}) - \frac{kA}{L/N}(T_{N-1} - T_N) \qquad \text{(Eq 5.12.2.8)}$$

<u>For Air Flow Upwards</u> (i.e., from segment N towards segment 1)

for i = N:

$$\frac{V}{N}\rho_r C_r \frac{dT_N}{dt} = \dot{m}C_p(T_{in} - T_N) - \frac{UPL}{N}(T_N - T_{env}) - \frac{kA}{L/N}(T_N - T_{n-1})$$

(Eq 5.12.2.9)

for i = 2, N - 1:

$$\frac{V}{N}\rho_r C_r \frac{dT_i}{dt} = \dot{m}C_p(T_{i+1} - T_i) - \frac{UPL}{N}(T_i - T_{env}) - \frac{kA}{L/N}(T_{i-1} - T_i) - \frac{kA}{L/N}(T_i - T_{i+1})$$

(Eq 5.12.2.10)

for i = 1

$$\frac{V}{N}\rho_r C_r \frac{dT_1}{dt} = \dot{m}C_p (T_2 - T_1) - \frac{UPL}{N}(T_1 - T_{env}) - \frac{kA}{L/N}(T_2 - T_1)$$

(Eq 5.12.2.11)

A value of N = 5 is recommended.

5.11.2.3   References

1. Hughes, P.M., Klein, S.A., and Close, D., "Packed Bed Thermal Storage Models for Solar Air Heating and Cooling Systems", Journal of Heat Transfer, May (1976).

5.11.3 Type 38: Algebraic tank (Plug-flow)

This component models the behavior of a temperature stratified storage tank using variable size segments of fluid. The size of segments is governed by the simulation time step, the magnitude of collector and load flow rates, heat losses and auxiliary input. The main advantage over fixed node simulation techniques (eg. Type 4) is that temperature stratification can be modeled with small segments in the temperature gradient zone without the need to use small simulation time steps to obtain a "good" solution. This model is most appropriate for tanks that exhibit a large degree of stratification.

There are two modes of operation. In mode 1, the tank has fixed inlet positions and the flow mixes with adjacent segments if its temperature is within 1/2 degree. Otherwise a new segment is created and temperature inversions are corrected by mixing appropriate segments above or below the inlets. In mode 2, the tank has variable inlet positions and new segments are inserted at the levels which produce no temperature inversions. This allows a maximum degree of stratification and is equivalent to the Type 4 model with a large number of nodes.

This "plug-flow" tank model is very similar to the extended SOLSYS model outlined in reference 1 with the additional features:

- An optional auxiliary heater subject to temperature and/or time control,

- conduction between segments,

- upright or horizontal cylindrical tanks, and

- different insulation thicknesses on the top and sides of upright tanks or eccentric location of the tank in the insulation jacket for horizontal tanks.

> Only one unit of Type 38 can be used per simulation.

5.11.3.1 Nomenclature

C_p	specific heat of fluid
H_a	height of auxiliary heater above bottom of tank
H_t	height of tank
H_{th}	height of thermostat above bottom of tank
H_r	height of entry of hot stream (above bottom of tank)
k	thermal conductivity
$\dot{m}_h$	mass flow rate of hot stream entering tank
$\dot{m}_L$	mass flow rate of load
$\dot{Q}_{aux}$	rate of auxiliary energy input to tank
$\dot{Q}_{env}$	rate of energy loss from tank
$\dot{Q}_{he}$	maximum rate of energy input to tank by auxiliary
$\dot{Q}_{in}$	rate of energy input to tank from hot fluid stream
$\dot{Q}_{sup}$	rate of energy supplied to load by tank

r_i	ratio of insulation thickness of top to sides of upright tanks or top to bottom insulation ratio for horizontal tanks
T_D	temperature of water delivered by tank to load
T_{env}	environmental temperature for losses
T_h	temperature of hot fluid entering tank
T_i	temperature of ith segment
T_I	initial temperature of preheat portion of tank
T_L	temperature of load stream entering tank
T_R	temperature of fluid return to heat source
T_{set}	thermostat set temperature
$\overline{T}$	average tank temperature
V_h	volume of fluid entering tank from heat source over a time interval Δt
V_i	volume of ith segment
V_L	volume of fluid entering tank from load over a time interval Dt
V_t	tank volume
UA	overall UA value of tank
$(UA)_f$	overall conductance for heat loss to flue of gas heater
ΔE	change in internal energy storage
Δt	simulation timestep
ΔT_{db}	thermostat temperature deadband
ρ	fluid density
γhtr	optional control function input (0 to 1) that disables or enables auxiliary heater

5.11.3.2   Mathematical Description

Figure 5.11.3–1 illustrates the concept of this tank model. In this example, the tank is initially divided into four segments of volume V_i and temperature T_i, so that no temperature inversions are present. In one time period, the heat source delivers a volume of liquid, V_h, equal to $\dot{m}_h \Delta t / \rho$ at a temperature T_h. Assuming T_h is greater than T_1, then a new segment is added at the top of the tank and the existing profile is shifted. At the same time, the fluid enters from the load with a volume, V_L, equal to $\dot{m}_L \Delta t / \rho$ and temperature of T_L. If T_L is less than T_4, then a segment is added at the bottom of the tank and the profile is shifted once more. The net shift of the profile in the tank is equal to the difference between the total heat source volume and load volume or $(\dot{m}_h - \dot{m}_L)\Delta t / \rho$. The segments and/or fraction of segments whose positions fall outside the bounds of the tank are returned to the heat source and load. The average temperature delivered to load for the example of Figure 5.11.3–1 is:

$$T_D = \frac{V_h T_h + (V_L - V_h)T_1}{V_L} \qquad \text{(Eq 5.12.3.1)}$$

and the average heat source return temperature, T_R, is equal to T_L. In general, for N segments the average delivery and heat source return temperatures are computed as follows:

If $V_h < V_L$, then

TR = TL

$$T_D = \left(V_h T_h + \sum_{i=1}^{k-1} T_i V_i + a T_k V_k \right) / V_L \qquad \text{(Eq 5.12.3.2)}$$

where a and k must satisfy

$0 \leq a \leq 1$

$$V_h + \sum_{i=1}^{k-1} V_i + a V_k = V_L \qquad \text{(Eq 5.12.3.3)}$$

If $V_h > V_L$, then

TD = Th

$$T_R = \left(V_L T_L + \sum_{i=k+1}^{N} T_i V_i + a T_k V_k \right) / V_h \qquad \text{(Eq 5.12.3.4)}$$

where a and k must satisfy

$0 \leq a \leq 1$

$$V_L + \sum_{i=k+1}^{N} T_i V_i + a T_k V_k = V_h \qquad \text{(Eq 5.12.3.5)}$$

In mode 1, the average delivery and heat source return temperatures are computed after the profile has been corrected for temperature inversions. Segments are combined until the equilibrium temperatures result in no temperature inversions. This process begins at each inlet and proceeds in the direction of the inversion.

The optional auxiliary heater is modeled as in the Type 4 component. If necessary, the segment containing the auxiliary is split into two segments at the actual position of the auxiliary. The auxiliary is on if the temperature of the segment containing the thermostat is either less than T_{set}-Δt_{db} or if the auxiliary was on for the previous time interval and the thermostat temperature is less than T_{set}. The segment containing the auxiliary is heated first, until it reaches the temperature of the segment above. These two segments are then heated together until they reach the temperature of the segment above them. This process continues until either the maximum heater input is used or the set temperature is reached. If a load flow is occurring and auxiliary is able to heat the top segment, then the delivered fluid is heated with a linear temperature profile.

Storage losses from the tank and conduction between segments are evaluated before the temperature profile has been adjusted for flows and auxiliary heat input. This is accomplished by solving the following differential equation for each segment:

$$\rho C_p V_i \frac{dT_i}{dt} = -(UA)_i (T_i - T_{env}) + (kA)_{i-1} \frac{(T_{i-1} - T_i)}{\Delta h_{i-1}} - (kA)_i \frac{(T_i - T_{i+1})}{\Delta h_{i+1}} \qquad \text{(Eq 5.12.3.6)}$$

where Δh_{i-1} = separation between centers of segments i-1 and i, and Δh_{i+1} = separation between centers of segments i and i+1.
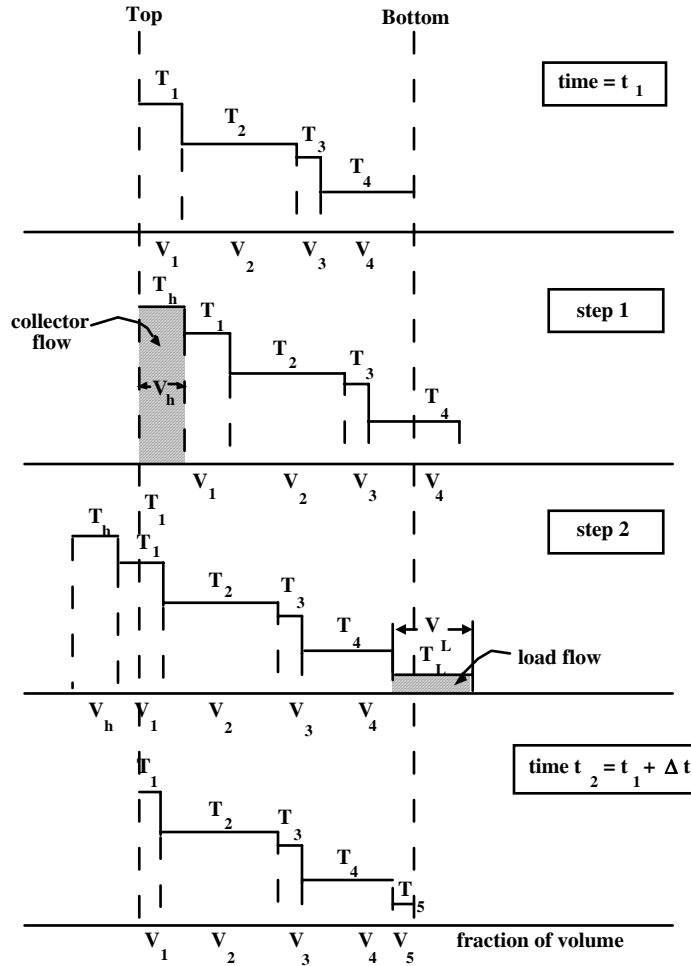
Figure 5.11.3–1: Example of the Extended SOLSYS SYSTEM (adapted from ref. 1)

When conduction is included, the set of coupled differential equations is solved by successive substitution. Conduction down the walls of the tank can be included by using an effective conductivity.

The overall conductance for heat loss from any segment, $(UA)_i$, depends upon its surface area and a user-supplied overall loss conductance UA. In addition an optional conductance for heat loss to a gas heater flue when the auxiliary is not operating can also be specified.

The total loss from the tank is:

$$\dot{Q}_{env} = \sum_{i=1}^{N} (UA)_i (T_i - T_{env})$$

(Eq 5.12.3.7)

The energy input to the tank due to the hot inlet stream is

$$\dot{Q}_{in} = \dot{m}_h C_p (T_h - T_R)$$

(Eq 5.12.3.8)

The energy supplied to the load is

$$\dot{Q}_{sup} = \dot{m}_L C_p (T_D - T_L)$$
(Eq 5.12.3.9)

The change in internal energy of storage is

$$\Delta E = \rho C_p \left(\sum_{i=1}^{N} V_i T_i - \sum_{i=1}^{N} V_i T_i \Big|_{t=TIME0} \right)$$
(Eq 5.12.3.10)

5.11.3.3   References

1. Kuhn, J.K. VanFuchs, G.F., and Zob, A.P., "Developing and Upgrading of Solar System Thermal Energy Storage Simulation Models," Draft Report for DOE, Boeing Computer Services Company, August 31 (1980).

5.11.4   Type 39: Variable volume tank

This component models a fully-mixed tank with a constant cross-sectional area that contains a variable quantity of fluid. In its simplest form, a single flow enters from a hot source and a single flow stream exits to a load as illustrated in Figure 5.11.4–1 (a). Since the incoming and outgoing flows need not be equal, the level of fluid in the tank can vary. The level is allowed to vary between user specified high and low level limits. If the lower limit is reached, the load flow necessary to maintain this level is output rather than the desired load flow. If the volume of fluid exceeds the upper limit, then the excess flow necessary to keep the tank at the upper limit is set as an output. There are two modes for handling excess flow when the upper limit is reached. In mode 1, excess flow mixes with the contents of the tank to simulate a recirculation flow stream as illustrated in Figure 5.11.4–1 (b). In this case, the temperature of the excess flow stream is the temperature of the contents of the tank. In mode 2, the excess incoming fluid stream is diverted from the tank as illustrated in Figure 5.11.4–1 (c). The temperature of the diverted stream is equal to that of the incoming flow stream.
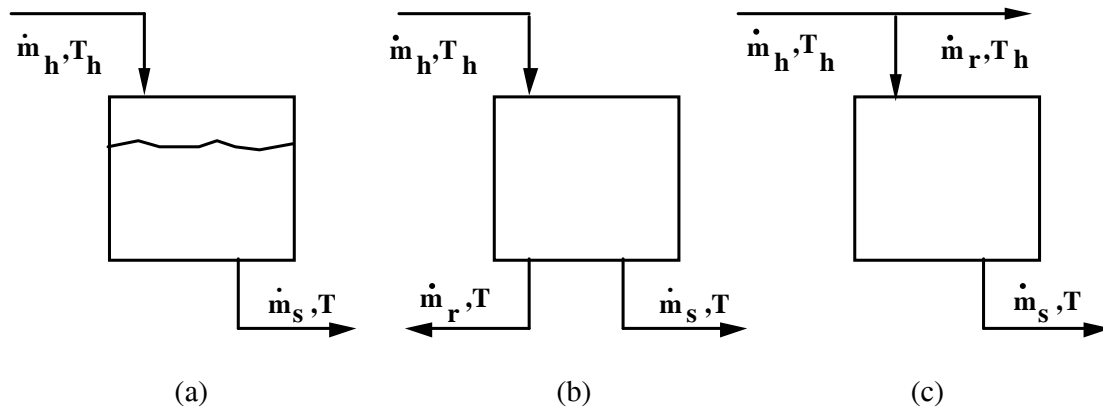
Figure 5.11.4–1: Variable Volume Tank Configurations

5.11.4.1   Nomenclature

A_x cross-sectional area of tank

C_{pf} specific heat of fluid in tank

C_x circumference of tank

$\dot{m}_h$ flow rate of incoming hot stream

$\dot{m}_i$ net incoming flow rate; $\dot{m}_h$ in mode 1; $\dot{m}_h - \dot{m}_r$ in mode 2

$\dot{m}_L$ flow rate required by load

$\dot{m}_o$ net flow leaving tank; $\dot{m}_s - \dot{m}_r$ in mode 1; $\dot{m}_s$ in mode 2

$\dot{m}_r$ flow rate of recirculation or diverted stream necessary to keep fluid level at the upper limit

$\dot{m}_s$ actual flow rate supplied to load

M instantaneous mass of fluid in tank

$\overline{M}$ average mass of fluid in tank over the timestep

M_I initial mass of fluid in tank

M_τ mass of fluid in tank at end of timestep

$M_{\tau-\Delta t}$	mass of fluid in tank at beginning of timestep
$\dot{Q}_{env}$	energy loss rate from tank to environment
t	time
T	instantaneous temperature of fluid in tank
$\overline{T}$	average fluid temperature in tank over timestep
T_{env}	environmental temperature for losses from tank
T_h	temperature of incoming hot flow stream
T_I	initial temperature of fluid in tank
T_τ	temperature of fluid at end of timestep
$T_{\tau-\Delta t}$	temperature of fluid at beginning of timestep
U_d	loss coefficient for dry portion of tank
U_w	loss coefficient for wetted portion of tank
$(UA)_t$	overall conductance for heat loss from tank
V_I	initial volume of fluid in tank
$\overline{V}$	average volume of fluid over timestep
V_{min}	minimum allowable volume of fluid in tank
V_{max}	maximum allowable volume of fluid in tank
V	volume of tank
ΔE	change in internal energy of fluid in the tank since the beginning of the simulation
$\Delta\dot{H}$	difference between the enthalpies of the outgoing and incoming flowstream per unit time
Δt	simulation timestep
ρ_f	fluid density

5.11.4.2   Mathematical Description

The variable volume tank is modeled as a fully-mixed variable mass of water. The two differential equations describing the rate of change of mass and internal energy are:

$$\frac{dM}{dt} = \dot{m}_i - \dot{m}_o \qquad\qquad \text{(Eq 5.12.4.1)}$$

$$C_{pf}\frac{d(MT)}{dt} = \dot{m}_i C_p T_h - \dot{m}_o C_p T - (UA)_t(T-T_{env}) \qquad\qquad \text{(Eq 5.12.4.2)}$$

The net flow into the tank, $\dot{m}_1$, is $\dot{m}_h$ in Mode 1 and $\dot{m}_h - \dot{m}_r$ in Mode 2. The net flow leaving the tank is $\dot{m}_s - \dot{m}_r$ in Mode 1 and $\dot{m}_s$ in Mode 2.

The solutions of (Eq 5.12.4.1) for the final and average mass for a given timestep are:

$$M_\tau = M_{\tau-\Delta t} + (\dot{m}_i - \dot{m}_o)\Delta t \qquad\qquad \text{(Eq 5.12.4.3)}$$

$$\overline{M} = \frac{M_\tau + M_{\tau-\Delta t}}{2} \qquad\qquad \text{(Eq 5.12.4.4)}$$

Simultaneous solution of (Eq 5.12.4.1) and (Eq 5.12.4.2) for final and average fluid temperatures for a timestep gives

$$T_\tau = \frac{a}{b} + \left(T_{\tau - \Delta t} - \frac{a}{b} \right) \left(1 + \frac{c\Delta t}{M_{\tau - \Delta t}} \right)^{-b/c} \qquad \text{(Eq 5.12.4.5)}$$

$$\overline{T} = \frac{a}{b} + \frac{M_{\tau\text{-}\Delta t} \left(T_{\tau\text{-}\Delta t} - \frac{a}{b} \right)}{(c\text{ - }b)\Delta t} \left(\left(1 + \frac{C\Delta t}{M_{\tau\text{-}\Delta t}} \right)^{(1\text{-}b/c)} - 1 \right) \qquad \text{(Eq 5.12.4.6)}$$

where,

$$a = \dot{m}_i T_h + \frac{(UA)_t}{C_{pf}} T_{env}$$

$$b = \dot{m}_i + \frac{(UA)_t}{C_{pf}}$$

$$c = \dot{m}_i - \dot{m}_o$$

For the situation where the incoming flow equals the total outgoing flow (i.e. no net change in mass), the following differential equation results:

$$M_{\tau\text{-}\Delta t} \frac{dT}{dt} = \dot{m}_i (T_h - T) - \frac{(UA)_t}{C_{pf}} (T - T_{env}) \qquad \text{(Eq 5.12.4.7)}$$

This equation is solved analytically.

The change internal energy, the difference in enthalpies per unit time between outgoing and incoming flow streams, and energy loss rate are calculated as:

$$\Delta E = C_{pf} \cdot \left(M_\tau T_\tau - M_I T_I \right) \qquad \text{(Eq 5.12.4.8)}$$

$$\Delta \dot{H} = \dot{m}_i C_{pf} T_h - \dot{m}_o C_{pf} \overline{T} \qquad \text{(Eq 5.12.4.9)}$$

$$\dot{Q}_{env} = (UA)_t \left(\overline{T} - T_{env} \right) \qquad \text{(Eq 5.12.4.10)}$$

The overall conductance for heat loss from the tank, $(UA)_t$, is calculated based upon average wetted and dry areas for the current timestep and user specified wet and dry loss coefficients.

5.11.5 Type 60: Stratified fluid storage tank with internal heat exchangers

This component models a stratified fluid storage tank with optional internal heaters and optional internal heat exchangers. This is the most detailed tank model available in the standard TRNSYS library.

5.11.5.1 Nomenclature

$A_{c,i}$	cross-sectional area of node i
$A_{s,i}$	surface area of node i
C	Constant (multiplier) in Nusselt number correlation
C_p	Tank Fluid specific heat
d_i , d_o	inside and outside diameters of heat exchanger tubes
h_o	outside convection coefficient for internal heat exchanger
i	node index. **i=1 is the top node, i=N is the bottom node**
k	tank fluid thermal conductivity
M_i	Mass of node i
$\dot{m}_{1in}$, $\dot{m}_{1out}$	Mass flowrate entering at inlet 1 – Mass flowrate leaving at outlet 1
$\dot{m}_{2in}$, $\dot{m}_{2out}$	Mass flowrate entering at inlet 2 – Mass flowrate leaving at outlet 2
$\dot{m}_{down}$	bulk fluid flowrate down the tank
$\dot{m}_{up}$	bulk fluid flowrate up the tank
n	exponent in Nusselt number correlation
N	Number of nodes
N_{uD}	Nusselt number for external flow around a tube of diameter D
Ra	Rayleigh number
t	time
T_{1in} , T_{1out}	Temperature at inlet 1 – Temperature at outlet 1
T_{2in} , T_{2out}	Temperature at inlet 2 – Temperature at outlet 2
T_{env}	Environment temperature
T_i	Temperature of node i
T_{set}	Setpoint temperature for a thermostat
T_{statN}	Temperature of the node containing the Nth thermostat
UA_{hx}	Heat exchanger overall UA value
U_i	Total loss coefficient for node i
U_{tank}	Loss coefficient (per unit area) of the tank
Δk	de-stratification conductivity
ΔT_{db}	Temperature dead band for a thermostat
ΔU_i	Additional loss coefficient for node i
$\Delta x_{i+1 \rightarrow i}$	center-to-center distance between node I and the node below it (i+1)
$\Delta x_{i-1 \rightarrow i}$	center-to-center distance between node I and the node above it (i-1)
γ_{htr}	heater control signal

5.11.5.2   Mathematical description

GENERAL DESCRIPTION

The thermal performance of a water-filled sensible energy storage tank, subject to thermal stratification, can be modeled by assuming that the tank consists of N (N $\leq$ 100) fully-mixed equal volume segments, as shown in Figure 5.11.5–1. The degree of stratification is determined by the value of N. If N is equal to 1, the storage tank is modeled as a fully-mixed tank and no stratification effects are possible.   Options of fixed or variable inlets, unequal size nodes, temperature dead band on heater thermostats, incremental loss coefficients, internal submersed heat exchangers, non-circular tanks, horizontal tanks, and losses to the flue of a gas auxiliary heater are all available.
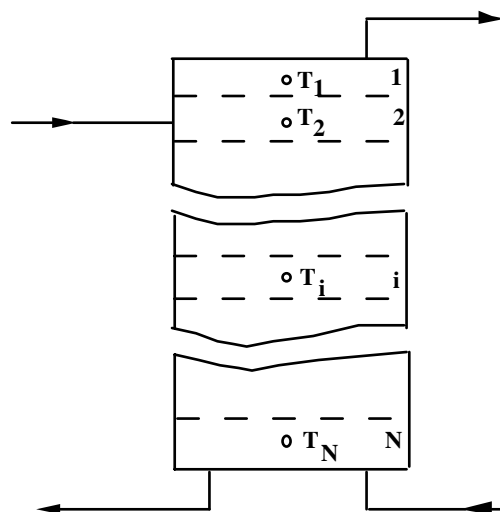
Figure 5.11.5–1: Stratified Fluid Storage Tank

To make it simple to change the number of nodes, tank component locations are entered as heights, measured from the floor up, rather than node numbers.   These components include: inlet and outlet flows, auxiliary heaters, thermostats, and heat exchangers.

There are two **inlet modes** available. In mode 1, the flow stream enters the node that is closest to it in temperature. With sufficient nodes, this permits a maximum degree of stratification. In mode 2, flow streams enter the tank at fixed positions, as specified by the user. At the end of each time interval, any temperature inversions that exist are eliminated by mixing of the appropriate adjacent nodes.

The **user may specify the height of each node** using the last set parameters. Optionally, equal size nodes may be specified quite simply by setting parameter 31 to zero.   The model will automatically divide the tank into equal segments.   In this case, no additional node size specifications are required.

The **volume of the tank** used by the model is assumed to be the actual volume of the tank.   A 300-liter hot water heater does not necessarily hold 300 liters of water.

OPTIONAL INTERNAL HEATERS

The model optionally includes two **electric resistance heating elements**, subject to temperature and/or time control. The control option allows the addition of electrical energy to the tank during

selected periods of each day (e.g., off-peak hours). The electric resistance heaters may operate in one of two modes.

Mode 1 is a master/slave relationship. It allows the bottom heating element to be enabled only when the top element is satisfied. In this control mode, it is impossible for both electric heaters to be on simultaneously. However, it is possible for both heaters to be on during the same TRNSYS time step (upper heater may be on during first half of the time step and lower heater may be on during the second half of the time step). Mode 1 is common to most domestic hot water applications.

In **Mode 2**, both heaters may be on simultaneously. This allows for quicker heating of the storage tank, but at a significantly higher electric demand. If no electric heating elements are present in the tank to be modeled, the user may set the control switch (inputs 8 and 9) to have a constant value of zero, or specify the heater power as zero.

The auxiliary heaters employ a temperature dead band. The heater is enabled if the temperature of the node containing the thermostat is less than (T_{set} - ΔT_{db}) or if it was on for the previous time step and the thermostat temperature is less than T_{set}. If the lower heater meets these criteria and the master/slave relationship is employed, a check will be made to see if the upper electric heater is off before enabling the second heating element.

The model allows for tanks with a **gas auxiliary heater**. The model treats gas auxiliary energy the same as electric energy, so the heat rate when the burner is firing is the same as if it was electric power. When the burner is on, no energy is lost to the flue. When the burner is off, energy is lost to the flue at a temperature T_{flue}, which is entered as a parameter. The user specifies the overall conductance for heat loss to the flue and the flue temperature.

The user must differentiate between electric and gas auxiliary heat. If gas heat is to be used, (only one heater may be gas) it must be auxiliary heater #2, and parameter 29 (GasAux Mode) must be set to 1. If both elements are electric, parameter 29 is set to 0.

TANK INSULATION

In many circumstances, the tank may not be uniformly insulated or users may wish to account for pipe entrances in the storage tank. It is possible for users to **incrementally insulate certain nodes** of stratified storage tanks by the specification of additional parameters. To utilize the incremental loss coefficients, the user must set the parameter 32 to 1 and specify the incremental loss coefficients. (This must be done for every node in the tank, even if some nodes have an additional loss coefficient of zero). The loss coefficient for the ith node is then:

$U_i = U_{tank} + \Delta U_i$ (ΔU_i can be positive or negative, just as long as $U_i > 0$)

A pressure relief valve has been added to the storage tank to account for **boiling** effects. The user must specify the boiling temperature of the fluid; venting will release sufficient energy to keep the tank at the boiling temperature. The loss of mass due to venting is neglected. Energy lost to boiling will be added to the energy lost to the environment. (Output 7) The boiling temperature can be obtained from saturated liquid/vapor tables for water.

TANK GEOMETRY AND CONFIGURATIONS

The program is capable of modeling tanks of any shape as long as the cross-sectional area is uniform. The user must enter the tank's height, volume and **perimeter**. If the tank is a cylinder, the user may enter a perimeter of -1 and the model will compute the perimeter automatically.

The Type 60 tank can also model horizontal cylindrical tanks. The user must enter a perimeter of -2. The model automatically divides the tank into N equal *volume* segments. If the user desires nodes of equal height, they must be entered manually (Hmode=1). Keep in mind that with this option, the tank's height will also be its diameter. All heights are still measured from the floor up.

The model includes the option for up to 3 **internal heat exchangers**. The user must specify the dimensions of the heat exchangers, as well as the temperature and flow rate of the inside fluid. The inside fluid can be water, water/propylene glycol mixture or water/ethylene glycol mixture. Two wall conductivity parameters are used: one for the conductivity of the heat exchanger material itself, and one for the conductivity of the heat exchanger wall, which allows for contact resistance. Contact resistance would be present with a double wall heat exchanger where the heat exchanger is a tube-within-a-tube design. Refer to the Mathematical Description section for details of the equations used.

DE-STRATIFICATION

To model de-stratification due to mixing at node interfaces and conduction along the tank wall, the user may enter an **additional conductivity parameter Δk**. The additional conductivity term is added to the conductivity of the tank fluid and is applied to all nodes. For rough calculations, one may calculate Δk as:

$$\Delta k = k_{tank\,wall} \frac{A_{c,tank\,wall}}{A_{c,water}}$$

Eq 5.11.5-1

Where $k_{tank\,wall}$ is the thermal conductivity of the tank wall and A_c is the cross-sectional area.

INTERNAL TIME STEP

To minimize errors, the Type60 tank model uses its own **internal time steps**. This has the advantage of results being unaffected by the size of the TRNSYS time step. The model internally computes the critical Euler time step. The user chooses the size of the internal time step by entering the fraction of the critical Euler time step. This has the effect of increasing either the model's speed or accuracy. The table below shows the relative effect of cutting the critical time step.

Table 5.11.5–1: Model time step size's effect on accuracy

Fraction of critical time step	Iterations / time step	Total iterations required	%error
1/1*10^7	1.0	10,000,000	0.000
1/100	3.0	300	0.002
1/50	3.0	150	0.007
1/20	4.0	80	0.048
1/10	4.8	48	0.192
1/6	5.5	33	0.536
1/4	6.5	26	1.221
1/3	7.7	23	2.199
1/2	10.0	20	5.154
1	21.0	21	26.622

The user specifies parameter 28 (**Crit Fraction**) as the denominator in the first column of the table shown above. For example, to use time steps that are 1/6 the critical Euler time step size, enter parameter 28 as 6.

ENERGY BALANCE

An energy balance written about the ith tank segment is expressed as:
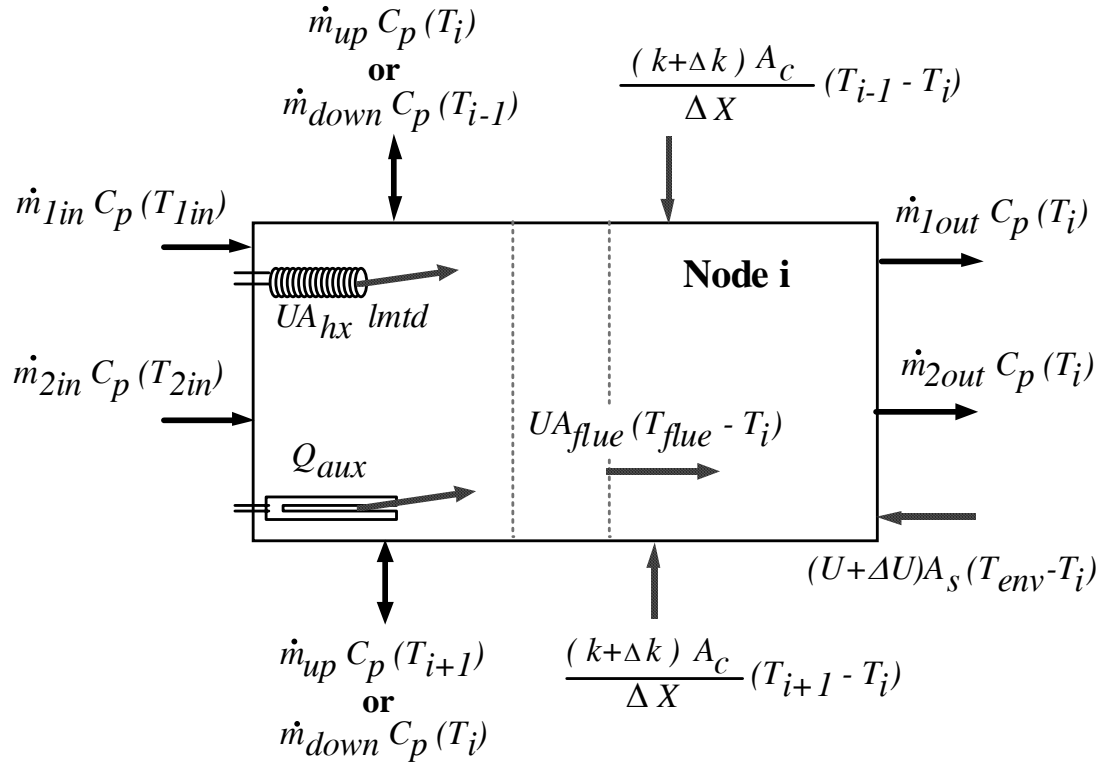
Figure 5.11.5–2: Graphical representation of energy flows into a node

Combining all energy flows into one equation, the differential equation for the temperature of node i is expressed as:

$$
\begin{aligned}
\left(M_i \, C_p\right)\frac{dT_i}{dt} = &\frac{\left(k + \Delta k\right) A_{c,i}}{\Delta x_{i+1 \to i}}\left(T_{i+1} - T_i\right) \\
&+ \frac{\left(k + \Delta k\right) A_{c,i}}{\Delta x_{i-1 \to i}}\left(T_{i-1} - T_i\right) + \left(U_{tank} + \Delta U_i\right) A_{s,i}\left(T_{env} - T_i\right) \\
&+ UA_{flue,i}\left(T_{flue} - T_i\right) + \dot{m}_{down}\, C_p\left(T_{i-1}\right) - \dot{m}_{up}\, C_p\left(T_i\right) \\
&- \dot{m}_{down}\, C_p\left(T_i\right) - \dot{m}_{up}\, C_p\left(T_{i+1}\right) + \gamma_{htr1}\, \dot{Q}_{aux1} + \gamma_{htr2}\, \dot{Q}_{aux2} \\
&+ UA_{hx1}\left(lmtd_1\right) + UA_{hx2}\left(lmtd_2\right) + UA_{hx3}\left(lmtd_3\right) \\
&+ \dot{m}_{1in}\, C_p\, T_{1in} - \dot{m}_{1out}\, C_p\, T_i + \dot{m}_{2in}\, T_{2in} - \dot{m}_{2out}\, C_p\, T_i
\end{aligned}
$$

Eq 5.11.5-2

Not all terms in Eq 5.11.5-2 will be non-zero. Only two of the $\dot{m}_{up} \setminus \dot{m}_{down}$ terms can be non-zero at once. Other terms, such as flows in/out and auxiliary heat may occur at different nodes; hence they would be zero for node i also.

The auxiliary heater is off if: $T_{statN} \geq T_{set}$, if $\gamma_{htr} = 0$, or if the heater was previously off and $T_{statN} \geq (T_{set} - \Delta T_{db})$. If a master/slave relationship is specified between the two auxiliary heaters, the lower auxiliary heater is also off if the first auxiliary heater is on. The model assumes that energy supplied to the tank from the heater is placed in the tank segment containing the heater, and then temperature inversions are eliminated.

The temperatures of each of the N tank segments are determined by the integration of their time derivatives expressed in the above equation. At the end of each time step, temperature inversions are eliminated by mixing appropriate adjacent nodes.

The UA_{hx} and logarithmic mean temperature difference (LMTD) of each heat exchanger is determined iteratively. The outside natural convection coefficient h_O is determined from:

$$h_O = \frac{Nu_D(k)}{d_O}$$

Eq 5.11.5-3

Where $Nu_D = C\ Ra^n$

A typical value for C is about 0.5 and n is usually 0.25. These values are generally constant, but can vary slightly for different log-mean temperature differences. Therefore, these values are entered as INPUTS. If the user has curve-fit information for C and n, they can be incorporated into the model using an equation. (UA_{hx}, lmtd, and T_{out} are OUTPUTS of the model and can be used as part of a curve fitting equation)

When modeling a tank with a heat exchanger coil, the program iterates from the node containing the inlet of the main coil to the node containing the outlet of the main coil. Figure 5.11.5–3 shows an example.
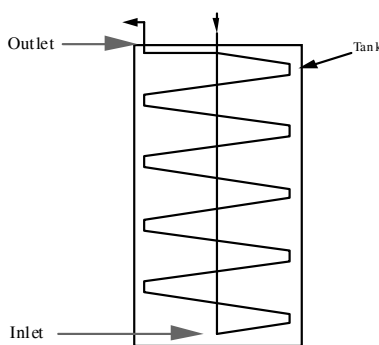
Figure 5.11.5–3: Proper heat exchanger inlet

Although the actual inlet to the heat exchanger is through the top of the tank (shown by the small black arrow), the user must designate the inlet height as shown by the large gray arrow. If the inlet and outlet were both specified as the top of the tank, the model would assume the entire heat exchanger was in the top node.

5.11.5.3   References

1. Klein, S.A., "A Design Procedure for Solar Heating Systems", Ph.D. Thesis, Department of Chemical Engineering, University of Wisconsin-Madison, (1976)

2. Newton, B.J., "Modeling of Solar Storage Tanks", M.S. Thesis, Department of Mechanical Engineering, University of Wisconsin-Madison, (1995)

5.12   *Utility*

This section contains several utility components that can be organized in the following categories: Data readers, Forcing functions and schedulers, Links with other programs, Integrators, and Specialized functions.

The components in each of those categories are listed here below:

Data readers

- Type 9 (Data reader) is able to read any free format or formatted text file. It can interpolate data or not and has several operation modes to handle initial values

- Type 89 (Data reader for Standard weather files) is a specialized weather data file reader for the most commonly available standard formats: standard TMY, TRNSYS TMY, standard TMY2, IWEC, EPW, CWEC.

  > Note that Type 109 (see section 5.14.1, page 5–470) provides a user-friendly alternative to the combination between Type 9 or 89 and Type 16.

Forcing functions and schedulers

- Type 14 (Forcing function) defines time-dependent profiles (forcing functions). The profile can be defined for any period of time 9e.g. one day, one week) and is then repeated.

- Type 41 (Forcing function scheduler) organizes different profiles (e.g. from Type 14) into a longer sequence, typically combining daily and weekly schedules into a yearly profile.

- Type 95 (Holiday calculator) performs a number of calendar computations based on the simulation start date and elapsed time. Outputs include time of day, day of week, etc. as well as switches indicating whether the time step falls during the week or week-end and during a holiday (holidays can be configured).

- Type 96 (Utility rate scheduler) calculates electric bills for grid-tied systems. It assumes net-metering and can take into account both usage (energy) and demand (max. power) charges

Links with other programs

- Type 62 calls Microsoft Excel, the spreadsheet program. Standard Excel functions, as well as advanced VBA macros, can be used to define relationships between inputs and outputs of the component

- Type 66 calls EES, the Engineering Equation Solver, where complex equations can be solved based on the component's inputs and sends the results back to TRNSYS

- Type 97 calls CONTAM, the bulk airflow modeling program developed by NIST

- Type 155 sends its inputs to Matlab (the Matworks), where standard M-files or Simulink simulations can be performed before returning the outputs to TRNSYS

- Type 157 calls COMIS, the airflow network solver (Note that the COMIS engine has also been integrated in a special version of Type 56 called TRNFLOW)

Integrators

- Type 24 (Quantity integrator) integrates variables with optional intermediate resets
- Type 55 (Periodic integrator) calculates some statistics (sum, min, max, etc.) on its inputs during a given period of time that may be repeated according to a set interval

Specialized functions

- Type 57 (unit conversion) performs various unit conversions.
- Type 70 (Parameter replacement) is used in parametric studies. It replaces a set of parameters in another Type with values read from a data file.
- Type 93 (Input value recall) can remember the value of its inputs for a given number of time steps. This can be useful to implement control strategies that are based on past values to prevent oscillations.

Note that printers and plotters are in the output category (see section 5.8, page 5–259)

5.12.1   Type 9: Data reader (Generic data files)

This component serves the purpose of reading data at regular time intervals from a logical unit number, converting it to a desired system of units, and making it available to other TRNSYS Units as time varying forcing functions.

Type 9 may be used in either a "free" or a "formatted" reading mode. In "free-formatted" reading the data lines need not be exactly identical in format – however each value must be separated from the previous value by a blank or a comma. "Formatted" reading with F or E FORTRAN format may be specified instead. Setting optional parameter FRMT to any positive number and supplying a FORTRAN FORMAT description after the line containing the Parameter values does this. All data lines will be read with this FORMAT.

5.12.1.1   Nomenclature

$V_i(n)$ ith value read from the nth line

m_i multiplication factor for the ith value

a_i addition factor for the ith value

$V_i'(n)$ ith value of the nth line after application of the multiplication and addition factors

t_{d1} time corresponding to values on the previous line

t_{d2} time corresponding to values on the next line

5.12.1.2   Operation modes

With TRNSYS 16, the definition of the simulation start time has changed. In TRNSYS 15 and before, the simulation time step was actually the end of the first time step. In TRNSYS 16, **the simulation start time is the moment in time at which the simulation is to begin**. **Other time steps are still referred to using the time at the end** of the time step. For example a hourly simulation over one year used to start at 1 and end at 8760. In TRNSYS 16 it starts at 0 and ends at 8760.

New operation modes were added to Type 9 to cope with that new definition and provide more flexibility to Type 9:

MODE 1

The first line in the data file is the simulation start time. Initial conditions are provided as instantaneous values for ALL variables (including the ones that are given as average values over the time step in the rest of the data file)

MODE 2

The first line in the data file is the simulation start time. Initial conditions are provided as instantaneous or averaged values over one timestep according to the options set for each variables (i.e. is a variable is provided as instantaneous values, initial conditions are assumed to be instantaneous as well).

MODE 3

The first line in the data file corresponds to the first time step of the simulation (**not** the initial time). No initial values are provided in the file.

MODE 4

The first line in the data file corresponds to time = 0. If the simulation start is not 0, lines are skipped accordingly in the data file. Initial conditions are provided as instantaneous values for ALL variables (including the ones that are given as average values over the time step in the rest of the data file)

MODE 5

The first line in the data file corresponds to time = 0. If the simulation start is not 0, lines are skipped accordingly in the data file. Initial conditions are provided as instantaneous or averaged values over one timestep according to the options set for each variables

MODE 6

The first line in the data file corresponds to the first timestep in a year. If the simulation does not start at the beginning of the year, lines are skipped in the data file. No initial values are provided in the file

5.12.1.3   Manipulations performed on variables

Each variable is associated to 4 parameters that tell TRNSYS whether or not to interpolate the data, whether the column in question contains instantaneous or interpolated data, and define a simple unit conversion operation.

AVERAGE OR INSTANTANEOUS VALUES

Each variable read by Type 9 can be an instantaneous or an average value over the data time step. TRNSYS always expects average values from Type 9 so instantaneous values are converted. Solar radiation is typically provided as average values over the time step, while temperature and humidity are often given as instantaneous values.

INTERPOLATION AND UNIT CONVERSION

Each variable can be interpolated or not, whether or not it is provided as an instantaneous or an average value. This is different from TRNSYS 15 where average values were never interpolated, while instantaneous values were always interpolated.

After interpolation and / or conversion to an average over the simulation time step, the variable can be converted to a different set of units, if required, by a simple linear relationship (the multiplier m and addition term a are provided as parameters):

$$V_i' (n) = m_i V_i (n) + a_i$$

5.12.1.4   Special Considerations

1. Up to 98 values may be read from each line. In "formatted" reading the values must be supplied in exactly the format specified. In "free format", values need only occur in the same sequence on each line, separated by at least one blank space or by a comma.

2. The data from line to line must be at constant time intervals (e.g., hourly solar radiation readings).

3. In free format, values are output in the same sequence as they appear on the data lines, i.e., if the 3rd value on each data line is solar radiation, then the 3rd OUTPUT will be the solar radiation value. In formatted reading the first OUTPUT will be the first value read with the specified format (not necessarily the first value on the data line.)

4. Format specification: in TRNSYS 15, Type 9 was using an "implied" Format statement. In TRNSYS 16, the Format statement must comply to the general rules for such statements in TRNSYS (see Volume 07, TRNEdit and Input file syntax). Because the variables read by TRNSYS will be real variables, the formats must be in F or E format.

5. Outputs may or may not be interpolated between data timesteps depending upon the parameter specifications. For instance, if the month, day, and year were read in, these should not be interpolated.

6. Outputs 99 and 100 are the times at the beginning (t_{d1}) and end (t_{d2}) of the current data interval, required by the TYPE 16 radiation processor for its interpolation of radiation data.

7. The data reader includes an additional 100 OUTPUTS. OUTPUT (100 + i) represents the value of OUTPUT (i) at the next simulation timestep if the value is interpolated, or OUTPUT (i) at the next data timestep if the value is not interpolated.

8. By specifying a negative first parameter in either of the data reader modes, the data reader will "skip" a number of lines into the data file. This feature is especially useful for starting a simulation at times other than hour one.

9. If wind direction is specified in the data file, the user must make sure that the convention used for in the generic data file is in accord with the convention in the other components used in the simulation.

5.12.1.5   Example

Let's use a very simple data file to show how the different parameters of Type9 are interpreted by TRNSYS. The following data points are given as input data file:

```
0
0
1
2
3
4
```

The first line contains the value during the initialization time step, and the next lines are the values during the following timesteps.

HOURLY DATA

Figure 5.1.1–1 shows the contents of a basic data file, if they are assumed to be values given every hour.
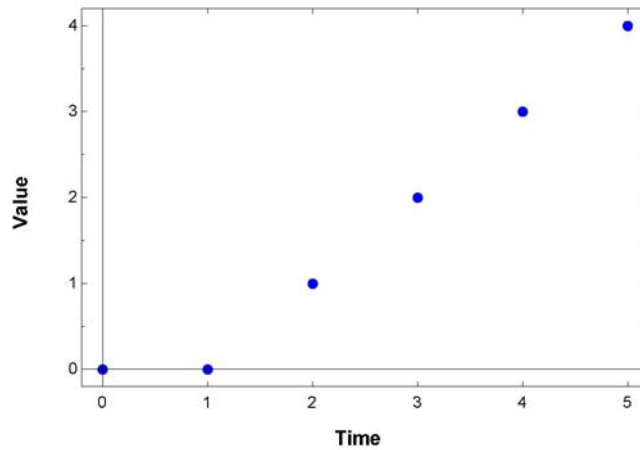
Figure 5.12.1–1: Data file

Table 5.12.1–1 shows the parametes for Type 9, if the data is assumed to start from the first line, it contains the information with 1-hour intervals and the data is to be interpreted as average values during the timestep.

Table 5.12.1–1: Parameters for Type9

No.	Parameter name	Value
1	Mode	2
2	Headers line to skip	0
3	No. of values to read	1
4	Time interval of data	**1 hr**
5	Interpolate or not?	**1 (interpolate)**
6	Multiplication factor	1
7	Addition factor	0
8	Average or instantaneous value	**0 (average)**

These parameters indicate TRNSYS to interpret the input data file as follows:

- T(0)=0, The initial value of the function

- Average value from 0 to 1 = 0, as specified in the data file, therefore the value at T(1)=0.

- Average value from 1 to 2 = 1, as specified in the data file, therefore the value at T(2)=2 in order to get an average of 1.

- Average value from 2 to 3 = 2, as specified in the data file, therefore the value at T(3)=2 in order to get an average of 2.

- Average value from 3 to 4 = 3, as specified in the data file, therefore the value at T(4)=4 in order to get an average of 3

In order to have these averages, the following instantaneous values yield these averages:

T(0)=0

T(1)=0

T(2)=2

T(3)=2

T(4)=4

The values reported by TRNSYS are average values over the timestep reported at the end of the timestep so we have:

- TRNSYS Time=0, Output=0

- TRNSYS Time=1,Output=0

- TRNSYS Time=2,Output=1

- TRNSYS Time=3,Output=2

- TRNSYS Time=4,Output=3

The resulting plot (see Figure 5.12.1–2) shows exactly the same values as the input data file, which is consistent with the fact that the values reported by TRNSYS are average values over the timestep reported at the end of the timestep.
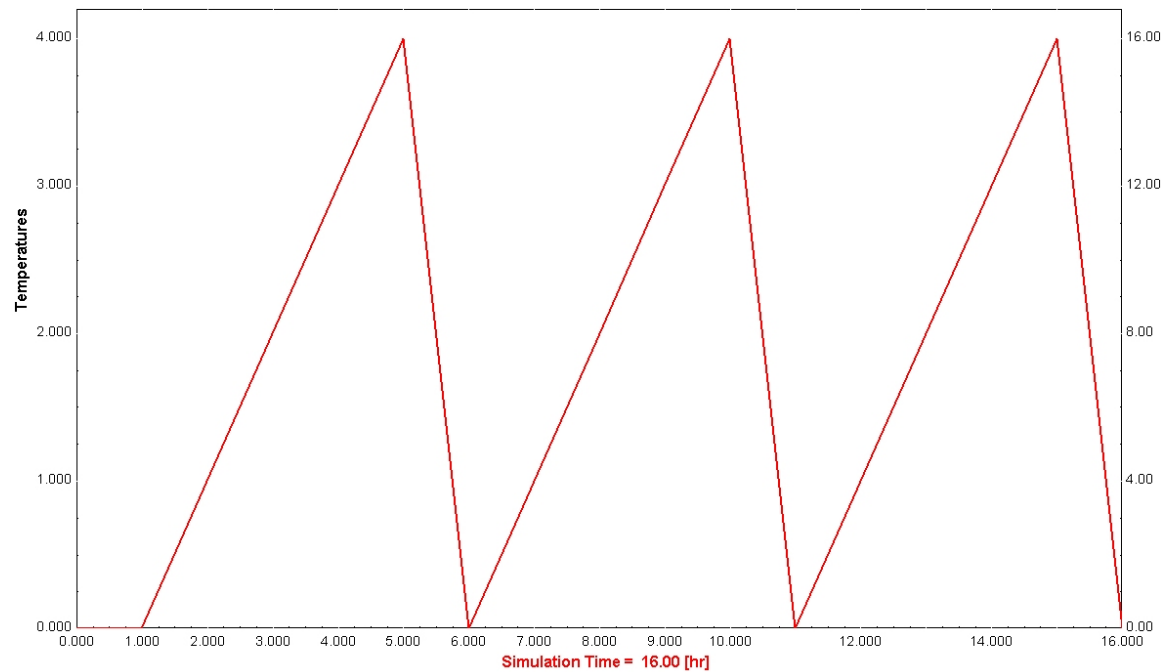
Figure 5.12.1–2: On-line plotter if data is interpreted as 1-hour intervals.

2-HOUR DATA - AVERAGES

Let's now use the same input data file, but assume that the data is provided for 2-hours intervals.

The input file is shown in Figure 5.12.1–3.
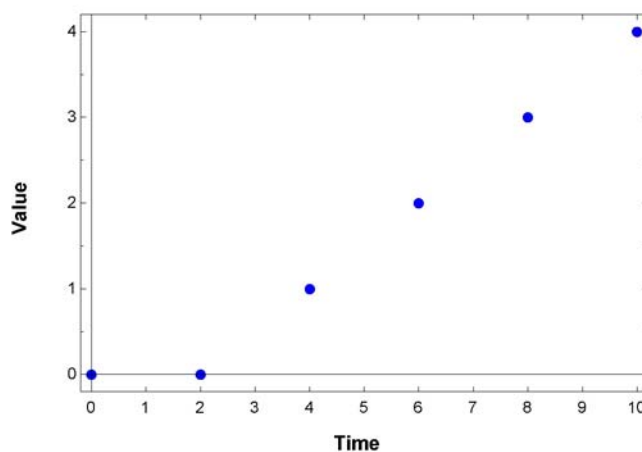
Figure 5.12.1–3: Data file assumed as 2-hour intervals.

Table 5.12.1–2: Parameters for Type9, assuming data is spaced in 2-hour intevals

No.	Parameter name	Value
1	Mode	2
2	Headers line to skip	0
3	No. of values to read	1
4	Time interval of data	**2 hr**
5	Interpolate or not?	**1 (interpolate)**
6	Multiplication factor	1
7	Addition factor	0
8	Average or instantaneous value	**0 (average)**

These parameters indicate TRNSYS to interpret the input data file as follows:

- $T(0)=0$, The initial value of the function

- Average value from 0 to 1 = 0, as specified in your data file, therefore the value at $T(1)=0$

- Average value from 1 to 2 = 1, as specified in your data file, therefore the value at $T(2)=2$ in order to get an average of 1

- Average value from 2 to 3 = 2, as specified in your data file, therefore the value at $T(3)=2$ in order to get an average of 2

- Average value from 3 to 4 = 3, as specified in your data file, therefore the value at $T(4)=4$ in order to get an average of 3

These average values can be the result of the following instantaneous values:

$T(0)=0$

$T(1)=0$

$T(2)=0$

$T(3)=1$

$T(4)=2$

$T(5)=2$

$T(6)=2$

The values reported by TRNSYS are average values over the timestep reported at the end of the timestep so we have:

TRNSYS Time=0, Output=0

TRNSYS Time=1,Output=0

TRNSYS Time=2,Output=0

TRNSYS Time=3,Output=0.5

TRNSYS Time=4,Output=1.5

TRNSYS Time=5,Output=2.0

TRNSYS Time=6,Output=2.0

Figure 5.12.1–4 shows the online plotter with these results.
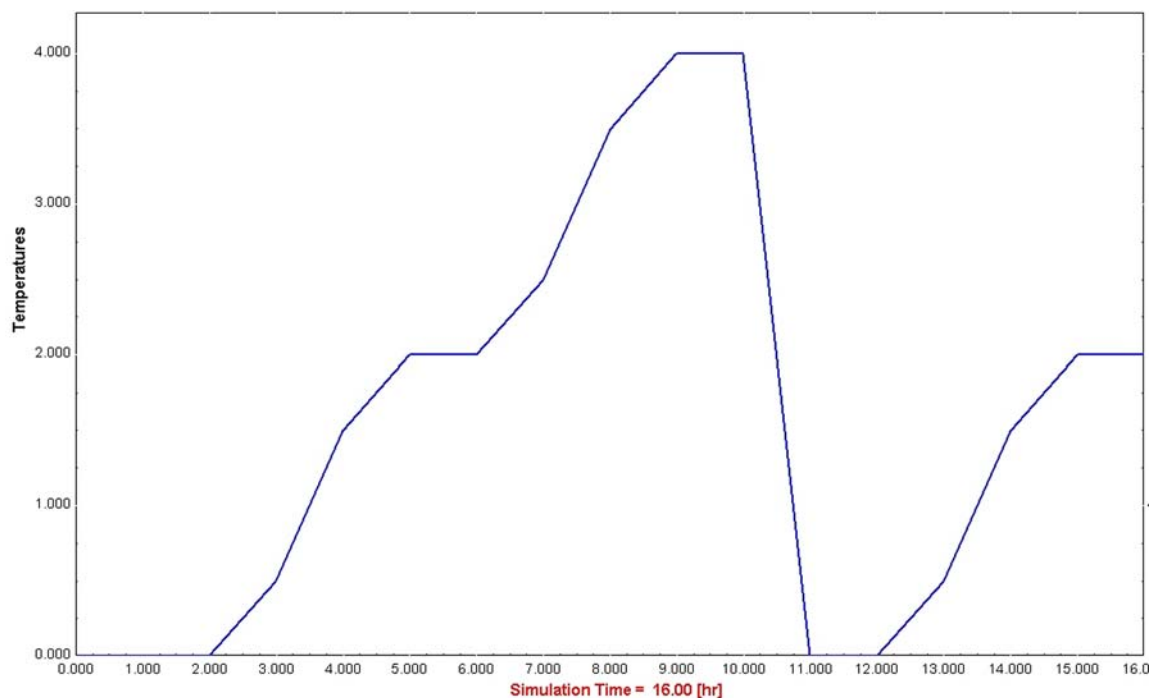
Figure 5.12.1–4: On-line plotter for the data interpreted as average values given in 2-hour intervals.

2-HOUR DATA – INSTANTANEOUS VALUES

Let's assume that the data file contains instantaneous values, specified in 2-hour intervals. Table 5.12.1–3 shows the required parameters.

Table 5.12.1–3: Parameters for Type9, assuming data is spaced in 2-hour intevals

No.	Parameter name	Value
1	Mode	2
2	Headers line to skip	0
3	No. of values to read	1
4	Time interval of data	**2 hr**
5	Interpolate or not?	**1 (interpolate)**
6	Multiplication factor	1
7	Addition factor	0
8	Average or instantaneous value	**1 (instantaneous)**

With these parameters, the points for the 2-hour case would then be

T(0)=0

T(2)=0

T(4)=1

T(6)=2

T(8)=3

The values reported by TRNSYS are average values over the timestep reported at the end of the timestep so we have:

TRNSYS Time=0, Output=0

TRNSYS Time=1,Output=0

TRNSYS Time=2,Output=0

TRNSYS Time=3,Output=0.25

TRNSYS Time=4,Output=0.75

TRNSYS Time=5,Output=1.25

TRNSYS Time=6,Output=1.75

Figure 5.12.1–5 shows the online plotter with these results.
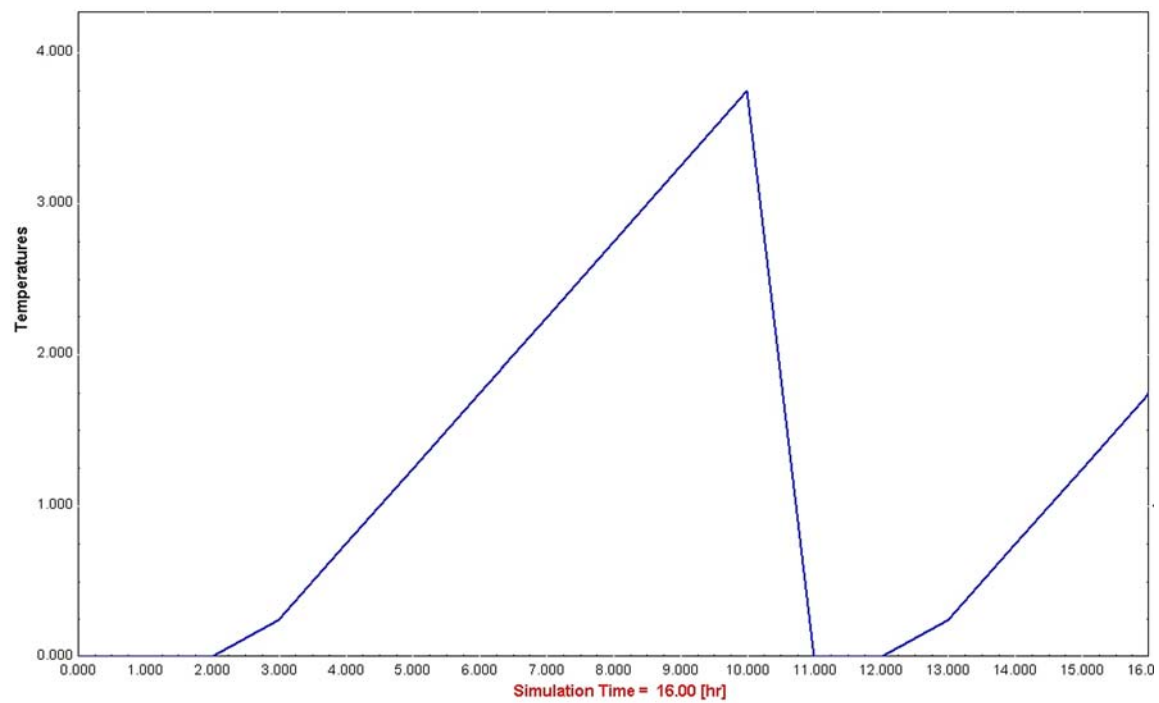
Figure 5.12.1–5: On-line plotter for the data interpreted as instantaneous values given in 2-hour intervals.

5.12.2   Type14: Time dependent forcing function

In a transient simulation, it is sometimes convenient to employ a time-dependent forcing function which has a behavior characterized by a repeated pattern. The purpose of this routine is to provide a means of generating a forcing function of this type. The pattern of the forcing function is established by a set of discrete data points indicating its values at various times through one cycle. Linear interpolation is provided in order to generate a continuous forcing function from this discrete data.

5.12.2.1   Nomenclature

TIME current value of time in simulation

C_T the cycle time (the time span after which the pattern repeats itself, which may be the total simulation time)

N   the number of segments defining the function (N+1 points must be specified)

V_o the initial value of the forcing function (occurs at TIME = 0, CT, 2CT, 3CT etc.)

V_i the value of the forcing function at point i

t_i the elapsed time from the start of the cycle at which point i and Vi are reached

$\overline{V}$ the linearly interpolated average value of the function over the timestep

t_o the initial value of time. Must be zero if the function repeats itself. IF CT is the total simulation time, t_o can be less than or equal to the initial simulation time

Δt the simulation timestep

5.12.2.2   Mathematical Description

The cycle must be completely specified requiring that t_N ($t_N = t_i$ at i = $_N$) be greater than or equal to C_T.

$\overline{V}$, the average value of the function, is calculated as follows:

$$t_c = \text{MOD}(TIME, C_T) - \Delta t/2$$ **Eq 5.12.2-1**

i is then found satisfying $t_{i-1} < t_c < t_i$ then

$$R = \frac{t_c - t_{i-1}}{t_i - t_{i-1}}$$ **Eq 5.12.2-2**

$$\overline{V} = V_{i-1} + R\left(V_i - V_{i-1}\right)$$ **Eq 5.12.2-3**

5.12.2.3   Special considerations

Both the instantaneous value of the forcing function are available as outputs. When step-like functions are to be defined, it is recommended to define the function by repeating each time value with two different values of V, and then use the average value (output(1)) in the simulation. This will guarantee the use of the exact same profile for any value of the time step.

E.g. to define an occupancy in a building between 8 AM and 5PM (occupancy is 0 at night, 1 during the day, and must change instantly from 0 to 1 and 1 to 0):

- Define the origin (time = 0, V = 0)
- Define the time at which the occupancy starts, repeating the value 0 (time = 8, V = 0)
- Repeat the time at which the occupancy stops with the value 1 (time = 8, V = 1)
- Define the time at which the occupancy stops, repeating the value 1 (time = 17, V = 1)
- Repeat the time at which the occupancy stops with the value 1 (time = 17, V = 0)
- Define the end of the period t_c (after that the cycle is repeated) (time = 24, V = 0)
- Use output(1) (average value over the time step)

5.12.3   Type 21: Time Values

This component returns different time values at the current time step, such as:

- current year of simulation

- current month of simulation

- current day of the simulation

- month of the year (1 – 12)

- day of the year (1 – 365)

- day of the month (1 – 28/30/31)

- day of the week (1 – 7)

- hour of the year (0 – 8760)

- hour of the month (0 – 744)

- hour of the week (0 – 168)

- hour of the day (0 – 24)

Type 21 may give these values relative to the initial time or in an absolute value from hour = 0.

5.12.4 Type 24: Quantity integrator

This component model is analogous to a piece of equipment in a physical system that integrates a quantity over a period of time; for example, a kWh meter that continuously totals the amount of electrical energy consumed. Whenever a quantity in a system simulation requires integration over the period of simulation, the use of this component will perform the required function.

Like Types 25, 27, 28, 29 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

Type 24 can integrate up to 250 variables and there is no specific limit on the number of Type 24 units that can be used in a simulation.

5.12.4.1 Nomenclature

X_i the ith quantity or rate to be integrated

Y_i the time integral of X_i

5.12.4.2 Mathematical Description

$$Y_i = \int_{time} X_i dt$$

Eq 5.12.4-1

5.12.5 Type 41: Forcing function sequencer

This component is useful for organizing daily profiles generated by TYPE 14 forcing functions into a sequence that forms an annual profile. Up to 20 different schedules may be considered for each day of a standard week. An additional set of profiles is allowed for non-standard days throughout the year. These might represent holidays or plant shut-down schedules.

5.12.5.1 Description

The user specifies the number of different inputs that will be provided for each day as the first parameter, N_v. A set of N_v inputs is then required for each day or set of days that has a unique set of profiles. Parameters 2-8 identify which set of inputs are to be used for each day of the week.

As an example, suppose that it is necessary to generate schedules for lighting and electric usage for a building.

The schedules for the weekdays differ from those on the weekend. In this case, it would be necessary to have four TYPE 14 forcing functions to generate daily profiles. One each for lights and electricity during the week and one each for on weekends. The first input might be an output from the TYPE 14 schedule for weekday lights. The second input would then be weekday electricity. Similarly, the third and fourth inputs would be for weekend lights and electricity.

If the first day of the year to be simulated falls on a Monday, then the first input set (Inputs 1 and 2) is used for days 1 through 5 and the second set is used for days 6 and 7. Therefore, parameter 1 would be 2 (2 set of inputs, electricity and lighting) and parameters 2-6 would be set to 1 and parameters 7 and 8 would be equal to 2.

It is possible to consider a different set of schedules for holidays than occur during the standard week. It is then necessary to specify additional parameters to establish the input set to be used and the days on which these schedules should occur. If for the previous example, an additional two schedules for lights and electricity were provided for 9 holidays (inputs 5 and 6), then the following additional parameters (9 - 19) would be required:

9. Nb of days for non-standard profile during the year: 9

10. Nb of input sets associated wit non-standard set: 3

11. 1st holiday (Day nb. In the year, 1st of January)   1

12. 2nd holiday (Day nb. In the year, 15th of February)   46

13. 3rd holiday (31st of May)   151

14. 4th holiday (4th of July)   185

Etc.

19. 9th holiday (25th of December)   359

5.12.6   Type 55: Periodic integrator

During a transient simulation, it is often desirable to know some basic statistics of an INPUT over a specified time range. This component calculates the count, mean, sample standard deviation, sum of squares, variance, minimum, time at which the minimum occurs, maximum, and time at which the maximum occurs of up to ten Inputs over a range of time periods specified by the user. In addition, the component will calculate the integral of the Input with respect to time or alternatively, the sum of the Input over the specified time range. This component has no physical counterpart in actual hardware but is included in the information flow diagram like any other component.

What makes this component especially useful is its ability to perform periodic summaries over a large number of user-specified time ranges. For example, with this component it is possible to determine the mean monthly value of solar radiation on a tilted surface from 8:00 a.m. to 9:00 a.m. Another example where this component would provide useful might be the determination of the annual compressor power used by a refrigeration system from 5:00 p.m. Friday to midnight Sunday.

For each Input (up to 10), the user must specify whether the Input should be integrated or summed, the starting time of the day for the periodic summary, the length of time for each period of the summary, the repeat time between summary periods, the reset time of the summary, and the absolute start and stop times for the summary.

5.12.6.1   Nomenclature

Lengthi   duration of period for Input i (hours)

Maxi   maximum value of Input i over the time range

Meani   mean value of Input i

Mini   minimum value of Input i over the time range

Ni   number of values of Input i per reset time

Repeati   time interval between periods for Input i (hours)

Reseti   time interval over which Input i should be investigated (hours)

Starti   absolute starting time for summary of Input i (hour of year)

SSDi   sample standard deviation of Input i

SSQi   sum of squares of Input i

Stopi   absolute stopping time for summary of Input i (hour of year)

Toni   relative starting hour of period for each summary of Input i

VALi   variable taking either the value of the Input or 0

Vari   variance of Input i over time period of interest

Yi   integral or sum of Input i over time period of interest

Δt simulation timestep

5.12.6.2   Mathematical Description

The user has the option of specifying whether Input i should be integrated or summed over the periods of interest. If the Input is to be integrated, the following formulation applies:

$$Y_i = \int_{Start_i}^{Stop_i} VAL_i \; dt \qquad\qquad \textbf{Eq 5.12.6-1}$$

If instead the Input is to be summed over the periods of interest:

$$Y_i = \sum_{Start_i}^{Stop_i} VAL_i \qquad\qquad \textbf{Eq 5.12.6-2}$$

where:

VAL_i = $INPUT_i$ if [Ton_i + n ($Repeat_i$)] $\leq$ TIME $\leq$ [Ton_i + $length_i$ n ($Repeat_i$)]   n = 0,1,2,3…
VAL_i = 0   otherwise

The total number of values of Input i to be evaluated per reset time is defined as the count of Input i. For the periodic integrator, the count of Input i may be expressed as:

$$N_i = \left(\frac{Length_i \; (hrs)}{\Delta t \; (hrs)} \right) \left(\frac{Re\,set_i \; (hrs)}{Re\,peat_i \; (hrs)} \right) \qquad\qquad \textbf{Eq 5.12.6-3}$$

The mean value of Input i is defined as the average value of Input i over the period of interest.

$$Mean_i = \frac{\displaystyle\sum_{Start_i}^{Stop_i} VAL_i}{N_i} \qquad\qquad \textbf{Eq 5.12.6-4}$$

To determine how the Inputs of i deviate from the mean value of Input i, the standard deviation of Input i is calculated. The standard deviation of Input i is a measure of the degree to which the values of Input i vary from the average value of Input i. The lower the standard deviation, the closer the values of Input i are grouped around the mean.

The periodic integrator calculates the <u>sample</u> standard deviation (SSD) of Input i over the time period.

$$SSD_i = \sqrt{ \frac{\displaystyle\sum_{Start_i}^{Stop_i} (VAL_i - Mean_i)^2}{N_i - 1} } \qquad\qquad \textbf{Eq 5.12.6-5}$$

Another measure of the degree to which Input i is grouped around the mean value of Input i is the variance. The variance is the summation of the squares of the difference between Input i and the mean value of Input i. Similar to the standard deviation, the lower the variance, the less the

individual values of Input i vary from the mean. A lower value of variance also implies that the mean is a more reliable estimate of the entire sample.

$$VAR_i = \frac{\sum\limits_{Start_i}^{Stop_i} (VAL_i - Mean_i)^2}{N_i - 1}$$

Eq 5.12.6-6

Note: The variance is simply the square of the sample standard deviation.

The summation of the squares of Input i, another measure of the deviation of Input i from its mean, is also kept by the periodic integrator and defined as:

$$SSQ_i = \sum\limits_{Start_i}^{Stop_i} (VAL_i - Mean_i)^2$$

Eq 5.12.6-7

5.12.6.3   Special Considerations

Up to 10 Inputs may be specified for the summary.

The required number of Parameters is equal to the number of Inputs supplied multiplied by seven.

The number of Outputs is equal to the number of Inputs multiplied by ten.

Outputs 1,11,21.... are either the integral of Input i with respect to time, or the summation of Input i over the specified time range. Care must be taken to choose the correct method of evaluating the Input.

5.12.7 Type 57: Unit conversion routine

Type 57 provides an easy way to perform unit conversion inside a TRNSYS input file. Users must describe the incoming variable type and units (temperature and °C for example) and the desired output variable units (°F for example) using tables provided at the end of this component description. The conversion routine checks the input to make sure it is of the correct variable type and units, performs the unit conversion, and provides the new output type and units to all units depending on this output.

The conversion routine can also be used to assign a variable type and units to an equation or constant name previously undescribed. The equation can now be passed to other components with the variable type and units known. Care should be taken when specifying the variable type of the equation or constant since input/output checking is not available for constants and equations (see Volume 08, Programmer's guide).

Users may add their own unit conversions and/or types to the Type 57 routine by adding to the file Units.lab (located in %TRNSYS16%\Exe), keeping the same format as that supplied. If a new variable type is added to the Units.lab file, the Type 57 source code must be changed to accept this new type:

- Redimension the Type variable
- Provide the two-letter designation of the variable type to the Type data statement

5.12.7.1 Nomenclature

a_i addition factor for converting input units to standard units

a_o addition factor for converting standard units to desired output units

m_i multiplication factor for converting input units to standard units

m_o multiplication factor for converting standard units to output units

$N_{table,i}$ table number corresponding to input variable type

$V_{in,i}$ variable type number specifying units of input variable from specified table

$V_{out,i}$ variable type number specifying desired units of output variable from specified table

X_{st} input variable after conversion to standard units

X_i ith input variable

Y_i output variable after conversion to desired output units

5.12.7.2 Mathematical Description

The steps to convert an input type to an output type are summarized below:

     1)   Input variable type read from parameter list ($N_{table,i}$)

     2)   Input units specifier read from parameter list ($V_{in,i}$)

     3)   Multiplication and addition factors for input variable read from file Units.lab (m_i and a_i respectively)

4)   Conversion from input units to standard units:

$$X_{st} = (X_i - a_i) / m_i$$

5)   Desired output units specifier read from parameter list ($V_{out,i}$)

6)   Multiplication and addition factors for desired output variable read from file Units.lab (m_o and a_o respectively)

7)   Conversion from standard units to desired output units:

$$Y_i = X_{st} * m_o + a_o$$

5.12.7.3   Special Considerations

- The required number of Parameters is equal to the number of Inputs supplied multiplied by three.
- The number of Outputs is equal to the number of Inputs.
- The maximum number of inputs per unit is set to 20.

5.12.7.4   Unit conversion tables

TABLE #1: TEMPERATURE

VAR. TYPE #	VAR. UNITS	VAR.TYPE	MULT. FACTOR	ADD. FACTOR
1	° C	TE1	1.0	0
2	° F	TE2	1.8	32
3	K	TE3	1.0	273.15
4	R	TE4	1.8	492

TABLE #2: LENGTH

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m	LE1	1	0
2	cm	LE2	100	0
3	km	LE3	1000	0
4	in	LE4	39.3701	0
5	ft	LE5	3.28084	0
6	miles	LE6	6.21371 E-04	0

TABLE #3: AREA

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m2	AR1	1	0
2	cm2	AR2	1 E+04	0
3	km2	AR3	1 E-06	0
4	in2	AR4	1550	0
5	ft2	AR5	10.7639	0
6	mi2	AR6	3.86102 E-07	0

TABLE #4: VOLUME

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m3	VL1	1	0
2	l	VL2	1000	0
3	ml	VL3	1 E+06	0
4	in3	VL4	6.10237 E+04	0
5	ft3	VL5	35.3147	0
6	gal	VL6	264.172	0

TABLE #5: SPECIFIC VOLUME

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m3/kg	SV1	1	0
2	l/kg	SV2	1000	0
3	ft3/lbm	SV3	16.0185	0
4	in3/lbm	SV4	2.76799 E+04	0

TABLE #6: VELOCITY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m/s	VE1	1.0	0
2	km/hr	VE2	3.6	0
3	ft/s	VE3	3.28084	0
4	ft/min	VE4	196.85	0
5	mph	VE5	2.23694	0

TABLE #7: MASS

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kg	MA1	1	0
2	g	MA2	1000	0
3	lbm	MA3	2.20462	0
4	ounces	MA4	35.274	0
5	ton	MA5	1.10231 E-03	0

TABLE #8: DENSITY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kg/m3	DN1	1.0	0
2	kg/l	DN2	0.001	0
3	lbm/ft3	DN3	6.2428 E-02	0
4	lbm/gal	DN4	8.3454 E-03	0

TABLE #9: FORCE

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	N	FR1	1.0	0
2	lbf	FR2	0.224809	0
3	ounce	FR3	3.59694	0

TABLE #10: PRESSURE

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	BAR	PR1	1	0
2	kPa	PR2	100	0
3	Pa	PR3	1 E+05	0
4	ATM	PR4	0.986923	0
5	psi	PR5	14.5038	0
6	lbf/ft2	PR6	2.08854 E+03	0
7	in. H2O	PR7	401.463	0
8	in. Hg	PR8	29.53	0

TABLE #11: ENERGY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ	EN1	1	0
2	kWh	EN2	2.77778 E-04	0
3	Cal	EN3	238.846	0
4	ft-lbf	EN4	737.562	0
5	hp-hr	EN5	3.72506 E-04	0
6	BTU	EN6	0.947817	0

TABLE #12: POWER

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ/hr	PW1	1	0
2	W	PW2	0.277778	0
3	kW	PW3	2.77778 E-04	0
4	hp	PW4	3.72505 E-04	0
5	BTU/hr	PW5	0.947817	0
6	BTU/min	PW6	1.57969 E-02	0
7	Tons	PW7	7.89847 E-05	0

TABLE #13: SPECIFIC ENERGY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ/kg	SE1	1	0
2	BTU/lbm	SE2	0.429923	0
3	ft-lbf/lbm	SE3	334.553	0

TABLE #14: SPECIFIC HEAT

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ/kg-K	CP1	1	0
2	W-hr/kg-K	CP2	0.277778	0
3	BTU/lbm-R	CP3	0.238846	0

TABLE #15: FLOW RATE

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kg/hr	MF1	1	0
2	kg/s	MF2	2.77778 E-04	0
3	lbm/hr	MF3	2.20462	0
4	lbm/s	MF4	6.12395 E-04	0

TABLE #16: VOLUMETRIC FLOW RATE

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m3/hr	VF1	1	0
2	m3/s	VF2	2.77778 E-04	0
3	l/hr	VF3	1000	0
4	l/s	VF4	0.277778	0
5	ft3/s	VF5	9.80958 E-03	0
6	ft3/hr	VF6	35.3144	0
7	gpm	VF7	4.40286	0

TABLE #17: FLUX

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ/hr-m2	IR1	1	0
2	W/m2	IR2	0.277778	0
3	BTU/hr-ft2	IR3	8.8055 E-02	0

TABLE #18: THERMAL CONDUCTIVITY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ/hr-m-K	KT1	1	0
2	W/m-K	KT2	0.277778	0
3	BTU/hr-ft-R	KT3	0.160497	0

TABLE #19: HEAT TRANSFER COEFFICIENTS

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	kJ/hr-m2-K	HT1	1	0
2	W/m2-K	HT2	0.277778	0
3	BTU/hr-ft2-R	HT3	4.89194 E-02	0

TABLE #20: DYNAMIC VISCOSITY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	N-s/m2	VS1	1	0
2	kg/m-s	VS2	1	0
3	poise	VS3	10	0
4	lbf-s/ft2	VS4	2.08854 E-02	0
5	lbf-hr/ft2	VS5	5.80151 E-06	0
6	lbm/ft-hr	VS6	2419.08	0

TABLE #21: KINEMATIC VISCOSITY

VAR. TYPE #	VAR. UNITS	VAR. TYPE	MULT. FACTOR	ADD. FACTOR
1	m2/s	KV1	1	0
2	m2/hr	KV2	3600	0
3	ft2/s	KV3	10.7639	0
4	ft2/hr	KV4	3.87501 E+04	0

MISCELLANEOUS

	VAR. TYPE
Dimensionless	DM1
Degrees	DG1
Percentage	PC1
Month	MN1
Day	DY1
Hour	TD1
Control function	CF1

5.12.8   Type 62: Calling Excel

5.12.8.1   Acknowledgement

Type 62 (Calling external programs - Excel) was originally programmed by Jochen Wriske and Markus Oertker at the Lehrstuhl für Technische Thermodynamik, RWTH Aachen. It was part of the TRNSYS 15 library of free components TRNLIB, and it was integrated to the standard library for TRNSYS 16.

5.12.8.2   Description

Type 62 implements a link with Excel. The Fortran routine communicates with Excel through a Component Object Model (COM) interface for fast data transfer.

Up to 10 inputs are sent to Excel. Those inputs are transferred to cells in the Excel worksheet that are named Inp1, Inp2, … , Inp10. You must define those cells in your Excel file (use CTRL-F3 for a shortcut).

In Excel, Outputs are calculated from the inputs using standard functions or advanced VBA macros. Please see the examples provided in "%TRNSYS16%\Examples\Calling Excel".

Up to 10 Outputs can be assigned to cells for which the names Out1 to Out10 have been defined.

Up to 20 Type 62 units can be used in one simulation.

5.12.8.3   Component configuration

Parameter 1 is a Mode reserved for future use.

The number of inputs and outputs are set by Parameter 2 and 3

Parameter 4 (Show Excel) will decided if Excel runs completely in the background (in invisible mode) or if it is visible (in which case TRNSYS is sent to the background).

The path and filename of your Excel file are provided in a LABEL statement. Type 62 will understand the following kind of pathnames:

- Relative to the deck (default if no path is specified)

  E.g. "My Excel File.xls"
- Absolute (if the path starts with "\" or if the second character is ":")

  E.g. "C:\Program Files\Examples\Data Files\Type62-CallingExcel.xls"
- Relative to the TRNSYS root directory (if the path starts with ".\")

  E.g. ".\Examples\Data Files\Type62-CallingExcel.xls", which is equivalent to the second example here above if TRNSYS is installed in "C:\Program Files\Trnsys16"

5.12.9 Type 66: Calling Engineering Equation Solver (EES) Routines

Engineering Equation Solver (EES) [1], is a non-linear equation solver that can be used to solve sets of equations without resorting to programming languages such as FORTRAN or C++. The advantage of EES is that equations are written in an algebraic format instead of in a programming language format. In its more recent versions (since 1998) EES supports Dynamic Data Exchange commands in order to exchange information with other programs. Dynamic Data Exchange (DDE) is a method of sending messages to other programs through the Microsoft Windows operating system. DDE is supported by many programs including the applications within Microsoft Office. Type66 makes use of DDE commands to launch EES, pass parameter and Input information to EES, ask EES to solve, and recuperate output information, which is then treated like output from any other TRNSYS component.

Type66 requires the EES Professional version because it makes use of the DDE (Dynamic Data Exchange) capability, which is only included with the Professional version. Contact your EES distributor to obtain a Professional version.

5.12.9.1 Mathematical Description

THE EES FILE

The first step in using Type66 is to develop the mathematics of the component in EES. Unfortunately, there are a number of features in EES that cannot be used directly from TRNSYS and Type66; parametric tables and diagram windows stand out as examples. What TRNSYS can easily access are blocks of simultaneous equations, procedures, functions, etc. Since the communication process is best illustrated with an example, the following shows a simple air compressor model written to be solved by EES. The EES file is set up to use temperatures in Kelvin and pressure in Pascals.

```
m_dot = m_dot_TRNSYS*convert(kg/hr,kg/s)
p_1 = p_1_TRNSYS*convert(atm,Pa)
p_2 = p2_TRNSYS*convert(atm,Pa)
T_1 = convertTemp(C,K,T1_TRNSYS)
w1 = w1_TRNSYS

"! Compressor performance"
"calculate specific heat of air"
C_p = SPECHEAT(AirH2O,T=T_1,P=p_1,w=w1)
"pressure ratio"
r_p = p_2/p_1
"calculate isothermal work"
W_isothermal = m_dot*R*T_1*ln(p_2/p_1)
"calculate actual work"
W_actual = m_dot*(n/(n-1))*R*T_1*((p_2/p_1)^((n-1)/n)-1)
"calculate isothermal efficiency"
eta_isothermal = W_isothermal/W_actual
"calculate outlet temperature"
T_2 = T_1*r_p^((n-1)/n)
"calculate heat transferred"
Q = m_dot*c_p*(T_2-T_1) - W_actual
```

```
"! TRNSYS outputs"
out1 = p_2*convert(Pa,atm)
out2 = convertTemp(K,C,T_2)
out3= eta_isothermal
out4 = Q*convert(kJ/s,MJ/hr)
out5 = W_actual*convert(kJ/s,MJ/hr)
out6 = W_isothermal*convert(kJ/s,MJ/hr)
```

To this point there is nothing special about the EES file; nothing has been written in a specialized format for TRNSYS's sake. The output variable labels out1, out2, etc. are simply variable names. The only slightly unusual feature of the EES file is that there are a number of "convert" statements included to take the units of the various Input variables provided by TRNSYS and change them into the units expected by EES based on the EES file's settings. On the output side, a number of unit conversions are included to put the variables back into TRNSYS's system of units.

Once the EES model has been developed, two statements are added, one before the EES model equations and one afterwards. These are the DDE statements that tell EES to get the Input variables from the Windows clipboard before solving the equations and then to post the results back onto the clipboard. The DDE statements inserted are of the form:

```
$Import 'CLIPBOARD' InputVariable1,InputVariable2,InputVariable3,...
```

and

```
$Export 'CLIPBOARD' OutputVariable1, OutputVariable2, OutputVariable3,...
```

For the example above, the DDE statements are:

```
$Import 'CLIPBOARD' p_1_TRNSYS,T1_TRNSYS,w1_TRNSYS,p2_TRNSYS,m_dot_TRNSYS,R,n

m_dot = m_dot_TRNSYS*convert(kg/hr,kg/s)
p_1 = p_1_TRNSYS*convert(atm,Pa)
... remainder of EES File removed ...
out5 = W_actual*convert(kJ/s,MJ/hr)
out6 = W_isothermal*convert(kJ/s,MJ/hr)

$Export 'CLIPBOARD' out1,out2,out3,out4,out5,out6
```

In other words, the EES file should expect TRNSYS (through Type66) to post seven variables on the clipboard and, once it has solved its own equations, should post six variables back to the clipboard before informing TRNSYS that it has successfully solved at the current iteration of the current time step.

THE TRNSYS INPUT FILE

Type66 normally has four parameters. The first parameter is the Type66 Input mode. When set to 1, all of the Type66 Inputs are sent to EES. When set to 2, the first Input is assumed to be a control signal having a value of 0 (OFF) or 1 (ON) and is NOT sent to EES. When OFF, the outputs of the model are set based on the value of the second parameter.

One of the difficulties in simulating the performance of a system component in EES comes in assessing the performance of the device when a system controller switches it off. EES lends itself quite well, for example, to simulating the steady state performance of a refrigeration cycle. If at any point in time the refrigeration cycle is to be turned off, an alternate set of EES equations must be developed. Often an EES procedure is also necessary to carry out the logic of "if Type66 Input 1 is 0 then solve system of equations A whereas if Type66 Input 1 is 1 then solve system of equations B." Quickly the advantages of developing components in EES evaporate. To alleviate the problem, Type66 is equipped with a MODE parameter having one of the following values and consequences.

Value of Parameter 2	Output Value Calculation Method When the Device is OFF
1	The performance of the EES component will be calculated at each iteration based exclusively on the contents of the EES file. Outputs are set based on the results of the EES calculations.
2	When the device is OFF (control signal set to 0) EES will not be called. The Type66 outputs will be held at their last calculated values until the control signal switches to ON (1) and EES is called again. The control signal Input is NOT sent to EES.
3	When the device is OFF (control signal set to 0) EES will not be called. The Type66 outputs will be set to values predefined amongst the Type66 parameter list until the control signal switches to ON (1) and EES is called again. The control signal Input is NOT sent to EES.
4	When the device is OFF (control signal set to 0) EES will not be called. The Type66 outputs will be set to 0 until the control signal switches to ON (1) and EES is called again. The control signal Input is NOT sent to EES.

The third parameter to Type66 is intended to control the amount of time the EES is allowed to take before TRNSYS decides that EES is not responding or that it cannot solve the system of equations. The allowable wait time is specified in milliseconds. In the initial TRNSYS 16 release, this parameter was not implemented. The user may enter any value they wish – TRNSYS will wait for a response from EES forever and may become hung in certain instances.

The fourth Type66 parameter is the number of outputs that will be set by the EES model or, in the case of a control signal set to 0, by Type66 itself.

If the second parameter (output mode) is set to 2, the model outputs are set to predefined values listed as parameters following the four standard parameters. An example follows:

```
UNIT 7 TYPE 66 Call EES (Predefined Output Values)
PARAMETERS 10
2               ! 1 Input mode
2               ! 2 Output mode
10000           ! 3 Allowable wait
6               ! 4 Number of outputs
2               ! 5 Value when OFF for output-1
100             ! 6 Value when OFF for output-2
0.8             ! 7 Value when OFF for output-3
-9              ! 8 Value when OFF for output-4
40              ! 9 Value when OFF for output-5
40              ! 10 Value when OFF for output-6
...
```

In Input mode 1, Type66 requires as many Inputs as are expected by the EES model. In Input mode 2, Type66 requires a control signal Input be provided before the list of Inputs that will be sent to the EES model. This first Input is not sent to EES.

Type66 also requires two labels. The first label tells Type66 where the EES executable program can be found. The second label tells Type66 where the EES file to be run can be found. As with other TRNSYS label statements, path names may contain spaces as long as they are enclosed in quote marks. An example follows:

```
...
LABELS 2
c:\EES32\ees.exe
"c:\Program Files\Trnsys16\Examples\Calling EES\compressor.ees"
```

5.12.9.2   References

1. Klein, S.A., Alvarado, F.L., EES-Engineering Equation Solver, 2004, F-Chart Software, Middleton, WI

2. Bradley, D.E. and Blair, N.J., "Simulation Synergy, Interconnecting Simulation Programs," Proceedings of ASES Annual Meeting 1999, Portland ME, (1999).

5.12.10   Type 70: Parameter replacement

Type 70 reads a specified text file and takes the values of variables found there and inserts them into the correct locations in the simulation. Type 70 can be used to modify a TRNSYS input file based on the contents of a file, which can be left behind by any other program.

5.12.10.1   Component configuration

Type 70 is called once during the first time step. It reads a series of numbers out of a text file (the file is given a logical unit number) and then inserts those numbers into the main TRNSYS PAR array at the location specified by the Unit number given in Parameter 3. Type70 can be used to replace the parameters one or more components in a simulation. The first parameter of Type70 is the logical unit number assigned to the external file containing replacement parameter values. Simulation Studio users need to specify an external file name in the "external files" tab of the Type70 proforma. Type70 then takes two parameters for each component that is to have its parameter list replaced. The first of these parameters is the number of consecutive parameters that must be replaced in a given component. Type70 always starts by replacing the first parameter but it does not necessarily have to replace all parameters for a given component. Say, for example, that the user wishes to replace only the fifth parameter of a given component. The user would specify that 5 parameters must be replaced for that component. The second of the pair of parameter indicates which component is to have its parameters replaced by designating its UNIT number. Users of the Simulation Studio will need to check the component order tab of the "control cards" tool or press the F2 key in order to find out what UNIT number has been assigned to each component in the simulation.

The external text file syntax is quite simple; the file will have one line for each UNIT that is to have its parameters replaced. Each line simply contains a list of the replacement parameters. To follow on the previous example, say that UNIT 3 is to have its parameters replaced and that the parameter list in UNIT 3's proforma is:

```
1.0  4.0  67.0  2.0  5.0
```

Recall that we want to change only the value of the fifth parameter. The single line in the external file might be:

```
1.0  4.0  67.0  2.0  17.0
```

Which would have the result of changing UNIT 3's fifth parameter from a value of 5 to a value of 17.

EXAMPLE

A program is written that provides the TRNSYS user with a number of slider bars to set up a 24 hour repeating schedule. The program is designed to output a text file (NewPars.txt) containing the 24 selected values of the sliders. When the simulation is run (by clicking Calculate or by pressing F8), Type 70 looks for the text file left behind by the program, reads the values and inserts them into the global PARS array at the appropriate location. The PARS array is a TRNSYS array that contains all the values of all the Parameters from all the different Types in the simulation. Type 70 is only called on the first time step; the newly modified Parameters will not be changed again during the course of the simulation. In the example at hand, the values would be inserted as Parameters for Type 14 (Forcing Function), which has been given UNIT number 15 in the simulation. The user has set the sliders so that they all have the value 1.5, and the logical UNIT number assigned to the slider program output file logical unit 30. The parameter list for Type70 would be:

Logical unit number of file containing parameter: 30

Number of consecutive parameters to be replaced: 24

The unit number in the deck to which the parameters belong: 15

The file NewPars.txt would have a single line:

```
1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5   1.5
1.5   1.5   1.5   1.5   1.5   1.5 1.5   1.5
```

5.12.11   Type 81: 1D interpolation from file

Type 81 reads a data file that contains the information of N dependent variables as function of one independent variable. The first column in the file should contain the independent variable x, and the next columns should contain the dependent variables $y(x)$. The data do not need to be ordered, as Type81 sorts the data and performs the interpolation. The current implementation only allows for linear interpolation.

5.12.12   Type 83: Differentiation of a signal

Type 83 calculates the derivative of a signal, based on the value during the previous time step.

Type 83 can integrate up to 100 variables and there is no specific limit on the number of Type 83 units that can be used in a simulation.

5.12.12.1   Nomenclature

x_i the ith quantity or rate to be derived

Δt the time step

5.12.12.2   Mathematical Description

$$\frac{\partial x_i}{\partial t} \approx \frac{\Delta x_i}{\Delta t} = \frac{x_{i,t} - x_{i,t-\Delta t}}{\Delta t}$$

Eq 5.12.12-1

5.12.13   Type 84: Moving Average

Type 84 calculates the moving average of a signal, during the previous N time steps.

Type 84 can calculate the moving average of up to 100 variables and there is no specific limit on the number of Type 84 units that can be used in a simulation.

5.12.13.1   Nomenclature

Δt time step

N   number of time steps

$\overline{x_i}$ average of variable x_i

5.12.13.2   Mathematical Description

$$\overline{x_i} = \frac{1}{N} \sum_{j=1}^{N} x_{i,j}$$ **Eq 5.12.13-1**

5.12.14   Type 89: Weather data reader (standard format)

This component serves the purpose of reading meteorological data at regular time intervals from a logical unit number, converting it to a desired system of units, and making it available to other TRNSYS UNITS as time varying forcing functions. It is designed to be expandable so that as other data formats become common, they can be added.

Ther is no specific limit on the number of Type 89 Units that can be used in a simulation

5.12.14.1   Operation modes and accepted file formats

In TRNSYS 16, the following standard weather data formats can be read-in by Type 89:

Mode	Format	Description & references
1, -1	TRNSYS TMY	Special TRNSYS format derived from US-TMY format (see hee below)
2, -2	TMY2	TMY2 format originally used for the US NSRDB database. Also used by all Meteonorm-generated weather files distributed with TRNSYS 16. [1]
3, -3	EPW	EnergyPlus / ESP-r weather format [2]. A large database of weather files is available on the EnergyPlus website: http://www.eere.energy.gov/buildings/energyplus/weatherdata.html
4, -4	IWEC	ASHRAE's International Weather for Energy Calculation data format [3]
5, -5	TMY (TMY1)	Original TMY format used by the NSRDB (National Solar Radiation Data Base) [4]
6,-6	CWEC	Canadian Weather for energy Calculation [5]

- If **Mode > 0**, Type 89 assumes that the first data line corresponds to initial values for the simulation (values at TIME = TIME0). This could happen if a file is generated by a utility program for a given period in the year.

- If **Mode < 0**, Type 89 assumes that the first data line is the first hour of a year (usually the case in standard files).

NOTE: Fundamentaly, the wind direction in TRNSYS depends on the convention given in the weather data file. The standard file-formats indicated in the above table use as convention N=0°, E=90°, etc. The user must check that this convention is in accord with the specific component that will use the information later in the simulation (i.e., COMIS or CONTAM).

5.12.14.2   Type 16 configuration

For most data file formats, Type 89 will print a message to the Listing file with instructions to configure Type 16. The example here below is printed after reading the TMY2 file for Uccle (Brussels), Belgium (.\Weather\Meteonorm\Europe\ BE-Uccle-64470.tm2):

```
UNIT   1 TYPE  89 DATA READER (TMY2 WEATHER FILE)
LOCATION: Uccle
TIME ZONE:   1. HR FROM UTC
LATITUDE:  50.80 DEG  LONGITUDE: 355.65 DEG W (  -4.35 DEG W)
ELEVATION:     105. M
HOURS OF TMY2 DATA ARE IN LOCAL STANDARD TIME, NOT SOLAR TIME.
BE SURE TO PERFORM RADIATION PROCESSING APPROPRIATELY.
SHIFT IN SOLAR TIME HOUR ANGLE (L_STANDARD - L_LOCAL): -10.65 DEG
```

5.12.14.3 The TRNSYS TMY data format

Note that other formats are described in the references

FIELD #	COL. #	FIELD
1	2-3	Month of the year
2	5-7	Hour of the month
3	10-13	Direct normal solar radiation integrated over previous hour, kJ/m²
4	15-18	Global solar radiation on horizontal surface, integrated over previous hour, kJ/m2 [1]
5	20-23	Dry bulb temperature, degrees*10 C
----	25-30	Humidity ratio * 10,000
6	32-33	Wind velocity, m/s
7	35-36	Wind direction, degrees/10 [2]

[1]   Note that this is not horizontal surface beam radiation.
[2]   Wind direction expressed as O for wind from north, 9 for east, 18 for south, etc.

5.12.14.4   References

[1] National Renewable Energy Laboratory. 1995. User's Manual for TMY2s (Typical Meteorological Years), NREL/SP-463-7668, and TMY2s, Typical Meteorological Years Derived from the 1961-1990 National Solar Radiation Data Base, June 1995, CD-ROM. Golden: NREL.

[2] Crawley, Drury B., Jon W. Hand, Linda K. Lawrie. 1999. "Improving the Weather Information Available to Simulation Programs," in *Proceedings of Building Simulation '99*, Volume II, pp. 529-536, Kyoto, Japan, September 1999. IBPSA.

[3] ASHRAE. 2001. International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM, Atlanta: ASHRAE

[4] National Climatic Data Center. 1981. Typical Meteorological Year User's Manual, TD-9734, Hourly Solar Radiation—Surface Meteorological Observations, May 1981. Asheville: National Climatic Data Center, U.S. Department of Commerce.

[5] Numerical Logics. 1999. *Canadian Weather for Energy Calculations, Users Manual and CD-ROM*. Downsview, Ontario: Environment Canada.

5.12.15   Type 93: Input value recall

The function of the input value recall component is quite simple. It is used to remember the values of up to 10 inputs over the course of the last N_{ts} timesteps. It is primarily useful for more complex control strategies using EQUATIONS in the TRNSYS input file.

5.12.15.1   Component configuration

Parameters

- The first parameter is the number of input variables that must be stored ($N_i \leq 10$)
- The second parameter is the number of time steps that must be stored. The current time step is counted as one ($N_{ts} \leq 500$).

Outputs

- Outputs $1..N_{ts}$ are the value of input 1 at time, time-step, … time-(N_{ts}-1)step
- Outputs N_{ts}+1..2 N_{ts} are the value of input 2 at time, time-step, … time-(N_{ts}-1)step
- Etc.

5.12.16   Type 95: Holiday calculator

The Type 95 Holiday Calculator performs a number of "calendar computations" based on the starting date of a TRNSYS simulation and the elapsed time. These results may be useful when dealing with time-dependent load patterns or utility rate schedules.   This component was originally developed for use with the Type 96 Rate Schedule Processor but may prove useful for other applications. (Note that Type 96 requires Inputs from Type 95).

The Outputs of Type 95 include the year, month, date, and day of week, and hour of day. Type 95 determines whether a particular timestep falls on a bank holiday.   Some holidays, such as Christmas, always fall on a particular date.   Others, such as President's Day, depend on the day of the week and do not fall on the same date from one year to the next. Type 95 will handle both sorts of holidays.   A default list is included for standard American holidays, but the user may define additional holidays.   Type 95 accounts for leap years and daylight savings time.   The component has no difficulty with calculations involving the year 2000 or beyond.

5.12.16.1   Nomenclature

$D_{hol,j}$	Date (day-of-month) of user-defined holiday j
DOW	Day-of-Week (0 = Sunday, 6 = Saturday)
DOY	Day-of-Year (1-366)
$FLAG_{DS}$	Flag to enable daylight savings time
$FLAG_{HOL}$	Output flag indicating whether timestep falls on a holiday
$FLAG_{WE}$	Output flag indicating whether timestep falls on a weekend
HOD	Hour-of-Day (0-23)
HOY	Hour-of-Year (0-8783)
$M_{hol,j}$	Month (1-12) of user-defined holiday j
$YEAR_{start}$	Year at start

5.12.16.2   Defining Holidays

Three "holiday operation" modes are available for Type 95. The only effect of choosing a mode is to define what days of the year will be considered to be holidays. All other calculations (date, day of week, etc.) will not be affected. Thus, the choice of mode is irrelevant for applications in which holidays play no role. The value of Parameter 1 defines the mode as follows:

Mode = 0   Use only standard American bank holiday list

Mode = 1   Use standard American bank holiday list **and** additional user-defined holidays

Mode = 2   Use user-defined holidays but **do not** use standard American bank holiday list

The default list of standard holidays is:

New Year's Day:	January 1st
Martin Luther King Jr. Day	3rd Monday in January
President's Days	3nd Monday in February
Memorial Day	Last Monday in May
Independence Day	July 4th
Labor Day	1st Monday in September
Columbus Day	2nd Monday in October
Veterans' Day	November 11th
Thanksgiving Day	4th Thurday in November
Christmas Day	December 25th

All of these holidays are included for Modes 0 and 1. Sometimes a holiday with a specific date, such as Independence Day, falls on a Saturday or Sunday. If this happens, the holiday will be automatically "moved" to Friday or Monday for that particular year. Easter is not included in the list because it always falls on a Sunday.

When using **Modes 1** and **2**, the user may define additional holidays by adding values to the end of the Parameter list. All user-defined holidays must be given a specific date, like Christmas or Independence Day. Type 95 does will support custom holidays that fall on a certain day of the week (1st Monday in April, etc.) Two numbers are added to the Parameter list for each additional user-defined holiday. These values are the month of the holiday (1-12) and the date (1-31).

EXAMPLE: Two additional holidays are desired: October 31st and December 24th.   Eight Parameters are used instead of the standard four. The additional four Parameters are 10, 31, 12, and 24.

5.12.16.3   Leap Year and Daylight Savings Time

Type 95 automatically assumes February to be 29 days long when the year is an even multiple of four. The optional daylight savings time is activated by entering 1 for Parameter 4. Daylight savings in disabled if Parameter 4 is set to any other value. Daylight savings begins with the first Sunday in April and extends through the last Sunday in October. When daylight savings is in effect, the clock time (HOD, or hour-of-day) calculated by Type 95 is shifted one hour ahead of simulation time.

5.12.16.4 Mathematical Description

The calculations for month, year, and hour of day are fairly simple, relying on modular division along with the length of each month. Montes [1998] gives a detailed explanation of computational methods for electronic calendars. The calculation for the day of the week (Sunday, Monday, etc.) is given in the following equation:

$$DOW = \left(36 + DOY + \frac{5y}{4} \right) \mod 7$$ **Eq 5.12.16-1**

where

$$DOY = Day - of - Year$$
$$y = year - \frac{14 - month}{12}$$ **Eq 5.12.16-2**

Some holidays occur on specific days of the week rather than on set dates. President's Day, for instance, occurs on the third Monday in February.   The formula for finding these "moving" holidays is:

$$Date = 1 + 7(N - 1) + \left[\left(DOW_{hol} - DOW_{ref} \right) \mod 7 \right]$$ **Eq 5.12.16-3**

where

$$DOW_{ref} = DOW\{Year, Month, Date = 1 + 7(N - 1)\}$$ **Eq 5.12.16-4**

Here, DOW_{hol} is the day of the week for the holiday in question: 1 for Monday, 2 for Tuesday, and so on. N is the number of occurrence for that day in the month, so N is set to 3 when solving for the third Monday in the month.

5.12.17 Type 96: Utility rate schedule processor

The Type 96 Utility Rate Schedule Processor calculates electric bills for grid-tied buildings. It may be used to determine savings in buildings employing electric parallel generation. This component accounts for both usage ($/kWh) and demand ($/kW) charges over the course of the simulation. Type 96 assumes that the area utility employs a "net metering" policy so that power generated on-site which exceeds the instantaneous load may be sold back to utility at the retail rate. Any parallel generation source may be used: photovoltaic arrays, wind turbines, or gas-fired microturbines, for example. Two Type 96 components may be employed in a simulation to compare utility bills with and without parallel generation. Type 96 relies on Inputs from the Type 95 Holiday Calculator, so a Type 95 component must be present for the simulation to function properly. The Type 96 component performs economic calculations but does not represent a physical part of a building's electrical system. It does not perform any of the functions of an inverter or charge controller, for instance.

The Utility Rate Schedule Processor needs power Inputs from the parallel generation at each time step as well as values for electrical consumption (building load). It also requires several time-dependent inputs such as month, day, and hour from the Type 95 Utility Rate Schedule Calendar. This information is combined with a utility rate schedule, read from a specially formatted text file, to calculate utility bills. Type 96 supports energy usage charges ($/kWh) and instantaneous power demand charges ($/kW). "Monthly demand charges" are based on the largest instantaneous power consumption over the course of that month. "Rolling demand" or "ratchet" charges may also be included, based on the largest instantaneous power consumption over the last twelve months. The rate schedule may include hourly and/or seasonal variations as well as reduced rates for weekends and holidays.

Type 96 generates two sets of output data. Several standard TRNSYS Outputs are produced at each timestep. These Outputs include the usage and demand rates and the value of the power consumed, generated, and fed back to the grid. In addition, Type 96 generates a pair of output files detailing a building's electric bill at each month. These files are identical in content but are formatted differently. One is intended to be opened from a text editor and the other should be opened as space-delimited text in a spreadsheet. Each "utility bill" file gives monthly reports on usage, monthly demand, and ratchet charges.

5.12.17.1 Nomenclature

$BILL_{TOT}$	Total cumulative utility bill over whole simulation, updated monthly [$]
Chg_{demand}	Monthly demand charge [$]
$BILL_{TOT}$	Total cumulative utility bill over whole simulation, updated monthly [$]
Chg_{demand}	Monthly demand charge [$]
$Chg_{ratchet}$	Ratchet charge based on greatest power consumption over last twelve months, assessed monthly [$]
Chg_{usage}	Energy usage charge, assessed monthly [$]
DIS_{OPHU}	Demand rate discount coefficient for low monthly on-peak hours of use [$/kW]
$FLAG_{HOL}$	Holiday flag: 1 indicates bank holiday, 0 indicates no holiday
$FLAG_{WK}$	Weekend flag: 1 indicates Saturday or Sunday, 0 indicates weekday
$FRAC_{par}$	Fraction of building load met by parallel generation

HOD	Hour-of-day
HOY	Hour-of-year
$LU_{bill,text}$	Logical unit number for utility bill output file (text-editor format)
$LU_{bill,spread}$	Logical unit number for utility bill output file (spreadsheet format)
LU_{sched}	Logical unit number for utility rate schedule input file
OPHU	On-peak hours of use: Ratio of on-peak energy consumption to maximum instantaneous on-peak load for a month
P_{buy}	Power purchased from utility [W]
P_{gen}	Parallel generation [W]
P_{load}	Electrical load of building [W]
P_{loss}	Total parallel generation losses [W]
$P_{maxsell}$	Maximum excess generation to be sold back to utility through net metering [W]
$P_{netload}$	Building load after subtracting parallel generation [W]
P_{sell}	Parallel generation exceeding load, sold back to utility through net metering [W]
P_{useful}	Parallel generation which goes to satisfy building load or is sold back to utility [W]
$Rate_{demand}$	Monthly demand rate [$/kW]
$Rate_{ratchet}$	Rate for twelve-month ratchet charge [$/kW]
$Rate_{usage}$	Energy usage rate [$/kWh]
SW_{HOL}	Switch to enable or disable off-peak rates for all holidays
SW_{WE}	Switch to enable or disable off-peak rates for all weekends
Val_{buy}	Value of purchased power at any timestep based on energy usage rate [$]
Val_{gen}	Value of parallel generation at any timestep based on energy usage rate [$]
Val_{load}	Value of building load based on energy usage rate [$]
Val_{sell}	Value of energy sold back to utility under net metering, based on energy usage rate [$]

5.12.17.2   Mathematical Description

At each time step, Type 96 determines a net building load, the difference between the building's energy consumption and parallel generation. If the net load is positive, the customer purchases power from the utility equal to the net load.

$$P_{netload} = P_{load} - P_{gen}$$

Eq 5.12.17-1

$P_{buy} = P_{netload}$ for $P_{netload} > 0$

Eq 5.12.17-2

$P_{buy} = 0$ for $P_{netload} \leq 0$

Type 96 assumes net metering, so power may be sold back to the utility when generation exceeds load. However, the user has the option to set $P_{maxsell}$, a maximum grid resale power rate. The resale power is calculated at each timestep as follows:

$$P_{sell} = 0 \qquad \text{for } P_{netload} \geq 0$$

$$P_{sell} = \left| P_{netload} \right| \quad \text{for } P_{netlaod} < 0 \text{ and } |P_{netload}| < P_{maxsell}$$

Eq 5.12.17-3

$P_{sell} = P_{maxsell}$ for $P_{netlaod} < 0$ and $|P_{netload}| \geq P_{maxsell}$

All power generated in excess of the load is lost if $P_{maxsell}$ is set to 0.

Type 96 sets the total power loss P_{loss} to any excess generation beyond the grid resale limit $P_{maxsell}$:

$P_{loss} = 0$ for $P_{sell} \leq P_{maxsell}$

Eq 5.12.17-4

$P_{loss} = P_{gen} - P_{load} - P_{maxsell}$ for $P_{sell} > P_{maxsell}$

The monthly usage charge is found by totaling power purchases and sales over the course of the month and multiplying by the usage rate at each timestep (the usage rate need not be constant):

$$Chg_{usage} = \Delta t \sum_{j=1}^{N} Rate_{usage,j} \left(P_{buy,j} - P_{sell,j} \right)$$

Eq 5.12.17-5

Here, *N* is the number of timesteps in the month and Δt is the length of the timestep in hours, as assigned in the TRNSYS SIMULATION statement.

Monthly demand charges are determined based on the largest single instantaneous **product of net load and demand rate** over the course of the month. Like energy usage rates, demand schedule in Type 96 may include hourly or seasonal variations. This means that the demand charge may coincide with the greatest single monthly load if the **demand rate** is greater at some other time. The monthly demand charge for a month with a length of *N* timesteps is:

$$Chg_{demand} = \max\left\{ \left(Rate_{demand,1} * P_{buy,1} \right) ... \left(Rate_{demand,N} * P_{buy,N} \right) \right\}$$

Eq 5.12.17-6

Twelve-month ratchet charges are calculated similarly, except that the period of N timesteps represents the last twelve months rather than a single month:

$$Chg_{ratchet} = \max\left\{\left(Rate_{ratchet,1} * P_{buy,1}\right)...\left(Rate_{rachet,N} * P_{buy,N}\right)\right\}$$

Eq 5.12.17-7

The usage, monthly demand, and ratchet rates are automatically found at each timestep. The rates are based on the contents of a special rate schedule text file (detailed in a later section) and the Outputs of the TRNSYS Rate Schedule Calendar, Type 95. The Calendar generates essential information such as the hour of day and flags indicating whether a particular timestep falls on a weekend or holiday.

5.12.17.3   Using Type 96 in Conjunction with Type 95

Type 96 must be connected to a Type 95 Holiday Calculator in order to function. (Type 95, however, may be used independently of Type 96 for applications other than rate schedule calculations.) **The Type 95 component should precede all Type 96 components in the TRNSYS Input file.** Table 5.12.17–1 outlines how the Outputs of Type 95 should be linked to the Inputs of Type 96.

Table 5.12.17–1: Linking Inputs and Outputs from Type 95 and Type 96

QUANTITY	Type 96 Input	Type 95 Output
Hour-of-Day	Input 1	Output 1
Hour-of-Year	Input 2	Output 2
Month	Input 3	Output 5
Year	Input 4	Output 7
Weekend Flag	Input 6	Output 8
Holiday Flag	Input 7	Output 9

5.12.17.4 Type 96 Output Files and Other Features

The Type 95 Holiday Calculator generates flags indicating whether each timestep falls on a holiday or a weekend. Most utility rate schedules include reduced usage and demand rates for all bank holidays and weekends. The values for these special off-peak rates are defined in the rate schedule text file, as described in the following section. Two "switches" in the Parameter list for Type 96 determine whether weekends and/or holidays should be billed at the special rates. Parameter 4 is the "weekend switch" and Parameter 5 is the "holiday switch." Setting these Parameters to 1 indicates that weekends or holidays should be billed under off-peak rates. Any other values indicate that Type 96 should ignore weekends or holidays.

Some utilities allow reductions in the monthly demand rate for customers with low monthly values for "on-peak hours of use," or OPHU. The OPHU is defined as the ratio of the total on-peak energy consumption over the course of the month (in kWh) divided by the maximum on-peak instantaneous power consumption (in kW):

$$OPHU \equiv \frac{Energy_{on-peak}}{Power_{max,on-peak}}$$

Eq 5.12.17-8

If the *OPHU* total is **less** than the user-defined value *OPHU$_{max}$*, the demand rate which would have been used to assess the demand charge for that month will be reduced according to the *OPHU* value. The "demand rate discount coefficient" *DIS$_{OPHU}$* acts as a multiplier for demand rate reduction as shown in the following formula:

$$Rate_{Demand,disc} = Rate_{Demand} - \left[DIS_{OPHU}\left(OPHU_{max} - OPHU\right)\right]$$

Eq 5.12.17-9

Parameter 7 is the demand rate discount coefficient *DIS$_{OPHU}$* in \$/kW. Parameter 8 is *OPHU$_{max}$*, the maximum allowable number of on-peak hours of use for the customer to be eligible for the demand rate discount. This discounting scheme is unusual; most utilities employ fixed demand rates. Setting either Parameter 7 or Parameter 8 to zero will disable the demand rate discount.

Type 96 generates two output files as the simulation runs. These two files contain identical information on the customer's monthly utility bills. One of these files is formatted to be read using a text editor such as the Microsoft Wordpad. The FORTRAN logical unit number for the text-editor file is given in Parameter 2. The second file is meant to be opened from a spreadsheet as space-delimited text. Parameter 3 assigns the logical unit number for the spreadsheet file. Figure 5.12.17–1 gives an example of the utility bill file output in the text-editor format. The building simulated here is an office highrise with very large electrical loads.

```
Month: JANUARY  Year: 1990

Total Energy Usage:                        684206.5 kW-hr
Usage Charge:                          $    21124.22
Maximum Load for Month:                     1654.28 kW
Monthly Demand Charge:                 $ 15368.2480
Twelve Month Rolling Demand Charge:    $    1124.91
MONTHLY ELECTRICITY CHARGE:            $    37617.38


Month: FEBRUARY   Year: 1990

Total Energy Usage:                        627883.4 kW-hr
Usage Charge:                          $    19317.23
Maximum Load for Month:                     1585.91 kW
Monthly Demand Charge:                 $ 14733.0674
Twelve Month Rolling Demand Charge:    $    1124.91
MONTHLY ELECTRICITY CHARGE:            $    35175.21
```

Figure 5.12.17–1 Type 96 Utility Bill Output File (Formatted for Text Editor)

5.12.17.5 External data file

Type 96 reads the utility rate schedule (usage and demand rates at various hours and seasons) from a text file at the beginning of the TRNSYS simulation. The rate schedule file is accessed only once over the entire simulation and all its contents are stored by Type 96. Parameter 1 assigns the logical unit number for this file. **A rate schedule file must be developed and saved before running any TRNSYS simulation employing Type 96.**

The rate schedule file may be created using a text editor such as the Microsoft Notepad, although a spreadsheet program is recommended to be sure the correct number of values are entered. **In this case the rate schedule file must be saved as tab-delimited text.** If a text editing application is employed instead, **you must hit the RETURN key after the last line of the file.** A sample rate schedule file, Type96-UtilityRateScheduler.dat, is included with TRNSYS 16 in the Examples\Data Files directory. This file may be used as a template for creating custom rate schedules.

The original version of the Type96-UtilityRateScheduler.dat file looks like:

```
1
0   8783    0.025…. [x10]    0.1….[x7]    0.025…[x7]    0.02    3.5….[x10]
5…[x7]    3.5…[x7]    3
1.55
```

The 1 on the first line indicates the number of 'annual rate divisions' in the schedule. One such division is needed each time the rate schedule changes over the course of a calendar year. Time-of-day changes are *not* considered in finding this number.   The original Type96-UtilityRateScheduler.dat schedule does not change over the course of the year, so there is only one annual rate division. On the other hand, rates might increase in the summer and go down again in the fall; this arrangement would require three annual rate divisions. The first would be from January 1st until, for instance, May 31st. The second might last from June 1st until August 31st, and the third might cover September 1st through December 31st.

The second line consists of 52 numbers specifying daily rate schedule information. A similar 'long' line is needed for each annual rate division.   Since the default Type96-UtilityRateScheduler.dat schedule does not change over the course of the year, only one such 'long' line is needed.

The first number on the long line is the hour of the year (starting at January 1, 12:00 am) at which that rate division begins. The second is the hour at which the division ends. In this case hour 8783 corresponds to 11:00 pm on December 31 in a leap year. The Type 95 calendar component handles leap years, so you should assume 366 days per year. You must include enough long lines to account for each hour in the year.

The next 24 numbers are hourly usage rates in $/kW-hr for weekdays. The first hour is midnight to 1:00 AM, the second 1:00 AM through 2:00 AM, and so on. The 25th number is the usage rate in $/kW-hr for weekends and holidays. However, this value is only used for weekends when Parameter 4 is set to 1. It is used for holidays only when Parameter 5 is set to 1.

Next are 24 numbers defining the hourly demand schedule in $/kW. The last number on the long line is the demand rate for weekends and holidays. The monthly demand charge is based on the greatest instantaneous net load, multiplied by the demand rate at that hour, over the course of that month.

The final number in the file is the "12-month rolling demand" rate in $/kW. If this is a non-zero number, a second demand charge (the "ratchet charge") will be assessed each month based on the largest instantaneous net load over the last 12-month period. Figure 5.12.17–2 summarizes the format of the rate schedule file.
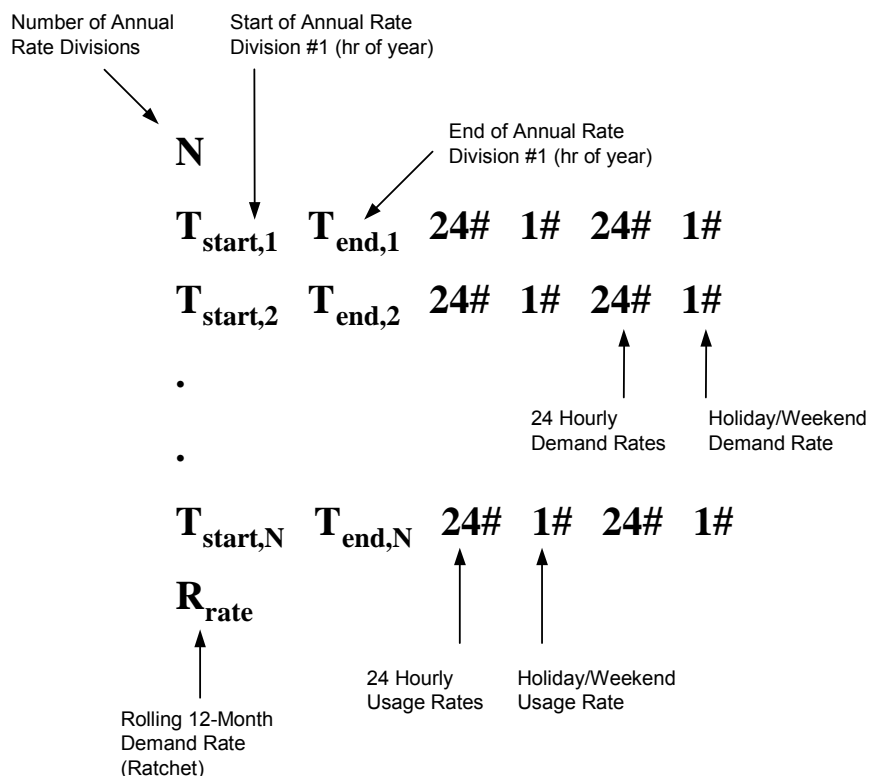

Figure 5.12.17–2 Type 96 Utility Bill Output File (Formatted for Text Editor)

5.12.18   Type 97: Calling CONTAM

This component provides a link between TRNSYS's Type56 Detailed Multizone Building and a bulk airflow modeling program called CONTAM developed by the US National Institute of Standards and Technology (NIST) [1,2].

The CONTAM program can be downloaded for free from the Indoor Air Quality and Ventilation Group's section of the National Institute of Standards and Technology's web site at:

http://www.bfrl.nist.gov/IAQanalysis/index.htm

To obtain a hard a copy, contact the Indoor Air Quality and Ventilation Group, Building and Fire Research Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8600, Gaithersburg, MD 20899-8600 USA, Phone: (301) 975 5900.

5.12.18.1   Mathematical Description

The process of creating a link between Type56 involves three steps. First, a building thermal model with appropriate Inputs and outputs is created using TRNBuild. Second, an airflow model of the same building is created using CONTAM. Third, the CONTAM building model and the TRNBuild building model are linked together using either the TRNSYS Simulation Studio or TRNSHELL.

THE THERMAL MODEL

Creation of the TRNBuild thermal model follows all of the same conventions as the creation of a normal building. The only difference is that infiltration into each zone and the coupling airflows between zones should all be defined as Inputs to Type56 (as opposed to being defined as constants or schedules). One note to bear in mind is that in TRNBuild and Type56 a coupling airflow from zone A to zone B does not automatically include a coupling airflow from zone B to zone A. These two airflows must be defined individually; CONTAM will calculate their values.

THE CONTAM MODEL

The CONTAM online documentation provides an excellent and complete source of information on setting up an airflow model. The process involves defining zones and defining air links that connect the zones to one another and that connect the zones to ambient conditions. Once the model is complete, the CONTAM [1,2] menu includes an option for generating a TRNSYS Input file. This file (extension *.air), much like Type56 and TRNBuild's *.inf file includes all of the information about the air flow model, including a list of required Inputs and a list of outputs that CONTAM will provide. Again as in the case of Type56, the TRNSYS Simulation Studio fills in the Type97 proforma "on the fly" based on information contained in the *.air file.

INPUT AND OUTPUT CONNECTIONS

In very general terms, Type56 takes infiltration and interzonal air flows from Type97 and calculates zone temperatures in return. Type97 takes these zone temperatures and recalculates the interzonal airflows based on the updated information. Iteration continues until both the zone temperatures and the interzonal air flows converge upon a solution.

With the original release of Type97 (TRNSYS v. 16.0), the inputs required by the model were atmospheric pressure, wind speed, wind direction, ambient temperature and the air temperature of each zone modeled in both Type57 and Type97. The CONTAM model had to remain completely static; the user created a set of air flow paths between the building and ambient and between the zones of the building and that configuration had to remain constant throughout the simulation. However, in CONTAM (and in its Fortran version, Type97), each air flow path is equipped with a multiplier that allows the user to either aggregate multiple identical openings into a single opening, or allows the user to restrict an opening as would be appropriate to model closing a window. With the release of TRNSYS 16.1, Type97 was modified so that the user may also provide a multiplier value for every path in the *.air file as inputs to Type97. The user may still elect to only provide the atmospheric and zone temperature inputs or may elect to also provide multipliers for the flow paths. There is one quirk about the model. CONTAM itself contains approximately a dozen different flow path models. The TRNSYS implementation of CONTAM (Type97) contains a much reduced set of flow path models. One of the restrictions is that an opening that allows air flow in both directions (an open interior door for example) is modeled as two openings in the *.air file, each allowing flow in only one direction. Because of this restriction, the user may notice that there are more flow paths listed in the *.air file than were specified in CONTAM. Care must be taken to look at the list of flow paths in the *.air file and to provide appropriate multipliers for each of them. If, for example, an interior door with bidirectional flow is to be modeled, the TRNSYS user will add two multiplier inputs to Type97 but will provide the same multiplier value for both of them. Users creating their TRNSYS input file by hand will find path information in the *.air file. Users of the TRNSYS Studio will note that as soon as they specify a *.air file in the Type97 proforma, all of the appropriate inputs are automatically read from the *.air file and are displayed just as they are for Type56.

The wind direction convention in CONTAM is N=0°, E=90°, etc.

5.12.18.2   References

1. W. Stuart Dols, George N. Walton, 2002. CONTAMW 2.0 User Manual. Multizone Airflow and Contaminant Transport Analysis Software. National Institute of Standards and Technology. Report NISTIR 6921. http://www.bfrl.nist.gov/IAQanalysis/index.htm

2. George N. Walton and W. Stuart Dols, 2003. CONTAM 2.1 Supplemental User Guide and Program Documentation. National Institute of Standards and Technology. Report NISTIR 7049. http://www.bfrl.nist.gov/IAQanalysis/index.htm

5.12.19   Type 101: Calling FLUENT

This Type couples TRNSYS and FLUENT. The connection launches FLUENT as a separate process and shares information via intermediate text files. You must have FLUENT installed on your computer in order to use this component. There are no specific limits on the number of inputs, outputs, or instances of Type 155 in a simulation.

5.12.19.1   Component configuration

The component was created in a very general fashion, in order to allow any kind of simulation that can be created with FLUENT. The communication between TRNSYS and FLUENT is done by means of two text files:

- **Script file** written by Type101, which contains the instructions for the FLUENT simulation. This script file takes advantage of FLUENT's capability to run in batch mode from a script file. The user should be knowledgeable in FLUENT's text commands in order to be able to modify Type101 and write the appropriate script file [1].

- **Results file** written by FLUENT, which contains the results from the FLUENT simulation. This file is read by Type101 in order to continue the simulation in TRNSYS. This file is deleted when Type101 reads its contents.

During a single time step, Type101 can be called at every single iteration or only after the other components have converged. This alternative allows for a static or dynamic coupling between the components in the simulation, as explained by Zhai and Chen [2].

In addition, Type101 can be controlled by the first input, which works as a control function, i.e., when it is 0 the component is not called and the outputs are the same as those during the previous time step; the component is called when the control function is equal to 1.

Source code:

The sourcecode must be changed in several locations in order to run the user-specific simulation:

1. During the initial time step manipulations, in order to initialize the boundary conditions and FLUENT case.

2. At the end of the initial time step manipulations, in order to set the initial values of the outputs.

3. At the beginning of a regular timestep call, in order to update the boundary conditions for the FLUENT case.

4. At the end of a regular timestep call, in order to update the output from the component that will be used in the rest of the TRNSYS components.

5. Inside the internal subroutines UPDATEBOUNDARY and READ_FLUENT_RESULTS. As indicated by their names, UPDATEBOUNDARY writes the scrip file with the new information for the current boundary conditions, and READ_FLUENT_RESULTS reads the output file created by FLUENT.

5.12.19.2   References

1. Fluent Inc. Fluent 6.1: User's Guide. 2003.
2. Zhai, Z., Chen, Q., Haves, P., and Klems, J.H., "On approaches to couple energy simulation and computational fluid dynamics programs", Building and Environment, (37), 857-864, (2002).

5.12.20   Type 155: Calling Matlab

This TRNSYS Type implements a link with Matlab. The connection uses the Matlab engine, which is launched as a separate process. The Fortran routine communicates with the Matlab engine through a Component Object Model (COM) interface. Type 155 can have different calling modes (e.g. iterative component or real-time controller).

You must have Matlab installed to use this component and Matlab's "bin\win32" folder must be on windows search path. At the time of writing Matlab Releases 13, 14 and 2006a are supported.

There are no specific limits on the number of inputs, outputs, or instances of Type 155 in a simulation.

> NOTE: When two or more instances of Type155 are used in the same project, all m-files share the same workspace in Matlab (they are "scripts", not "functions") so variables like trnInfo, trnTime, etc. and any local variable used in different m-files will be overwritten at each call.

5.12.20.1   Component configuration

PARAMETERS

- Parameter 1 is a Mode reserved for future use.
- The number of inputs and outputs are set by Parameters 2 and 3
- Parameter 4 (Calling Mode) describes the iterative behavior of this component. The values 0 and 10 are defined:
  - 0: Standard Iterative component (called at each call of each time step). In this case Type 155 sets INFO(9) to 1 (See Volume 08, Programmer's guide)
  - 10: Non-iterative component called at the end of each time step, after integrators and printers - This is suitable for a controller that calculates its outputs for one time step based on the converged ("measured") values of previous time step. In this case Type 155 sets INFO(9) to 2 (See Volume 08, Programmer's guide).

MATLAB M-FILE

The path and filename of your Matlab file are provided in a LABEL statement. Type 155 will understand the following kind of pathnames (Note that Matlab m-files cannot have spaces or special characters in their names):

- Relative to the deck (default if no path is specified)

  E.g. "My_M_File.m"

- Absolute (if the path starts with "\" or if the second character is ":")

  E.g. "C:\Program Files\Examples\Data Files\Type155_CallingMatlab.m"

- Relative to the TRNSYS root directory (if the path starts with ".\")

  E.g. ".\Examples\Data Files\Type155_CallingMatlab.m", which is equivalent to the second example here above if TRNSYS is installed in "C:\Program Files\Trnsys16"

5.12.20.2   Structure of the M-File

The same m-file will be called at each call to Matlab. Hence, the m-file must handle the different TRNSYS calls, very nuch like what a TRNSYS Type is doing (Note that very simple components will not have to perform any special operation).

An example is provided here below and in .\Examples\Data Files\Calling Matlab. There is also a more complex example in .\Examples\Calling Matlab.

A few points are worth noting:

- The m-file called by Type 155 is a Matlab "batch file", not a function (variables are created by TRNSYS in the main workspace).

- Matlab does not only receive the inputs in trnInputs but also other information about the simulation:

  - trnInfo (a copy of the INFO array)

  - trnTime (simulation time)

  - trnStartTime (simulation start time)

  - trnStopTime (simulation stop time)

  - trnTimeStep (simulation time step)

  - mFileErrorCode (see here below)

- Matlab must return outputs in trnOutputs. In order to prevent memory access violations in case the m-file fails, TRNSYS creates the output array (trnOutputs) with the correct size before running the m-file. As long as you do not reduce the size or delete the output array in your m-file, all errors will result in nice error handling and not a memory access violation.

- Another mechanism is implemented to prevent TRNSYS from continuing a simulation in case the m-file fails:

  - Before running the m-file, TRNSYS creates a variable called mFileErrorCode which is initialized to 1

  - If the value of that variable is not zero when Matlab returns, the simulation will stop and TRNSYS will display en error message with the value of mFileErrorCode. This can be used by the m-file to give a hint about what happened if the value of mFileErrorCode is incremented at different places in the m-file. In the example here below, if the m-file returns an error code of 200, something happened during a post-convergence call.

EXAMPLE   (".\EXAMPLES\DATA FILES\TYPE155_CALLINGMATLAB.M")

```
% Type155_CallingMatlab.m
% -------------------------------------------------------------------------
%
% Example M-file called by TRNSYS Type 155
%
% Data passed from / to TRNSYS
% ---------------------------
%
% trnTime (1x1)        : simulation time
% trnInfo (15x1)       : TRNSYS info array
% trnInputs (nIx1)     : TRNSYS inputs
% trnStartTime (1x1)   : TRNSYS Simulation Start time
% trnStopTime (1x1)    : TRNSYS Simulation Stop time
% trnTimeStep (1x1)    : TRNSYS Simulation time step
```

```
% mFileErrorCode (1x1) : Error code for this m-file. It is set to 1 by TRNSYS
%                        and the m-file should set it to 0 at the
%                        end to indicate that the call was successful. Any non-
%                        zero value will stop the simulation
% trnOutputs (nOx1)    : TRNSYS outputs
%
%
% Notes:
% ------
%
% You can use the values of trnInfo(7), trnInfo(8) and trnInfo(13) to identify
% the call (e.g. first iteration, etc.)
% Real-time controllers (callingMode = 10) will only be called once per time
% step with trnInfo(13) = 1 (after convergence)
%
% The number of inputs is given by the size of trnInputs and by trnInfo(3)
% The number of expected outputs is given by trnInfo(6)
% -----------------------------------------------------------------------------
% This example implements a very simple component. The component is iterative
% (should be called at each TRNSYS call)
% -----------------------------------------------------------------------------

% TRNSYS sets mFileErrorCode = 1 at the beginning of the M-File for error
% detection. This file increments mFileErrorCode at different places. If an
% error occurs in the m-file the last succesful step will be indicated by
% mFileErrorCode, which is displayed in the TRNSYS error message
% At the very end, the m-file sets mFileErrorCode to 0 to indicate that
% everything was OK

mFileErrorCode = 100;    % Beginning of the m-file


% --- Process Inputs and global parameters ------------------------------------
% -----------------------------------------------------------------------------
nI = trnInfo(3);
nO = trnInfo(6);

MyInput = trnInputs(1);

mFileErrorCode = 110;    % After processing inputs


% --- First call of the simulation: initial time step (no iterations) ---------
% -----------------------------------------------------------------------------
% (note that Matlab is initialized before this at the info(7) = -1 call, but
% the m-file is not called)

if ( (trnInfo(7) == 0) & (trnTime-trnStartTime < 1e-6) )

    % This is the first call (Counter will be incremented later for this very
    % first call)
    iCall = 0;
    % This is the first time step
    iStep = 1;
    % Do some initialization stuff, e.g. initialize history of the variables
    % for plotting at the end of the simulation
    % (uncomment lines if you wish to store variables)
    nTimeSteps = (trnStopTime-trnStartTime)/trnTimeStep + 1;
    history.inputs = zeros(nTimeSteps,nI);
    % No return, normal calculations are also performed during this call
    mFileErrorCode = 120    % After initialization call

end
```

```matlab
% --- Very last call of the simulation (after the user clicks "OK") -----------
% -----------------------------------------------------------------------------

if ( trnInfo(8) == -1 )

    mFileErrorCode = 1000;
    % Do stuff at the end of the simulation, e.g. calculate stats, draw plots,
    % etc...
    mFileErrorCode = 0; % Tell TRNSYS that we reached the end of the m-file
                        % without errors
    return

end


% --- Post convergence calls: store values ------------------------------------
% -----------------------------------------------------------------------------

if (trnInfo(13) == 1)

    mFileErrorCode = 200;   % Beginning of a post-convergence call
    % This is the extra call that indicates that all Units have converged. You
    % should do things like:
    % - calculate control signal that should be applied at next time step
    % - Store history of variables
    history.inputs(iStep) = MyInput;
    % Note: If Calling Mode is set to 10, Matlab will not be called during
    % iterative calls.
    % In that case only this loop will be executed and things like incrementing
    % the "iStep" counter should be done here
    mFileErrorCode = 0; % Tell TRNSYS that we reached the end of the m-file
                        % without errors

    return  % Do not update outputs at this call

end

% --- All iterative calls -----------------------------------------------------
% -----------------------------------------------------------------------------

% --- If this is a first call in the time step, increment counter ---

if ( trnInfo(7) == 0 )
    iStep = iStep+1;
end

% --- Process Inputs ---

mFileErrorCode = 130;   % Beginning of iterative call

% Do calculations here
MyResult = MyInput*2;
% --- Set outputs ---
trnOutputs(1) = MyResult;

mFileErrorCode = 0; % Tell TRNSYS that we reached the end of the m-file without
                    % errors


return
```

5.12.20.3   Troubleshooting when upgrading to Release 2006a

You may experience problems if the Release 2006a is installed without unistalling the previous versions of Matlab. If you get an error when using Type155 after installing Release 2006a, you should check the Windows path variable in order to have the right link to the latest version of Matlab:

-   In Control Panel, double click on System. Click on tab 'Advanced'.

-   On the tab 'Advanced', click on button 'Environment Variables'.

-   In the lower pane, called 'System variables', scroll down until you find the variable 'path'. Click on 'Edit'.

-   In the box, 'Variable value', make sure that there is only one entry for Matlab, and that it corresponds to the latest release.

   For example, **C:\Program Files\MATLAB\R2006a\bin\win32**

If you are not sure about the path to the main Matlab directory, type 'matlabroot' on the Matlab command prompt. In the previous example, you should get **C:\Program Files\MATLAB\R2006a.**

5.12.21   Type157: Calling COMIS

The simulation code COMIS (COMVEN) has been adapted to be a separate type for TRNSYS to model air flow models. COMIS can be downloaded from http://software.cstb.fr

> Although the proforma for Type 157 is distributed with TRNSYS, using the Type requires you to download the Type itself and the COMIS engine (COMIS 3.0 is free of charge but unsupported by CSTB, COMIS 3.1 is fully supported and can be purchased from CSTB)
>
> You will receive a manual for Type 157 with the Type itself

5.13 Weather Data Reading and Processing

This category only contains Type 109, the combined Data Reader and Solar Radiation Processor. Type 109 reads weather data in various standard formats (TMY2, TRY) and also in free (user-specified) format. A TRNSYS Studio plugin allows to convert Japanese AMeDAS weather data files to a format that is understood by Type 109.

5.14.1   Type 15: Weather Data Processor

This component reads and interprets weather data available in a series of standardized formats. The data files currently implemented are: Typical Meteorological Year (TMY), Typical Meteorological Year version 2 (TMY2), EnergyPlus Weather, International Weather for Energy Calculations (IWEC), and Canadian Weather for Energy Calculations (CWEC). In addition to reading data files, Type15 calculates total, beam, sky diffuse, ground reflected solar radiation, the angle of incidence of beam solar radiation, the slope and azimuth of as many surfaces as the user cares to define. The Type further includes calculation of mains water temperature and effective sky temperature for radiation calculations. It also outputs a number of indicators such as heating and cooling season, monthly and annual maximum, minimum and average temperature.

5.14.1.1   Nomenclature

Eo,sky	[0..1]	Clear sky emissivity
Tdewpt	[ºC]	Dew point temperature
time	[hr]	The hour of the year (simulation time)
pressure	[millibars]	Atmospheric pressure
Esky	[0..1]	Emissivity of the sky in the presence of clouds
fcloud	[0..1]	Fraction of sky covered by opaque clouds
fcloud	[0..1]	Emissivity of clouds
Tamb	[ºC]	Ambient temperature
T_{mains}	[ºC]	Mains temperature
$\bar{T}_{amb}$	[ºC]	Average annual air temperature
	[ºC]	Maximum difference between monthly average ambient temperatures
$T_{amb,\max}$	[1..365]	Julian day of the year

day

5.1.1.2.   Mathematical Description

Most of Type15 is the conglomeration of standard TRNSYS Type89 (Standard Format Weather Data Reader), standard TRNSYS Type16 (Radiation Processor), and a Thermal Energy System Specialists Utility Library component for calculating effective sky temperature (Type575). It was born out of frustration at continually having to connect up the same three components for every single TRNSYS building simulation. In addition to the three components, Type15 also calculates a number of other useful weather related values based on algorithms published by the United States Department of Energy's Building America Program [1]. Since Types 16 and 89 are standard components whose mathematical descriptions are included in this manual, the weather reading and solar radiation processing algorithms of Type15 are not discussed in this section. This section is devoted to a discussion of the sky temperature model [2], Building America algorithms, and other Type15 outputs.

SKY TEMPERATURE

Calculation of the sky temperature begins with an estimation of the clear sky emissivity based on the dew point temperature. The dew point correlation for clear sky emissivity is:

$$E_{o,sky} = 0.711 + 0.56 * \left(\frac{T_{dewpt}}{100}\right) + 0.73 * \left(\frac{T_{dewpt}}{100}\right)^2 \qquad \text{Eq 5.14.1-1}$$

The clear sky emissivity is then corrected for time of day in order to account for the differences in radiative transfer between the night time black sky and the day time blue sky, as shown in the following equation in which time is the hour of the year.

$$E_{o,sky} = E_{o,sky} + 0.013 * \cos\left(2\pi * \frac{MOD(time,24)}{24}\right) \qquad \text{Eq 5.14.1-2}$$

The clear sky emissivity is then corrected for atmospheric pressure. While Type15 reads pressure from data files in Pascals or atmospheres (depending on the file format), the model takes makes an internal conversion to millibars, the pressure units for which the equation was developed.

$$E_{o,sky} = E_{o,sky} + 0.00012 * (pressure - 1000) \qquad \text{Eq 5.14.1-3}$$

The emissivity of the sky in the presence of clouds is calculated by multiplying the clear sky emissivity by the fraction of the sky that is covered by clouds and by the emissivity of the clouds themselves, as shown in the following equation. The fraction of sky covered by opaque clouds has a value between 0 (no cloud cover) and 1 (complete cloud cover). Depending upon the mode of this component, the fraction of sky covered by opaque clouds may be entered either as a value between 0 and 1 or as a percentage (0 to 100).

$$E_{sky} = E_{o,sky} + (1.0 - E_{o,sky}) * f_{cloud} * \varepsilon_{cloud} \qquad \text{Eq 5.14.1-4}$$

Finally, the sky temperature is computed using the correlation shown in the equation.

$$T_{sky} = E_{sky}^{1/4}(T_{amb} + 273.13) - 273.13 \qquad \text{Eq 5.14.1-5}$$

MAINS WATER TEMPERATURE

Type15 provides an output of the temperature at which water might be expected to exit a buried distribution system. The algorithm was developed by Christensen and Burch at the U.S. National Renewable Energy Laboratory. The mains water temperature algorithm is:

$$T_{mains} = (\overline{T}_{amb} + offset) + ratio\left(\frac{T_{amb,\max}}{2}\right)\sin\left(\frac{360}{365}(day - 15 - lag) - 90\right) \qquad \text{Eq 5.14.1-6}$$

In which offset is defined as 3 ºC (6 ºF), *ratio* is defined by the equation:

$$ratio = 0.22 + 0.0056(\overline{T}_{amb} - 6.67) \qquad \text{Eq 5.14.1-7}$$

And in which *lag* is defined by:

$$lag = 1.67 - 0.56\left(\overline{\overline{T}}_{amb} - 6.67\right)$$ **Eq 5.14.1-8**

The offset, lag, and ratio values were obtained by fitting data compiled by Abrams and Shedd [3], the Florida Solar Energy Center [4], and Sandia National Labs [5].

GROUND REFLECTANCE

The user is asked to supply values of ground reflectance for snow covered and non-snow covered ground among Type15's parameters. Because all of the standard data file formats include data fields for whether or not the ground is covered by snow, it is relatively easy for Type15 to change the ground reflectance accordingly. The ground reflectance computed by Type15 follows a step function and depends only on the value of the "snow covered ground" flag in the data file being read. The ground reflectance is set as its own output and is also used in calculating the amount of ground reflected solar radiation that falls on each surface defined in Type15.

HEATING AND COOLING SEASON INDICATORS

The Building America Program Performance Analysis Procedures document includes a method by which indicators for typical heating equipment use and typical cooling equipment use can be calculated. Type15 sets one of its outputs (the heating season indicator)to a value of "1" if heating equipment is typically used during that month and to a value of "0" otherwise. Type15 sets another output (the cooling season indicator) to a value of "1" if cooling equipment is typically used and to a value of "0" otherwise. The methodology for determining heating season is as follows:

The heating system is typically enabled during a month in which the monthly average temperature is less than 21.94 °C and during December and January if the annual minimum air temperature is less than 15 °C. The cooling system is typically enabled during a month in which the monthly average temperature is above 18.89 °C and during July and August. Lastly, if there are two consecutive months during which the heating system is enabled the first month and the cooling system is enabled the second month (or vice versa) then both systems should be allowed to operate during both months.

MONTHLY AND ANNUAL CONDITIONS

Type15 outputs the minimum, maximum and average monthly and annual temperature as the simulation progresses. The values are all calculated during Type15's initialization at the beginning of the simulation so the values do not represent running averages, minima or maxima.

5.1.1.2.   References

[1]   Hendron, R. et. al., "Building America Performance Analysis Procedures" (revision 1), Building America, U.S. Department of Energy, NREL/TP-550-35567

[2]   Berdahl, Martin M., "Characteristics of Infrared Sky Radiation in the U.S.A.", Solar Energy Journal, 33.4 (1984): 321.

[3]   Abrams, D.W., and Shedd, A.C., 1996. "Effect of Seasonal Changes in Use Patterns and Cold Inlet Water Temperature on Water Heating Load",   ASHRAE Transactions, AT-96-18-3.

[4]   Parker, D., 2002. "Research Highlights from a Large Scale Residential Monitoring Study in a Hot Climate". FSEC-PF369-02. Cocoa, FL, Florida Solar Energy Center.

[5]   Kolb, G., 2003. Private communication. Sandia National Laboratories, Albuquerque, NM.

5.14.2 Type 109: Combined data reader and solar radiation processor

This component serves the main purpose of reading weather data at regular time intervals from a data file, converting it to a desired system of units and generating direct and diffuse radiation outputs for an arbitrary number of surfaces with arbitrary orientation and inclination.

Type 109 reads some standard weather data file formats, as well as a user-specified format according to a syntax explained here below.

5.14.2.1 Nomenclature

A_I	Anisotropy index
a_i	Addition factor for the ith value
a/c	Weighted circumsolar solid angle
f	Modulating factor for Reindl titlted surface model
F_1'	Reduced brightness coefficient (circumsolar)
F_2'	Reduced brightness coefficient (horizon brightening)
I_o	Extraterrestrial radiation
I_{on}	Extraterrestrial radiation at normal incidence
I_b	Beam radiation on horizontal surface
I_{bn}	Beam radiation at normal incidence
I_{bT}	Beam radiation on tilted surface
I_d	Diffuse radiation on horizontal surface
I_{dn}	Direct normal beam radiation
I_{dT}	Diffuse radiation on tilted surface
I	Total radiation on a horizontal surface
I_T	Total radiation on a tilted surface
I_{gT}	Ground reflected radiation on a tilted surface
k_T	Ratio of total radiation on a horizontal surface to extraterrestrial radiation
L_{loc}	Longitude of a given location
L_{unit}	Logical unit number from which data lines are to be read
m_i	Multiplication factor for the ith value
R_b	Ratio of beam radiation on tilted surface to beam on horizontal
R_d	Ratio of diffuse radiation on tilted surface to diffuse on horizontal

R_r	Ratio of reflected radiation on tilted surface to total radiation on horizontal
rh	Relative humidity (%)
T_a	Ambient temperature
$V_i(n)$	ith value read from the nth line
$V_i'(n)$	ith value of the nth line after application of the multiplication and addition factors
Y_i	ith time interpolated value
α	Solar altitude angle (90 - θ_Z)
β	Slope of surface, positive when tilted in the direction of the azimuth specification
β'	Slope of tracking axis
δ	Solar declination angle
Δ_{td}	Time interval at which data is provided (e.g., Δ_{td} = 1 for hourly data).
Δ	Sky brightness parameter
ε	Sky clearness parameter
γ	Azimuth angle of surface; angle between the projection of the normal to the surface into the horizontal plane and the local meridian. (facing equator = 0, west positive, east negative)
γ'	Azimuth angle of axis; angle between the projection of the axis line onto the horizontal plane and local meridian. (Same sign convention as for γ)
γ_s	Solar azimuth angle
θ	Angle of incidence of beam radiation on surface
θ_Z	Solar zenith angle
ρ_g	Ground reflectance
ϕ	Latitude

5.14.2.2   Operation modes

There are four different modes of weather data format handling:

- a userdefined mode (MODE 1) for arbitrary weather data
- MODE 2 to read in TMY2-data format
- MODE 3 to read in the German TRY-data format
- VDI- MODEs 91x and 92x according to the german standard VDI 2078.

This data reader is also able to read in general data (which may be any kind of data without restriction to weather data), converting it to a desired system of units and making it available to other TRNSYS UNITS as time varying forcing functions.

TYPE 109 uses free-formatted reading for user defined data. Each value must be separated from the previous value by a blank or a comma for MODE 0 or MODE 1.

5.14.2.3   Special Considerations

- Up to 5 UNITS of TYPE 109 may be specified.

- The data from line to line must be at constant time intervals (e.g., hourly ambient temperature readings).

- In user defined data mode (MODE 0), values are output in the same sequence as they appear on the data lines, i.e. if the 3rd value on each data line is CO_2 concentration, then the 3rd OUTPUT will be the CO_2 concentration value.
  In every weather data mode, the OUTPUTS have the same predefined order in order to facilitate the connection process.

- In user defined data mode (MODE 0), up to 20 comment lines may precede the data lines. Comment lines must not begin with a number.

- Outputs may or may not be interpolated between data timesteps depending upon the parameter specifications. For instance, if the number of occupants of a room were read in, these should not be interpolated.

- If Simulation ends with Weather Data containing radiation $\neq$ 0 the output for radiation data is set to zero for the last hour of simulation.

- The wind direction in TRNSYS depends on the convention given in the weather data file. The standard file-formats indicated in the above table use as convention N=0°, E=90°, etc. The user must check that this convention is in accord with the specific component that will use the information later in the simulation (i.e., COMIS or CONTAM).

5.14.2.4   Mathematical Description

Type 109 uses the same algorithms as Type 16 to calculate solar radiation on tilted surfaces (with the same tilted surface radiation modes 1 to 4) and to calculate the position of one – and two-axes tracking surfaces. Please refer to section 5.9.1, page 5–286, for more details.

The Radiation data is checked for values > 0 before sunrise and after sunset and is interpolated for time steps smaller or larger than the time difference between two data lines. The internal radiation Processor generates direct and diffuse radiation outputs for an arbitrary number of surfaces with any azimuth and slope. Moreover, standard outputs are Temperature, relative humidity, wind velocity as well as wind direction. Up to four more data columns may be processed using user defined weather data in MODE 1.

HORIZONTAL RADIATION MODES

Type 109 needs two components of solar radiation (e.g. beam and diffuse horizontal) in order to calculate the radiation on a tilted surface. It can use different combinations:

- I_b and I_d

- I and I_d

- I and I_{bn}

- I, T_{amb} and RH. The diffuse radiation is estimated using Reindl's full correlation (6a)

- I. The diffuse radiation is estimated using Reindl's reduced correlation

5.14.2.5   Data file syntax in Mode 1

HEADER SYNTAX

The header contains keywords, followed by the respective values. Keywords are contained between <brackets>.

An example for the German location Würzburg is shown here below:

```
<userdefined>
 <longitude>      -9.9        ! East of greenwich: negative
 <latitude>       49.8
 <gmt>            1           !time shift from GMT, east: positive (hours)
 <interval>       1           !Data file time interval between consecutive lines (hours)
 <firsttime>      1           !Time corresponding to first data line (hours)
 <var>   IBEAM_H<col>    5 <interp> 0 <add> 0 <mult>    1 <samp> -1 !...to get radiation in W/m²
 <var>   IBEAM_N<col>    0 <interp> 0 <add> 0 <mult>    1 <samp>  0 !...to get radiation in W/m²
 <var>   IDIFF_H <col>   6 <interp> 0 <add> 0 <mult>    1 <samp> -1 !...to get radiation in W/m²
 <var>   IGLOB_H<col>    0 <interp> 0 <add> 0 <mult>    1 <samp>  0 !...to get radiation in W/m²
 <var>   TAMB   <col>    3 <interp> 2 <add> 0 <mult>    1 <samp>  0 !...to get °C
 <var>   RHUM   <col>    4 <interp> 1 <add> 0 <mult> 100 <samp>  0 !...to get rel. hum. in %
 <var>   WSPEED<col>     2 <interp> 1 <add> 0 <mult>    1 <samp>  0 !...to get wind speed in m/s
 <var>   WDIR   <col>    1 <interp> 1 <add> 0 <mult>    1 <samp>  0 !...to get wind dir. in degr.
 <var>   udef1   <col>  12 <interp> 0 <add> 0 <mult> 100 <samp>  0 !...to get ... in ...
 <var>   test    <col>   9 <interp> 1 <add> 0 <mult> 100 <samp>  0 !...to get ... in ...
 <var>   idefix  <col>   8 <interp> 2 <add> 0 <mult> 100 <samp>  0 !...to get ... in ...
 <var>   udef4   <col>  11 <interp> 0 <add> 0 <mult> 100 <samp>  0 !...to get ... in ...
<data>
 270    2.6    .7    .93    0    0    -10    3.2    1e3    .2    8     0    1
 330    1.5    .6    .94    0    0    -11    3.2    2e3    .2    8.1   0    1
```

The whole header is enclosed by two keywords <userdefined> and <data>, marking the beginning and end of the header section:

```
<userdefined>
   .
   .
   .
<data>
```

Inside this header, the following keywords *must* appear:

Keyword	Units		Description
<longitude>	VALUE	(degrees)	east of greenwich: negative
<latitude>	VALUE	(degrees)	
<gmt>	VALUE	(hours)	time shift from GMT, east: positive
			if solar time ⌡ write "solar"
<interval>	VALUE	(hours)	data file time interval Δt_d between consecutive lines
<firsttime>	VALUE	(hours)	time corresponding to first data line

It is extremely important to specify the correct values. Any difference in geographical data or time will lead to an artificial time shift. For radiation data, this results in a wrong amount of direct or diffuse radiation on tilted surfaces. This will cause warnings in the listing file:

```
***** WARNING  FROM UNIT 12 TYPE 109 DATA READER
          RADIATION AT TIME  6.25  HAS A VALUE OF  23  BUT SUN IS DOWN
          IN DATA COLUMN  5  -- SUNRISE AT  6.67, SUNSET AT 17.21
```

Weather data variables are indicated by the keyword <var>, followed by specific names:

Specific Name	Description
IBEAM_H	Beam radiation on horizontal
IBEAM_N	Beam radiation at normal incidence
IDIFF_H	Sky diffuse radiation on horizontal
IGLOB_H	Global radiation on horizontal
TAMB	Ambient temperature
RHUM	Relative humidity of ambient air
WSPEED	Wind speed
WDIR	Wind direction

One or more of these variables have to appear in the user defined data header. Please use the variable names like indicated in the listing above, when the corresponding physical variable is available. There is special type of interpolation for radiation data, which can't be changed by the user, since behavior at sunrise and sunset has to be taken into account. Thus the values of the keyword <interp> are ignored for radiation data.

Up to 4 extra quantities can be read in, like "udef1" in the Würzburg example.

If the column number equals 0 inside a <var> definition line, this indicates to skip the information.

Moreover, information about the columns containing the respective values, the interpolation mode, the ability of data manipulation through addition and multiplication factors as well as the value which determines the data corresponding time interval are indicated by additional keywords. The keywords belong to a certain variable and have to appear in a one line statement and in a fixed order:

```
<var> NAME <col> VALUE <interp> VALUE <add> VALUE <mult> VALUE <samp> VALUE
```

Keyword	Value	Description
<col>		Number of the column for variable NAME. If value = 0, the variable will be skipped and the respective output set to zero
<interp>	0	No interpolation
	1	Linear interpolation
	2	Five point spline interpolation (Akima)
<add>		addition factor a_i
<mult>		multiplication factor m_i
<samp>	-1	column value is a mean value related to the time interval Δt_d ending at the time corresponding to actual data line

0   column value is a mean value related to the time interval $\Delta t_d/2$ before and after the time corresponding to actual data line

1   column value is a mean value related to the time interval Δt_d starting at the time corresponding to actual data line

Addition and multiplication factors have to be chosen in a way that values have the following units:

Variable	Unit
Radiation	[W/m²]
Temperature	[°C]
Relative humidity	[%]
Wind speed	[m/s]
Wind direction	[degrees]

It is recommended to avoid spline interpolation for relative humidity data, because the smoothing of data may result in a relative humidity of more than 100% for data with a sudden increase from 90 to 99% for example. The same is valid for wind speed to avoid negative values. So spline interpolation is applicable in the case of temperature or additional user defined data columns.

5.14.2.6 References

3. SOLMET, Volume 2 - Final Report, "Hourly Solar Radiation Surface Meteorological Observations," TD-9724, (l979).

4. Randall, C.M. and Whitson, M.E., Final Report, "Hourly Insolation and Meteorological Data Bases Including Improved Direct Insolation Estimates," Aerospace Report No. ATR-78(7592)-l, (l977).

5. Duffie, J.A. and Beckman, W.A., Solar Energy Thermal Processes, Wiley, New York, l974.

6. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, l972.

7. Braun, J.E. and Mitchell, J.C., "Solar Geometry for Fixed and Tracking Surfaces," Solar Energy, vol. 31, No. 5, October, 1983.

8. (a) Reindl, D. T., Beckman, W. A., Duffie, J. A., "Diffuse Fraction Correlations", Solar Energy, Vol. 45, No. 1, 1990, pp. 1-7.
(b) Reindl, D. T., Beckman, W. A., Duffie, J. A., "Evaluation of Hourly Tilted Surface Radiation Models", Solar Energy, Vol. 45, No. 1, 1990, pp. 9-17.

9. Hay, J.E., Davies, J.A., "Calculation of The Solar Radiation Incident on An Inclined Surface", Proceedings First Canadian Solar Radiation Workshop, pp. 59-72, (1980).

10. Perez, R., Stewart, R., Seals, R., Guertin, T., "The Development and Verification of The Perez Diffuse Radiation Model", Sandia Report SAND88-7030, (Sandia National Laboratories, Albuquerque, New Mexico, 87185, USA) October, 1988.

5.15. Index of components by type number

Type number	Name	Section	Page
1	Flat Plate Collector (Quadratic Efficiency)	Solar Thermal Collectors	5–333
2	Differential Controller	Controllers	5–15
3	Variable Speed Pump or Fan without Humidity Effects	Hydronics	5–193
4	Stratified Fluid Storage Tank	Thermal Storage	5–369
5	Heat exchanger	Heat exchangers	5–109
6	Auxiliary Heater	HVAC	5–121
8	Three Stage Room Thermostat	Controllers	5–17
9	Data Reader (Generic Data Files)	Utility	5–397
10	Rock Bed Storage	Thermal Storage	5–375
11	Tee Piece, Flow Diverter, Flow Mixer, Tempering Valve	Hydronics	5–195
12	Energy/(Degree Day) Space Heating or Cooling Load	Loads and Structures	5–214
13	Pressure Relief Valve	Hydronics	5–199
14	Time Dependent Forcing Function	Utility	5–408
16	Solar Radiation Processor	Physical Phenomena	5–286
17	Waste Heat Recovery	Heat exchangers	5–115
18	Pitched Roof and Attic	Loads and Structures	5–220
19	Detailed Zone (Transfer Function)	Loads and Structures	5–224
20	Dual Source Heat Pump	HVAC	5–123
22	Iterative Feedback Controller	Controllers	5–19
23	PID Controller	Controllers	5–23
24	Quantity Integrator	Utility	5–410

25	Printer	Output	5–261
27	Histogram plotter	Output	5–263
28	Simulation Summary	Output	5–265
29	Economic Analysis	Output	5–272
30	Collector Array Shading	Physical Phenomena	5–296
31	Pipe or Duct	Hydronics	5–201
32	Simplified Cooling Coil	HVAC	5–127
33	Psychrometrics	Physical Phenomena	5–300
34	Overhang and Wingwall Shading	Loads and Structures	5–237
35	Window with Variable Insulation	Loads and Structures	5–241
36	Thermal Storage Wall	Loads and Structures	5–243
37	Attached Sunspace	Loads and Structures	5–249
38	Algebraic Tank (Plug Flow)	Thermal Storage	5–379
39	Variable Volume Tank	Thermal Storage	5–385
40	Microprocessor Controller	Controllers	5–28
41	Forcing Function Sequencer	Utility	5–414
42	Conditioning Equipment	HVAC	5–131
43	Part Load Performance	HVAC	5–133
45	Thermosyphon Collector with Integral Collector Storage	Solar Thermal Collectors	5–339
47	Shepherd and Hyman Battery models	Electrical	5–39
48	Regulator / Inverter	Electrical	5–44
50	PV-Thermal Collector	Electrical	5–47
51	Cooling Tower	HVAC	5–135
52	Detailed Cooling Coil	HVAC	5–141
53	Parallel Chillers	HVAC	5–149
54	Hourly Weather Data Generator	Physical Phenomena	5–302

55	Periodic Integrator	Utility	5–416
56	Multizone Building and TRNBuild	Loads and Structures	5–253
57	Unit Conversion Routine	Utility	5–420
58	Refrigerant Properties	Physical Phenomena	5–306
60	Stratified Fluid Storage Tank with Internal Heat Exchangers	Thermal Storage	5–389
62	Calling Excel	Utility	5–426
64	Shading by External Object with Single Shading Mask	Physical Phenomena	5–308
65	Online Plotter	Output	5–280
66	Calling EES	Utility	5–428
67	Shading by External Object	Physical Phenomena	5–313
68	Shading by External Object (obsolete)	Physical Phenomena	5–323
69	Effective Sky Temperature	Physical Phenomena	5–325
70	Parameter replacement	Utility	5–432
71	Evacuated Tube Solar Collector	Solar Thermal Collectors	5–345
72	Performance Map Solar Collector	Solar Thermal Collectors	5–351
73	Theoretical Flat Plate Collector	Solar Thermal Collectors	5–357
74	Compound Parabolic Concentrating Collector	Solar Thermal Collectors	5–361
77	Simple Ground Temperature Profile	Physical Phenomena	5–327
80	Calculation of Convective Heat Transfer Coefficients	Physical Phenomena	5–329
88	Lumped Capacitance Building Type	Loads and Structures	5–255
89	Weather data reader (standard format)	Utility	5–435
90	Wind Eneergy Conversion System	Electrical	5–49
91	Constant Effectiveness Heat Exchanger	Heat exchangers	5–117
92	ON/OFF Auxiliary Cooling Device	HVAC	5–153
93	Input value recall	Utility	5–442

94	Photovoltaic Array	Electrical	5–67
95	Holiday Calculator	Utility	5–444
96	Utility Rate Schedule Processor	Utility	5–448
97	Calling CONTAM	Utility	5–456
100	Electrolizer controller	Hydrogen Systems	5–165
102	DEGS Dispatch Controller	Electrical	5–77
105	Master level controller for SAPS	Hydrogen Systems	5–167
107	Single Effect Hot Water Fired Absorption Chiller	HVAC	5–155
108	Five Stage Room Thermostat	Controllers	5–34
109	Weather Data Reading and Processing	Utility	5–470
110	Variable Speed Pump	Hydronics	5–204
111	Variable Speed Fan/Blower with Humidity Effects	Hydronics	5–206
112	Single Speed Fan/Blower with Humidity Effects	Hydronics	5–208
114	Constant Speed Pump	Hydronics	5–210
120	Diesel Engine Generator Set	Electrical	5–79
121	Simple Furnace / Air Heater	HVAC	5–161
155	Calling Matlab	Utility	5–461
157	Calling COMIS	Utility	5–466
160	Advanced Alkaline Electrolyzer	Hydrogen Systems	5–171
164	Compressed gas storage	Hydrogen Systems	5–177
170	Proton-Exchange Membrane Fuel Cell	Hydrogen Systems	5–181
173	Alkaline Fuel Cell	Hydrogen Systems	5–189
175	Power Conditioning Unit	Electrical	5–83
180	Photovoltaic Array (with data file)	Electrical	5–85
185	Lead-acid baterry with gassing effects	Electrical	5–91

188	AC-Busbar	Electrical	5–97
194	Photovoltaic Array	Electrical	5–99