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ESATAN-TMS Thermal Training Manual

Prepared by:
ITP Engines UK Ltd.
Whetstone, Leicester, UK

CONTENTS

Introduction

The purpose of this manual is to introduce the ESATAN™ thermal analysis package by means of a number of example problems, each of which is designed to illustrate certain important features. The examples get more complex as the manual progresses, so it is recommended that they be read in the order given.

Most of the examples are pure thermal, but the last four describe FHTS models for the benefit of users for whom thermohydraulic analysis is of interest. It is assumed that you have some degree of computer programming experience.

This manual is not intended to provide a complete description of the syntax of ESATAN input files: we recommend that you have the User Manual open alongside to refer to. Nor is it an exhaustive account of ESATAN features. Once you have understood the fundamentals, we suggest that you browse the User Manual to see how more advanced functions are supported.

Example	Problem/Model Description	Concepts introduced	ESATAN features introduced
1.	Temperature distribution in a metal bar with constant heat load at one end, fixed temperature at the other. Steady state.	Thermal-mathematical model. Network analysis to predict temperature: nodes & conductors. Steady state solution.	ESATAN input file. D-node. B-node. GL-conductor. Heat load QR. Control constants NLOOP, RELXCA. Comments. Mortran in operations blocks. Library routines: solver SOLVIT, tabular output PRNDTB. How to run ESATAN; preprocess and solution. (MDB file, log file, generated Fortran file.) Output file.
2.	Cooling of a metal bar by radiation, starting from uniform temperature. Transient.	Radiative heat exchange. Temperature-dependent material properties. Transient solution Temperature scales. User output.	GR-conductor. Mortran in data blocks. Arrays. Interpolation library routine. Control constants DTIMEI, TIMEND, OUTINT. Implicit transient solver, SLFWBK. Block-output library routine, PRNDBL. Control constants TABS, STEFAN. $VARIABLES2.
3.	It is required to know the maximum temperature and heat flux for a uniformly distributed heat load on a PCB. PCB, uniform load, held at edges, conduction only, 5 x 4 nodes plus 1 boundary. Steady state. Re-run with finer mesh.	2-d network. Distributed load. Parametrisation of model. Effect of level of discretisation	Local constants. FOR-DO loops in data blocks. Heat-flux output routine (PRQNOD).
4.	Electronics unit: box containing 3 identical PCBs. Radiation between PCBs and box sides. Box treated as boundary. Steady state.	Submodelling.	$MODEL (submodel). $REPEAT. Supernodes. Inter-model links. FLUXGL, FLUXGR. User constants.

Example	Problem/Model Description	Concepts introduced	ESATAN features introduced
5.	As 4, but different heat load on each PCB. Cool air passing over each PCB. Steady state.	Parametrisation of submodel. Convection cooling.	$ELEMENT (user). $SUBSTITUTIONS. GF-conductors.
6.	Electronic instrument e.g. imaging radar, with time-dependent dissipation (on/off). Temperature regulated by cryogenic cooler with performance curve. 20 to 50 nodes. Transient.	Control logic.	Events. User-subroutines. $INITIAL. $VARIABLES1. Nodal & conductance library functions – NODFNC, CNDFNC. Table arrays. CSV output library routine, PRNCSV
7.	Radiator sizing. Steady state.	Cyclic transient analysis. Parametric analysis.	Cyclic solver, SOLCYC. Cyclic interpolation, INTCYC. $PARAMETERS. User-defined nodal entities.
8.	A simple fluid loop	Fluid nodes. Mass flow links. Pumps.	F-node. J-node M-conductor. GP-conductor. PUMP_CF element. Fluid state definition.
9.	A single-phase steady state fluid loop	Single-phase fluid. Heat exchangers. Temperature control valve.	GL as convective HTC. Mass sink/source, FM. Control constant SOLTYP. Status-setting library routine, STATST. Solver FLTNSS.
10.	A single-phase transient fluid loop	Expansion and contraction losses.	Library functions ACLOSS, NUVRE. Output routine PRNDPT. Solver FLTNTS.
11.	A two-phase fluid loop	Two-phase fluid. Side-branch accumulator.	R-node. Solver FGENFI.

Example 1 A Heated Metal Bar in Steady State

We begin with a very simple example to introduce the basic concepts of thermal analysis by the lumped-parameter or network method, and how the model is represented in ESATAN.

Consider a rectangular metal bar, insulated along its length, with one end held at a constant 20 °C while a heat flux of 100 W is applied to the other. The metal has a thermal conductivity of 240 W/m °C, a specific heat of 900 J/kg °C and a density of 2 700 kg/m^3. The bar is 20 cm × 4 cm × 4 cm. We want to know the temperature distribution in the bar when it has reached steady state, i.e. when it has been left long enough for the temperature at each point to be constant in time.

***

The first step in the analysis of this thermal problem is to divide the bar into sections and associate a discrete *node* with each section, as shown in Figure 1-1. All the properties of a section – thermal capacitance, temperature, impressed heat flux, etc. – are then considered to apply at the node (hence the term *lumped parameter*).

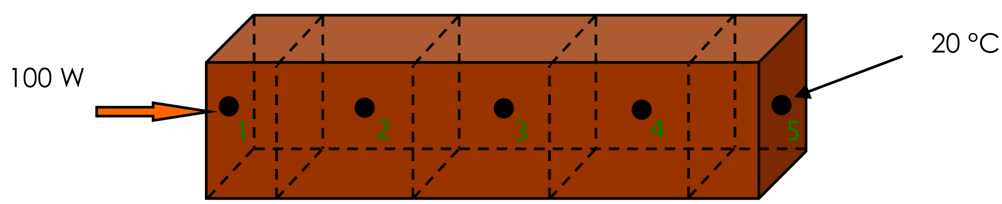

Figure 1-1 Heated bar with nodal discretisation

For our model we have discretised the bar into five nodes as shown; in general, the more nodes we use the more accurate the solution will be – the thermal engineer normally uses his or her experience to decide on the appropriate level of discretisation. Note that nodes 1 and 5 have half the volume of the others; this is because the boundary conditions are to be applied at the end surfaces of the bar, rather than within its interior. The thermal capacitance, *C*, of each node is calculated from the expression

$$C = \rho V c\ ,$$

where ρ is the density, V the volume and c the specific heat.

Nodes between which heat is expected to flow are coupled by *conductors*. A conductance is usually calculated by assuming that the heat flows one-dimensionally from one section to the next parallel to a line between the nodes (which is certainly the case here). With this assumption, the conductance, G_L, is given by the formula

$$G_L = \frac{kA}{x}$$

where k is the thermal conductivity of the material, A is the cross-sectional area of the bar and x the distance between the nodes. The subscript L on the conductance reflects the linearity of the dependence on temperature of the heat flux, Q, along the conductor:

$$Q = G_L \ \Delta T$$

where ΔT is the temperature difference between the nodes.

We now have a *network* of nodes and conductors (admittedly a very simple one; in general there may be multiple conductors at a node). To complete the lumped-parameter model we must identify the boundary conditions. In the present case these are the fixed temperature at one end and the heat flux applied at the other.

***

Having thus defined our *thermal-mathematical model*, we can now represent it in an ESATAN model file and ask ESATAN to perform the solution. The file is shown in Listing 1-1.

Listing 1-1 Model file for heated bar model

```
$MODEL HEATED_BAR
#
#   A simple metal bar, insulated along its length with one end fixed at
# 20 deg C and 100 W applied to the other.
#
###############
# Data Blocks #
###############
#
$NODES
#
D1 = 'Bar end with heat source', T = 50.0, C = 97.2, QR = 100.0;
D2 = 'Bar middle', T = 50.0, C = 194.4;
D3 = 'Bar middle', T = 50.0, C = 194.4;
D4 = 'Bar middle', T = 50.0, C = 194.4;
B5 = 'Bar end at fixed temp', T = 20.0, C = 97.2;
#
$CONDUCTORS
#
GL(1, 2) = 7.68;
GL(2, 3) = 7.68;
GL(3, 4) = 7.68;
GL(4, 5) = 7.68;
#
$CONSTANTS
#
   $CONTROL
#
   RELXCA = 0.001;       #  Convergence criterion
   NLOOP = 1000;         #  Maximum number of iterations
#
#####################
# Operations Blocks #
#####################
#
```

Listing 1-1 Model file for heated bar model

```
$EXECUTION
#
      HEADER = 'Heated metal bar - steady state'
#
# Steady-state solution
#
      CALL SOLVIT
#
$OUTPUTS
#
      CALL PRNDTB(' ', 'L, T, QR', CURRENT)
#
$ENDMODEL HEATED_BAR
```

First the name of the model is declared with the `$MODEL` keyword. All ESATAN keywords must be in upper case; a common convention is to also use upper case for the model name, but this isn't mandatory.

Comments in the input deck are denoted by a '#' character: everything on the line after a '#' is disregarded. It is usual for empty comment lines to be used to improve the readability of the input deck.

The `$NODES` block is, unsurprisingly, where the nodes in the model are defined. Each node is given a number prefixed by a letter denoting the node type; we have two types of node in our model, *diffusion* (`D`) and *boundary* (`B`). For diffusion nodes the temperature will be calculated by the selected ESATAN solver, while at a boundary node the temperature remains fixed at the value given by the user. Following the node number is an optional label, up to 24 characters long and enclosed in single quotes. The remaining attributes are assigned in a comma-separated list, each attribute being designated by a short mnemonic. Temperature (`T`) is mandatory, the value given being used as an initial estimate for the solution; here, we have guessed that 50 °C will be a reasonable starting point. All other attributes are optional, defaulting to zero if not specified. The capacitance (`C`) is calculated for each node as described above, and we have assigned an appropriate heat source (`QR`) to node 1. The units used are SI. Note the semicolon terminating each node definition.

The `$CONDUCTORS` block comes next, each conductor referencing the pair of nodes it connects. The linear conductance values (`GL`s) are obtained as described above.

In order to run a solution, various parameters are needed to specify, for instance, what level of convergence is required. In ESATAN these are known as *control constants*, and are set in the `$CONTROL` sub-block of `$CONSTANTS`. (Later we shall see that there are also 'user constants'.) Convergence on temperature is controlled by `RELXCA` – the small this value, the better the convergence – and the number of iterations the solver will perform before giving up is specified by `NLOOP`.

So far we have been discussing the *data blocks*, in which the model's topology (the network), physical characteristics, and other parameters are defined. Next come the *operations blocks* in which the operations to be carried out on the model are specified. The formats of the two block-types are significantly different, the former being quite free-format and the latter bearing a strong resemblance to FORTRAN 77. Indeed, the language used in the operations blocks is an extension of this programming language known as *Mortran*. The most obvious aspect of the operations blocks, a direct result of this heritage, is that **each statement must be indented by 6 spaces**. This is often forgotten by the inexperienced ESATAN user.

In the `$EXECUTION` block the character control constant `HEADER` is assigned an appropriate value to be echoed in the output (character control constants cannot be defined in the `$CONTROL` block), and we then have a call to the chosen solution routine, `SOLVIT`, which will perform the steady-state analysis using a successive-point iteration method. ESATAN has a library of such subroutines performing various tasks which the user can invoke in the operations blocks.

Next comes the `$OUTPUTS` block. The contents of this block are executed at appropriate points during the solution, depending on the type of solver; for a steady state, this is when the solution is complete, i.e. either convergence has been reached or else the maximum number of iterations is exceeded. Here we call `PRNDTB` to give table output of labels, temperatures and heat sources for all nodes. (To understand the precise meaning of the arguments to the routine, please refer to the User Manual.)

The model is closed with the $ENDMODEL line. The model name on this line is optional but recommended. You should be aware that on some systems, notably Windows, the last input line must be terminated with a carriage return.

***

The model file may be given any name, but by custom it is usually called *<model>.d* where *<model>* is the same name given on the `$MODEL` line but in lower case; thus, our example model would be saved in a file called *heated_bar.d*. We can now ask ESATAN to run the model. There are two principal steps involved in this, *preprocess* and *solve*. Preprocessing involves parsing the input deck and constructing a machine-readable *model database*. In the solve step, a FORTRAN program is generated, compiled and executed which reads the model database and calls the appropriate library subroutines to carry out the analysis and provide the required output.

In addition to the model database, the preprocessor always produces a *log file* which echoes the input deck and reports any errors or potential errors found, as well as giving a summary of the structure of the model – the number of nodes, the number of conductors, etc. If ESATAN fails to preprocess your model you should look in the log file to see why. Further errors may be detected during the FORTRAN generation, in which case a second log file is produced.

Files generated by ESATAN are given the basename *<MODEL>*, i.e. the model name in upper case, truncated for historical reasons to 8 characters. The following table lists the main file-name extensions used.

File	**Extension**
Model database	.MDB
Preprocessor log file	.log

File	Extension
FORTRAN-generation log file	.lgf
Solution progress monitoring	.MON
Standard solution output	.out

So, for our simple bar model ESATAN produces files called *HEATED_B.MDB*, *HEATED_B.log*, *HEATED_B.MON* and *HEATED_B.out*, among others.

***

The contents of the solution output file *HEATED_B.out*, resulting from the above model, are shown in Listing 1-2. (In fact, this is not quite true: when first produced, the output contains a FORTRAN 'carriage control' character at the beginning of each line and should be translated using an appropriate utility, such as UNIX's *asa* or *fpr*, to yield the properly formatted text as shown.)

Listing 1-2 Solution output with `RELXCA=0.001`

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     1
14 FEBRUARY 2006                 17:12:05                             HEATED_BAR

Heated metal bar - steady state




 TIMEN =      0.00      MODULE SOLVIT      LOOPCT =    19
ENBALA = 1.980E-03      ENBALR = 2.E-05


TABLE OUTPUT WITH ZENTS = 'L,T,QR'
FOR NODES OF ZLABEL = ' '

================================================================================

HEATED_BAR


         NODE   LABEL                              T             QR

           1    Bar end with heat source         72.08        100.00
           2    Bar middle                       59.06          0.00
           3    Bar middle                       46.04          0.00
           4    Bar middle                       33.02          0.00
           5    Bar end at fixed temp            20.00          0.00
```

At the top of each page of output – in this example there is only one page – ESATAN writes a header giving information such as the time of the run and the model name. Then, as mentioned above, the contents of the character control constant `HEADER` are echoed. Following this are values of certain control constants which are calculated during solution; here we have the solution time (`TIMEN` – usually zero for a steady state), the name of the solver (`MODULE`), the number of iterations needed to converge (`LOOPCT`), the system absolute energy balance (`ENBALA`) and the system relative energy balance (`ENBALR`). These last two, `ENBALR` in particular, are indicators of how good a solution has been found. Finally, the data requested in the call to `PRNDTB` – node label and temperature – is output (node number is always output).

We can see from Listing 1-2 that the temperature varies linearly along the bar, as one would expect, with the hot end reaching 72 °C. The solution was reached in 19 iterations and, as can be confirmed easily by hand-calculation, is very accurate.

It is instructive to run the model again with a larger value for the convergence criterion. Listing 1-3 shows the output obtained with `RELXCA` set to 0.5.

Listing 1-3 Solution output with `RELXCA=0.5`

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     1
14 FEBRUARY 2006                 17:13:00                             HEATED_BAR

Heated metal bar - steady state





 TIMEN =      0.00      MODULE SOLVIT      LOOPCT =     8
ENBALA =    1.2878      ENBALR = 0.0127


TABLE OUTPUT WITH ZENTS = 'L,T,QR'
FOR NODES OF ZLABEL = ' '

================================================================================

HEATED_BAR


         NODE   LABEL                              T             QR

           1    Bar end with heat source         73.09       100.00
           2    Bar middle                       59.79         0.00
           3    Bar middle                       46.45         0.00
           4    Bar middle                       33.19         0.00
           5    Bar end at fixed temp            20.00         0.00
```

Although the solution has been found faster, in only 8 iterations, it has lost some accuracy, as indicated by the energy balance values: the hot-end temperature differs by 1 °C from the previous run. This trade-off between speed and accuracy is an important consideration for the thermal engineer.

***

Note that the capacitances are not actually needed for a steady state analysis, but we defined them anyway so that the model can be used to find a transient, or time-dependent, solution. Nor is capacitance necessary for a boundary node.

The ordering of the blocks in the input deck does not necessarily have to be as shown in this example. The data blocks must come before the operations blocks, and `$NODES` before `$CONDUCTORS`, but otherwise there is some freedom: see the User Manual for details.

Finally, we leave it as an exercise for the reader to re-run the model using the sparse-matrix solver `SOLVFM` and compare the results. A very, very accurate solution is obtained in just two iterations (as is to be expected since, mathematically, the problem posed in this case is linear and therefore exactly soluble). Indeed, `SOLVFM` is the preferred steady-state solver for small to medium-sized thermal models, i.e. where memory limits will not be exceeded.

Example 2 Transient Cooling of a Metal Bar

In this example we modify the metal bar model of Example 1, introducing radiative heat exchange, temperature-dependent material properties and transient analysis. We also consider how to use different temperature scales in ESATAN.

Our metal bar has the same dimensions (20 cm × 4 cm × 4 cm) as before. Now, however, we are going to assume the bar has been heated to a uniform 400 K and then allow it to cool by thermal radiation from its entire surface to an environment with an ambient temperature of 295 K. The density of the metal is still taken to be 2 700 kg/m^3 but the conductivity and specific heat now vary with temperature as shown in the table below. The infra-red emissivity of the bar is 0.8. The objective is to monitor the temperature of the bar over a period of one hour.

T [K]	250	300	345	375	420
k [W/m K]	235	237	240	241	239
c [J/kg K]	862	896	922	939	960

***

We use the same discretisation as previously but now with an additional boundary node, which we number 999, to represent the environment (Figure 2-1).

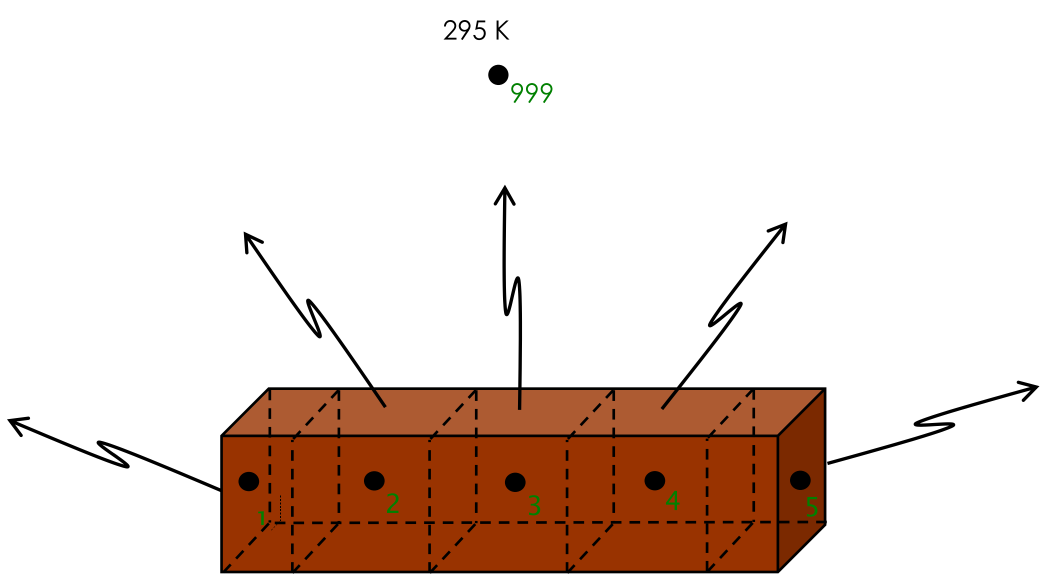

Figure 2-1 Cooled bar with discretisation

Now, the net heat flux transferred by radiation between two faces i and j at temperatures T_i and T_j, respectively, is given by

$$Q = \sigma\varepsilon_i A_i B_{ij} (T_i^4 - T_j^4)$$

where σ is the Stefan-Boltzmann constant, ε_i the emissivity of face *i*, A_i the surface area of *i*, and B_{ij} the *radiative exchange factor* (REF) between *i* and *j*. The REF is defined as the fraction of the energy emitted by *i* which is finally absorbed by *j*, this energy arriving at *j* either directly or via reflection or transmission by other faces in the model; where there is a direct line of sight, $B_{ij} = \alpha_j F_{ij}$ in which α_j is the absorptivity of face *j* and F_{ij} is the view factor between *i* and *j*. In ESATAN, the quantity

$$G_R = \varepsilon_i A_i B_{ij}$$

is known as the radiative conductance.

In general REFs are difficult to calculate, often requiring a specialised tool such as ESATAN-TMS Workbench to determine. However, in some situations we can make certain simplifying assumptions. In the present case it is reasonable to assume that the environment will effectively absorb all thermal energy radiated from the bar. (Even if the environment reflects a proportion of the energy, the chances are it will hit another part of the environment rather than the bar, and will quickly be absorbed after a few such reflections.) Thus, the REFs between nodes in the bar and the environment can be taken as unity, and we have $G_R = \varepsilon_i A_i$ for all our radiative conductances.

***

The ESATAN input file for this model is shown in Listing 2-1. The initial node temperatures, which will be taken as the starting values for the transient simulation, are given in kelvins; we shall see later how ESATAN recognises this, the default being to use degrees Celsius. The capacitances are now functions of temperature, specific heat being evaluated by quadratic (2nd-order) interpolation on the array `SpecHt`, using the library routine `INTRP1`. Note how the temperature of node *n* is referenced simply as `T`*n*, and that simple arithmetic expressions are allowed in data blocks.

Similarly, the linear conductances are defined using interpolation, this time 1st-order, on the array `Cond` to evaluate conductivity at the average temperature of each node pair. The user should be aware that definitions such as this and the nodal capacitance result in Mortran being generated 'invisibly' by the preprocessor in the operations block `$VARIABLES1`. Although we don't have a `$VARIABLES1` block explicitly defined in our model, there is in effect always one present in the final executable, and it is called repeatedly during solution – essentially, at the start of every iteration for a steady state and every time step for a transient. The user need not be concerned at this point with the precise details, but the concept is worth bearing in mind.

In this model we also define a radiative conductor (`GR`) from each node in the bar to the boundary node, number 999, representing the environment. Strictly we should define additional nodes around the surface of the bar for coupling to the boundary, but we shall assume that the temperature gradient through the thickness of the bar at any given time is not significant, i.e. the surface of each section is at the same temperature as the centre.

In the $CONSTANTS block, under $CONTROL, we first define RELXCA and NLOOP as before, although now they govern the convergence of each time step of the transient solution. It's common for a looser convergence criterion to be used and fewer iterations to be allowed for each time step for a transient compared to a steady state, because of the overall CPU time involved. Then we have three control constants solely relating to the time-dependent nature of the solution: DTIMEI is the length of time step we wish the solver to use, TIMEND is the required end time of the simulation – the start time being zero by default – and OUTINT is the output interval, i.e. the period of simulation time at which the $OUTPUTS block gets executed. Then we assign TABS, the absolute-temperature offset, which determines the scale of both input and output temperatures. A value of zero implies absolute temperatures (kelvins), while the default of 273.15 indicates degrees Celsius.

Next, in the $ARRAYS block, are defined the two arrays mentioned above. Both are real-valued and 2-dimensional, and for each the first dimension is 2 (as required for use of the INTRP1 library routine, in the $NODES block). The array elements are laid out in two columns for readability: as in any data block, a statement can extend over several lines, being terminated only when a semi-colon is encountered.

In the $EXECUTION block we now open a file on unit 51 called *t.dat* in which to store the temperatures of the bar as the solution proceeds (OPEN is a standard FORTRAN 77 statement). The solution routine to be called is SLFWBK, which uses a forward-backward differencing scheme to integrate the heat equation in time.

A new operations block is introduced next, namely $VARIABLES2. For a transient solution this is executed repeatedly, at the end of every time step (for a steady state, it is called only at the end of solution). Hence, by writing to the file we opened in the $EXECUTION block, we obtain a full temperature history, i.e. temperature versus time for all computed time steps (TIMEN being the control constant holding the current solution time). Contrast this with $OUTPUTS, which gives 'snapshots' at intervals of OUTINT seconds. In this block we now have a call to PRNDBL which produces block-format output of the requested entities.

Listing 2-1 ESATAN definition for cooled bar model

```
$MODEL COOLED_BAR
#
#   A simple metal bar allowed to cool from 400 K by radiation to the
# environment at 295 K. Temperature-dependent material properties.
#
###############
# Data Blocks #
###############
#
$NODES
#
D1 = 'Bar end', T = 400.0, C = 0.108 * INTRP1(T1, SpecHt, 2);
D2 = 'Bar middle', T = 400.0, C = 0.216 * INTRP1(T2, SpecHt, 2);
D3 = 'Bar middle', T = 400.0, C = 0.216 * INTRP1(T3, SpecHt, 2);
D4 = 'Bar middle', T = 400.0, C = 0.216 * INTRP1(T4, SpecHt, 2);
D5 = 'Bar end', T = 400.0, C = 0.108 * INTRP1(T5, SpecHt, 2);
```

Listing 2-1 ESATAN definition for cooled bar model

```
#
B999 = 'Environment', T = 295.0;
#
$CONDUCTORS
#
GL(1, 2) = INTRP1((T1 + T2) / 2.0D0, Cond, 1) * 0.0016 / 0.05;
GL(2, 3) = INTRP1((T2 + T3) / 2.0D0, Cond, 1) * 0.0016 / 0.05;
GL(3, 4) = INTRP1((T3 + T4) / 2.0D0, Cond, 1) * 0.0016 / 0.05;
GL(4, 5) = INTRP1((T4 + T5) / 2.0D0, Cond, 1) * 0.0016 / 0.05;
#
GR(1, 999) = 0.8 * (4 * 0.001 + 0.0016);    # 5 faces
GR(2, 999) = 0.8 * 4 * 0.002;               # 4 faces
GR(3, 999) = 0.8 * 4 * 0.002;               # 4 faces
GR(4, 999) = 0.8 * 4 * 0.002;               # 4 faces
GR(5, 999) = 0.8 * (4 * 0.001 + 0.0016);    # 5 faces
#
$CONSTANTS
#
   $CONTROL
#
   RELXCA = 0.01;              # Convergence criterion
   NLOOP = 100;                # Maximum number of iterations per time step
   DTIMEI = 10.0;              # Desired time-step length
   TIMEND = 60.0 * 60.0;       # Solution end time
   OUTINT = 20.0 * 60.0;       # Output interval
#
   TABS = 0.0;                 # Temperatures in kelvins
#
$ARRAYS
#
   $REAL
#
   Cond(2, 5) = 250., 235.,
                300., 237.,
                345., 240.,
                375., 241.,
                420., 239.;
#
   SpecHt(2, 5) = 250., 862.,
                  300., 896.,
                  345., 922.,
                  375., 939.,
                  420., 960.;
#
#####################
# Operations Blocks #
#####################
#
$EXECUTION
#
      HEADER = 'Cooled metal bar - transient'
#
# Open temperature data file
#
      OPEN(UNIT = 51, FILE = 't.dat')
#
# Transient solution
#
      CALL SLFWBK
#
$VARIABLES2
#
# Write temperatures to data file
#
      WRITE(51, 510) TIMEN, T1, T2, T3
 510  FORMAT(F10.2, 3(1X, F7.2))
```

Listing 2-1 ESATAN definition for cooled bar model

```
#
$OUTPUTS
#
      CALL PRNDTB(' ', 'L, T, C', CURRENT)
      CALL PRNDBL(' ', 'GL', CURRENT)
#
$ENDMODEL COOLED_BAR
```

***

The standard output file, *COOLED_B.out* (Listing 2-2), shows the temperatures, capacitances and conductances at the requested 20-minute intervals. After an hour, the bar has cooled by 67 K. It is practically isothermal throughout this period, since the conduction heat transfer through the bar is much greater than the radiative exchange with the environment.

Listing 2-2 Output for cooled bar model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     1
 7 MARCH 2006                    15:48:14                             COOLED_BAR

Cooled metal bar - transient




 TIMEN =      0.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   13.3087  AT NODE 1 IN SUB-MODEL  COOLED_BAR


TABLE OUTPUT WITH ZENTS = 'L,T,C'
FOR NODES OF ZLABEL = ' '

================================================================================

COOLED_BAR


         NODE   LABEL                            T             C

           1    Bar end                       400.00        102.74
           2    Bar middle                    400.00        205.49
           3    Bar middle                    400.00        205.49
           4    Bar middle                    400.00        205.49
           5    Bar end                       400.00        102.74
         999    Environment                   295.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     2
 7 MARCH 2006                    15:48:14                             COOLED_BAR

Cooled metal bar - transient




 TIMEN =      0.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   13.3087  AT NODE 1 IN SUB-MODEL  COOLED_BAR
```

Listing 2-2 Output for cooled bar model

```
BLOCK OUTPUT WITH ZENTS = 'GL'
FOR NODES OF ZLABEL = ' '


COOLED_BAR

VALUES FOR CONDUCTORS GL :
GL(1,2) =       7.68      GL(2,1) =       7.68      GL(2,3) =       7.68
GL(3,2) =       7.68      GL(3,4) =       7.68      GL(4,3) =       7.68
GL(4,5) =       7.68      GL(5,4) =       7.68

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     3
 7 MARCH 2006                    15:48:14                             COOLED_BAR

Cooled metal bar - transient




 TIMEN =   1200.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   13.0443  AT NODE 5 IN SUB-MODEL  COOLED_BAR


TABLE OUTPUT WITH ZENTS = 'L,T,C'
FOR NODES OF ZLABEL = ' '

================================================================================

COOLED_BAR


         NODE   LABEL                              T             C

           1    Bar end                         367.38        100.98
           2    Bar middle                      367.45        201.97
           3    Bar middle                      367.48        201.98
           4    Bar middle                      367.45        201.97
           5    Bar end                         367.37        100.98
         999    Environment                     295.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     4
 7 MARCH 2006                    15:48:14                             COOLED_BAR

Cooled metal bar - transient




 TIMEN =   1200.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   13.0443  AT NODE 5 IN SUB-MODEL  COOLED_BAR


BLOCK OUTPUT WITH ZENTS = 'GL'
FOR NODES OF ZLABEL = ' '


COOLED_BAR

VALUES FOR CONDUCTORS GL :
GL(1,2) =       7.70      GL(2,1) =       7.70      GL(2,3) =       7.70
GL(3,2) =       7.70      GL(3,4) =       7.70      GL(4,3) =       7.70
```

Listing 2-2 Output for cooled bar model

```
GL(4,5) =       7.70      GL(5,4) =       7.70

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     5
 7 MARCH 2006                    15:48:14                                COOLED_BAR

Cooled metal bar - transient





 TIMEN =   2400.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   12.9214  AT NODE 5 IN SUB-MODEL  COOLED_BAR


TABLE OUTPUT WITH ZENTS = 'L,T,C'
FOR NODES OF ZLABEL = ' '

================================================================================

COOLED_BAR


         NODE   LABEL                              T             C

           1    Bar end                         346.90         99.70
           2    Bar middle                      346.95        199.41
           3    Bar middle                      346.97        199.41
           4    Bar middle                      346.95        199.41
           5    Bar end                         346.90         99.70
         999    Environment                     295.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     6
 7 MARCH 2006                    15:48:14                                COOLED_BAR

Cooled metal bar - transient





 TIMEN =   2400.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   12.9214  AT NODE 5 IN SUB-MODEL  COOLED_BAR


BLOCK OUTPUT WITH ZENTS = 'GL'
FOR NODES OF ZLABEL = ' '


COOLED_BAR

VALUES FOR CONDUCTORS GL :
GL(1,2) =       7.68      GL(2,1) =       7.68      GL(2,3) =       7.68
GL(3,2) =       7.68      GL(3,4) =       7.68      GL(4,3) =       7.68
GL(4,5) =       7.68      GL(5,4) =       7.68

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     7
 7 MARCH 2006                    15:48:14                                COOLED_BAR

Cooled metal bar - transient
```

Listing 2-2 Output for cooled bar model

```
 TIMEN =   3600.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   12.8597  AT NODE 5 IN SUB-MODEL  COOLED_BAR


TABLE OUTPUT WITH ZENTS = 'L,T,C'
FOR NODES OF ZLABEL = ' '

================================================================================

COOLED_BAR


         NODE   LABEL                              T             C

           1    Bar end                         333.11         98.85
           2    Bar middle                      333.14        197.70
           3    Bar middle                      333.15        197.70
           4    Bar middle                      333.13        197.70
           5    Bar end                         333.10         98.85
         999    Environment                     295.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.0)  PAGE     8
 7 MARCH 2006                    15:48:14                             COOLED_BAR

Cooled metal bar - transient





 TIMEN =   3600.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =   12.8597  AT NODE 5 IN SUB-MODEL  COOLED_BAR


BLOCK OUTPUT WITH ZENTS = 'GL'
FOR NODES OF ZLABEL = ' '


COOLED_BAR

VALUES FOR CONDUCTORS GL :
GL(1,2) =       7.65      GL(2,1) =       7.65      GL(2,3) =       7.65
GL(3,2) =       7.65      GL(3,4) =       7.65      GL(4,3) =       7.65
GL(4,5) =       7.65      GL(5,4) =       7.65
```

The current simulation time is reported in the header as `TIMEN` and the length of the time step as `DTIMEU`. Also shown is `CSGMIN`, the minimum *CSG* value in the model. This is essentially the ratio of the capacitance of a node to the sum of conductances connected to it, and indicates the response time of the node to any kind of heat input. (Where radiative conductors are involved, an effective conductance is derived by linearising the T^4 terms; a precise definition is given in the ESATAN Engineering Manual.) As a general rule, to ensure that the variation of temperature with time is modelled sufficiently accurately at all nodes, a time step length of the order of `CSGMIN` should be chosen.

Figure 2-2 shows the temperature of node 1 plotted against time, using the data saved in *t.dat*; the temperature decays smoothly, as one would expect.

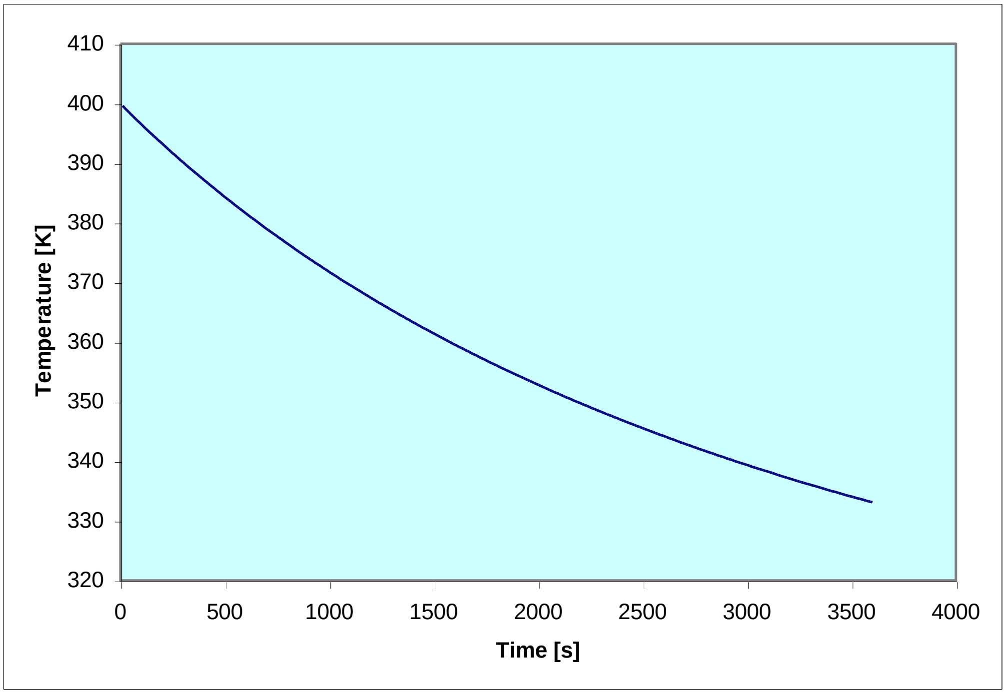

Figure 2-2 Predicted temperature of node 1

Example 3 A Printed Circuit Board

This example illustrates how a model may be built parametrically through the use of local constants and `FOR-DO` loops.

Suppose we have a printed circuit board (PCB) of dimensions 320 mm × 270 mm × 1.6 mm. The PCB is multilayer with four copper planes, each one being 37 μm thick and, for the purpose of predicting the temperature, continuous and extending to the full dimensions of the board. It is clamped along the entire length of both long edges, with a clamping interface conductance of 7 W/K per metre length, and it has a total on-board heat dissipation from the electronic components of 20 W, which can be assumed to be evenly distributed. We need to determine the highest temperature obtained on the PCB if the casing it is clamped to reaches a maximum of 50 °C. We are also interested in the heat fluxes the PCB has to transport.

The relevant material properties, which we assume to be constant for simplicity, are as follows. Copper: k = 394 W/m K, c = 386 J/kg K, ρ = 8 900 kg/m^3; PCB material: c = 1800 J/kg K, ρ = 1500 kg/m^3.

***

For the purposes of this example thermal gradients through the PCB will be ignored, that is to say, at any location the PCB will be assumed isothermal from one face to the other. Conduction by the PCB material itself will be assumed negligible compared to that by the copper layers. Any local perturbations due to the clamping and heat loss by radiation will also be ignored.

We choose to discretise the PCB with a 5 × 4 mesh as shown in Figure 3-1. Note how the node numbering scheme reflects the row and column each node occupies. The two sides of the casing are represented by a single boundary node, 99999. The heat load is applied uniformly across the PCB, i.e. 1 W per node.

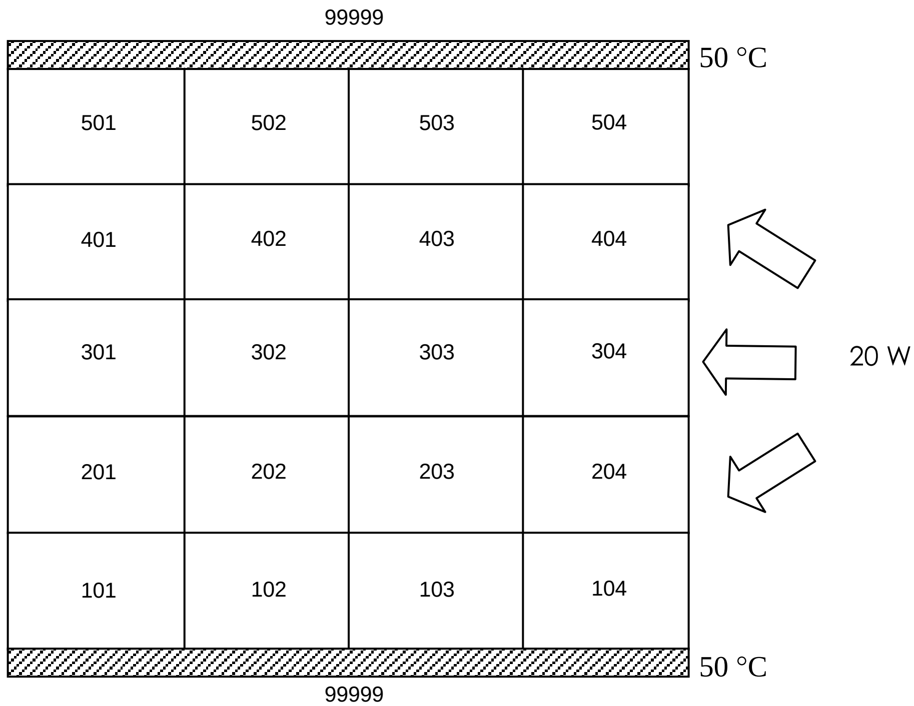

Figure 3-1 PCB meshing

The conductances within the PCB are calculated in the same way as in the previous two examples, although they now run in two directions. On the other hand, those between the PCB and the casing actually involve conductors in series, i.e. from the node centre to the edge of the PCB followed by the interface conductance. The overall conductance of two conductors in series is obtained by summing the reciprocals and inverting the result:

$$\overline{G} = \frac{1}{{}^{1}\!/\!{}_{G_1} + {}^{1}\!/\!{}_{G_2}}$$

***

Listing 3-1 Input file for PCB model

```
$MODEL PCB
#
# Model of a Printed Circuit Board (PCB). The long edges of the PCB are retained
# by clamps and it has a 20 W dissipation which is considered to be evenly
# distributed. The temperature of the casing that the PCB attaches to is
# 50 deg C.
#
###############
# Data Blocks #
###############
#
# ****************************************************************************
```

Listing 3-1 Input file for PCB model

```
$LOCALS
# ******************************************************************************
#
   $REAL
   k_copper        = 394.0;    # Thermal conductivity of copper
   cp_copper       = 386.0;    # Specific heat capacity of copper
   rho_copper      = 8900.0;   # Density of copper
   t_copper        = 0.000037; # Thickness of a single copper layer
   pcb_length      = 0.32;     # Length of PCB
   pcb_width       = 0.27;     # Width of PCB
   pcb_thick       = 0.0016;   # Thickness of PCB
   cp_pcb          = 1800.0;   # Specific heat capacity of PCB material
   rho_pcb         = 1500.0;   # Density of PCB material
   kiface_clamp    = 7.0;      # Interface conductance of clamp per unit length
   pcb_power       = 20.0;     # PCB dissipation
#
   $INTEGER
   n_layers        = 4;        # Number of layers of copper in PCB
   n_length        = 4;        # Number of nodes along the length of the PCB
   n_width         = 5;        # Number of nodes across the width of the PCB
#
# ******************************************************************************
$NODES
# ******************************************************************************
#
# PCB nodes
#
FOR KL1 = 100 TO (n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO n_length DO
      KL3 = KL1 + KL2;
      DKL3 = 'PCB node',
         T = 0.0,
         C = ((pcb_length / n_length) * (pcb_width / n_width)
              * t_copper * n_layers * rho_copper * cp_copper)
             + ((pcb_length / n_length) * (pcb_width / n_width)
                * (pcb_thick - (n_layers * t_copper)) * rho_pcb * cp_pcb),
         QI = pcb_power / (n_length * n_width);
   END DO
END DO
#
# Casing node
#
B99999 = 'Casing - boundary', T = 50.0;
#
# ******************************************************************************
$CONDUCTORS
# ******************************************************************************
#
# CONDUCTORS ALONG THE LENGTH OF THE PCB
#
# First define the conductors along the length of the PCB
#   Only the copper layers are considered
#
FOR KL1 = 100 TO (n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO (n_length - 1) DO
      KL3 = KL1 + KL2;
      KL4 = KL3 + 1;
      GL(KL3, KL4) = k_copper * (pcb_width / n_width) * (t_copper * n_layers)
                     / (pcb_length / n_length);
   END DO
END DO
#
# ******************************************************************************
#
# CONDUCTORS ACROSS THE WIDTH OF THE PCB
#
```

Listing 3-1 Input file for PCB model

```
# Now define the conductors across the width of the PCB
#   Only the copper layers are considered
#
FOR KL1 = 100 TO ((n_width - 1) * 100) STEP 100 DO
   FOR KL2 = 1 TO n_length DO
      KL3 = KL1 + KL2;
      KL4 = KL3 + 100;
      GL(KL3, KL4) = k_copper * (pcb_length / n_length) * (t_copper * n_layers)
                     / (pcb_width / n_width);
   END DO
END DO
#
# ****************************************************************************
#
# INTERFACE CONDUCTORS
#
# Finally define the couplings of the clamped board edge to the casing
#
FOR KL1 = 100 TO (n_width * 100) STEP ((n_width-1) * 100) DO
   FOR KL2 = 1 TO n_length DO
      KL3 = KL1 + KL2;
      GL(KL3, 99999) = 1.0
                       / (1.0 / (kiface_clamp * (pcb_length / n_length))
                          + 1.0 / (k_copper * (pcb_length / n_length)
                                   * (t_copper * n_layers)
                                   / (pcb_width / (n_width * 2.0))));
   END DO
END DO
#
# ****************************************************************************
$CONSTANTS
# ****************************************************************************
#
   $CONTROL
#
   RELXCA  = 0.001;        # Convergence criterion
   NLOOP   = 100;          # Maximum number of iterations
   WIDTH   = 90;           # Page width of output file
#
#####################
# Operations Blocks #
#####################
#
# ****************************************************************************
$EXECUTION
# ****************************************************************************
#
      HEADER = 'Simple Parametrised PCB Model'
#
      CALL SOLVFM
#
# ****************************************************************************
$OUTPUTS
# ****************************************************************************
#
      CALL PRNDTB(' ', 'L, T, QI, C', CURRENT)
      CALL PRQNOD('PCB node', CURRENT)
      CALL PRNDBL(' ', 'GL', CURRENT)
#
$ENDMODEL PCB
```

The first new aspect of the input file for this model (Listing 3-1) is the `$LOCALS` block. Here we can define named parameters known as *local constants* for use in other blocks to make the model more transparent and easier to modify. For instance, we have real-valued constants representing material properties and integer-valued ones to control the fineness of the meshing. `$LOCALS` is often the first block in a model since a local constant must be defined before it is referenced.

The uniform grid layout of the PCB discretisation lends itself to defining the nodes using nested `FOR-DO` loops. An ESATAN `FOR-DO` loop – not to be confused with a FORTRAN `DO` loop – may only be used in a data block and takes the form

```
FOR KLn = i TO j DO
    ...
END DO
```

where *n*, *i* and *j* are integers. `KLn` is known as a *local index* and is used only in the context of such a loop; it does not need to be explicitly declared and can also be assigned using an integer expression involving other local indices, local constants and literal values, but it has scope only within the block in which it is defined. A node can be defined using `KLn` in place of the node number. Each node is assigned an *internal heat source*, `QI`, proportional to the surface area of the PCB covered by the node.

The conductors in our model are also defined using nested `FOR-DO` loops, with `KLn` in place of the node numbers. As can be seen, both nodal and conductor entities can be assigned using simple arithmetic expressions of local constants.

The control constant `WIDTH` is introduced in the `$CONSTANTS` block. This determines the number of columns in the standard output page, and is set to 80 by default. We have increased it in our model in order to accommodate all the entities requested for output in the call to `PRNDTB`.

Since the boundary conditions are static, we can determine the maximum temperature by performing a steady state solution; hence we call `SOLVFM` in the `$EXECUTION` block.

Even though the nodal capacitances and the conductances are constant in this model, we have requested them in the output to aid verification of the model. The output routine `PRQNOD` reports on the heat flux in all conductors connected to the specified nodes.

***

The output from the model is shown in Listing 3-2. We can see first of all that the temperatures are symmetric about the third row of the PCB (nodes 301 to 304), and that they do not vary within each row; in other words, as the output from `PRQNOD` confirms, the heat flows transversely outwards to the casing (a positive value indicating heat flow *into* the first node of the pair). This is, of course, to be expected from the symmetry of the boundary conditions. The hottest point on the PCB is at 92 °C.

Listing 3-2 Results for PCB model (5 × 4 grid)

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.0)      PAGE    1
14 MARCH 2006                         10:41:23                                      PCB

Simple Parametrised PCB Model




 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =     3
ENBALA = 4.263E-14      ENBALR = 2.E-15


TABLE OUTPUT WITH ZENTS = 'L,T,QI,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

PCB


         NODE   LABEL                              T             QI            C

          101    PCB node                        68.93         1.00         19.13
          102    PCB node                        68.93         1.00         19.13
          103    PCB node                        68.93         1.00         19.13
          104    PCB node                        68.93         1.00         19.13
          201    PCB node                        86.30         1.00         19.13
          202    PCB node                        86.30         1.00         19.13
          203    PCB node                        86.30         1.00         19.13
          204    PCB node                        86.30         1.00         19.13
          301    PCB node                        92.09         1.00         19.13
          302    PCB node                        92.09         1.00         19.13
          303    PCB node                        92.09         1.00         19.13
          304    PCB node                        92.09         1.00         19.13
          401    PCB node                        86.30         1.00         19.13
          402    PCB node                        86.30         1.00         19.13
          403    PCB node                        86.30         1.00         19.13
          404    PCB node                        86.30         1.00         19.13
          501    PCB node                        68.93         1.00         19.13
          502    PCB node                        68.93         1.00         19.13
          503    PCB node                        68.93         1.00         19.13
          504    PCB node                        68.93         1.00         19.13
        99999    Casing - boundary               50.00         0.00          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.0)      PAGE    2
14 MARCH 2006                         10:41:23                                      PCB

Simple Parametrised PCB Model




 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =     3
ENBALA = 4.263E-14      ENBALR = 2.E-15



HEAT FLUX IN CONDUCTORS ATTACHED TO NODES OF ZLABEL = 'PCB node'
```

Listing 3-2 Results for PCB model (5 × 4 grid)

```
PCB

LINEAR    HEAT FLUX
(101,102)   :       0.00     (101,201)   :       1.50     (101,99999) :      -2.50
(102,101)   :       0.00     (102,103)   :      -0.00     (102,202)   :       1.50
(102,99999) :      -2.50     (103,102)   :       0.00     (103,104)   :       0.00
(103,203)   :       1.50     (103,99999) :      -2.50     (104,103)   :      -0.00
(104,204)   :       1.50     (104,99999) :      -2.50     (201,101)   :      -1.50
(201,202)   :       0.00     (201,301)   :       0.50     (202,102)   :      -1.50
(202,201)   :       0.00     (202,203)   :      -0.00     (202,302)   :       0.50
(203,103)   :      -1.50     (203,202)   :       0.00     (203,204)   :       0.00
(203,303)   :       0.50     (204,104)   :      -1.50     (204,203)   :      -0.00
(204,304)   :       0.50     (301,201)   :      -0.50     (301,302)   :      -0.00
(301,401)   :      -0.50     (302,202)   :      -0.50     (302,301)   :       0.00
(302,303)   :      -0.00     (302,402)   :      -0.50     (303,203)   :      -0.50
(303,302)   :       0.00     (303,304)   :      -0.00     (303,403)   :      -0.50
(304,204)   :      -0.50     (304,303)   :       0.00     (304,404)   :      -0.50
(401,301)   :       0.50     (401,402)   :       0.00     (401,501)   :      -1.50
(402,302)   :       0.50     (402,401)   :       0.00     (402,403)   :      -0.00
(402,502)   :      -1.50     (403,303)   :       0.50     (403,402)   :       0.00
(403,404)   :       0.00     (403,503)   :      -1.50     (404,304)   :       0.50
(404,403)   :       0.00     (404,504)   :      -1.50     (501,401)   :       1.50
(501,502)   :       0.00     (501,99999) :      -2.50     (502,402)   :       1.50
(502,501)   :       0.00     (502,503)   :      -0.00     (502,99999) :      -2.50
(503,403)   :       1.50     (503,502)   :       0.00     (503,504)   :       0.00
(503,99999) :      -2.50     (504,404)   :       1.50     (504,503)   :      -0.00
(504,99999) :      -2.50

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     3
14 MARCH 2006                         10:41:23                                        PCB

Simple Parametrised PCB Model




 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =     3
ENBALA = 4.263E-14      ENBALR = 2.E-15


BLOCK OUTPUT WITH ZENTS = 'GL'
FOR NODES OF ZLABEL = ' '


PCB

VALUES FOR CONDUCTORS GL :
GL(101,102)   =       0.04      GL(101,201)   =       0.09
GL(101,99999) =       0.13      GL(102,101)   =       0.04
GL(102,103)   =       0.04      GL(102,202)   =       0.09
GL(102,99999) =       0.13      GL(103,102)   =       0.04
GL(103,104)   =       0.04      GL(103,203)   =       0.09
GL(103,99999) =       0.13      GL(104,103)   =       0.04
GL(104,204)   =       0.09      GL(104,99999) =       0.13
GL(201,101)   =       0.09      GL(201,202)   =       0.04
GL(201,301)   =       0.09      GL(202,102)   =       0.09
GL(202,201)   =       0.04      GL(202,203)   =       0.04
GL(202,302)   =       0.09      GL(203,103)   =       0.09
GL(203,202)   =       0.04      GL(203,204)   =       0.04
GL(203,303)   =       0.09      GL(204,104)   =       0.09
GL(204,203)   =       0.04      GL(204,304)   =       0.09
GL(301,201)   =       0.09      GL(301,302)   =       0.04
GL(301,401)   =       0.09      GL(302,202)   =       0.09
GL(302,301)   =       0.04      GL(302,303)   =       0.04
GL(302,402)   =       0.09      GL(303,203)   =       0.09
```

Listing 3-2 Results for PCB model (5 × 4 grid)

```
GL(303,302)   =      0.04     GL(303,304)   =      0.04
GL(303,403)   =      0.09     GL(304,204)   =      0.09
GL(304,303)   =      0.04     GL(304,404)   =      0.09
GL(401,301)   =      0.09     GL(401,402)   =      0.04
GL(401,501)   =      0.09     GL(402,302)   =      0.09
GL(402,401)   =      0.04     GL(402,403)   =      0.04
GL(402,502)   =      0.09     GL(403,303)   =      0.09
GL(403,402)   =      0.04     GL(403,404)   =      0.04
GL(403,503)   =      0.09     GL(404,304)   =      0.09
GL(404,403)   =      0.04     GL(404,504)   =      0.09
GL(501,401)   =      0.09     GL(501,502)   =      0.04
GL(501,99999) =      0.13     GL(502,402)   =      0.09
GL(502,501)   =      0.04     GL(502,503)   =      0.04
GL(502,99999) =      0.13     GL(503,403)   =      0.09
GL(503,502)   =      0.04     GL(503,504)   =      0.04
GL(503,99999) =      0.13     GL(504,404)   =      0.09
GL(504,503)   =      0.04     GL(504,99999) =      0.13
GL(99999,101) =      0.13     GL(99999,102) =      0.13
GL(99999,103) =      0.13     GL(99999,104) =      0.13
GL(99999,501) =      0.13     GL(99999,502) =      0.13

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.0)      PAGE    4
14 MARCH 2006                         10:41:23                                     PCB

Simple Parametrised PCB Model




GL(99999,503) =      0.13     GL(99999,504) =      0.13
```

Having studied the results of our model, we can now easily repeat the analysis using a finer discretisation. We change the value of the local constant `n_width` to 9 (choosing an odd number to ensure we get a row of nodes on the line of symmetry), re-preprocess the input deck and re-run the model. As can be seen from Listing 3-3, the maximum temperature is now predicted to be 91 °C. In general, a finer mesh will give more accurate results; the thermal engineer must use his or her judgement to decide whether to accept the predictions given by the first version of the model or to re-run the analysis with a more detailed discretisation.

Listing 3-3 Results for PCB model (9 × 4 grid)

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.0)      PAGE    1
14 MARCH 2006                         10:42:08                                     PCB

Simple Parametrised PCB Model





 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =     3
ENBALA = 5.684E-14      ENBALR = 3.E-15


TABLE OUTPUT WITH ZENTS = 'L,T,QI,C'
FOR NODES OF ZLABEL = ' '
```

Listing 3-3 Results for PCB model (9 × 4 grid)

```
=========================================================================================

PCB


         NODE   LABEL                              T             QI            C

         101    PCB node                         62.50          0.56         10.63
         102    PCB node                         62.50          0.56         10.63
         103    PCB node                         62.50          0.56         10.63
         104    PCB node                         62.50          0.56         10.63
         201    PCB node                         75.01          0.56         10.63
         202    PCB node                         75.01          0.56         10.63
         203    PCB node                         75.01          0.56         10.63
         204    PCB node                         75.01          0.56         10.63
         301    PCB node                         83.94          0.56         10.63
         302    PCB node                         83.94          0.56         10.63
         303    PCB node                         83.94          0.56         10.63
         304    PCB node                         83.94          0.56         10.63
         401    PCB node                         89.30          0.56         10.63
         402    PCB node                         89.30          0.56         10.63
         403    PCB node                         89.30          0.56         10.63
         404    PCB node                         89.30          0.56         10.63
         501    PCB node                         91.08          0.56         10.63
         502    PCB node                         91.08          0.56         10.63
         503    PCB node                         91.08          0.56         10.63
         504    PCB node                         91.08          0.56         10.63
         601    PCB node                         89.30          0.56         10.63
         602    PCB node                         89.30          0.56         10.63
         603    PCB node                         89.30          0.56         10.63
         604    PCB node                         89.30          0.56         10.63
         701    PCB node                         83.94          0.56         10.63
         702    PCB node                         83.94          0.56         10.63
         703    PCB node                         83.94          0.56         10.63
         704    PCB node                         83.94          0.56         10.63
         801    PCB node                         75.01          0.56         10.63
         802    PCB node                         75.01          0.56         10.63
         803    PCB node                         75.01          0.56         10.63
         804    PCB node                         75.01          0.56         10.63
         901    PCB node                         62.50          0.56         10.63
         902    PCB node                         62.50          0.56         10.63
         903    PCB node                         62.50          0.56         10.63
         904    PCB node                         62.50          0.56         10.63

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     2
14 MARCH 2006                      10:42:08                                           PCB

Simple Parametrised PCB Model




         NODE   LABEL                              T             QI            C

       99999    Casing - boundary                50.00          0.00          0.00


. . .
```

Example 4 An Electronics Unit

This example introduces the concept of submodels and the related aspects of supernodes and inter-model links.

The subject here is an electronics unit housing three identical printed circuit boards (PCBs) as described in Example 3. The unit is constructed in typical fashion (Figure 4-1) with separate machined details forming the baseplate, sides and top of the unit, made out of aluminium. It is assumed that the front and rear panels of the unit have no significance with respect to the structural or thermal performance of the unit and may therefore be ignored. As in Example 3 each PCB has a uniformly distributed dissipation of 20 W and is fixed along its length using clamps integral with the baseplate and top of the unit. Some of the dissipation from each PCB is conducted into the unit structure through the clamps which provide a clamping interface conductance of 7 W/K per metre length. Radiative heat transfer between adjacent PCBs and between the PCBs and unit side panels must also be considered; the PCB surfaces are considered to have an infrared emissivity, ε, of 0.7 and the inside of the casing an emissivity of 0.1.

The base, sides and top of the unit may all be considered to be at fixed, uniform temperatures of 65 °C, 59 °C and 67 °C, respectively, obtained from a higher-level analysis. The temperature distribution on each PCB in steady state is required.

***

The discretisation of each PCB is exactly the same as in the model of Example 3. The baseplate, sides and top of the unit are each represented by a separate boundary node (Figure 4-1).

The radiative couplings are calculated using a standard formula for the heat flux per unit area, q, exchanged between two infinite parallel plates:

$$q = \frac{\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}.$$

From this we obtain the radiative conductance

$$G_R = \frac{A_1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}.$$

Of course, this is an approximation, but we assume that radiative heat exchange makes only a second-order contribution to the thermal problem and so the error involved is acceptable.

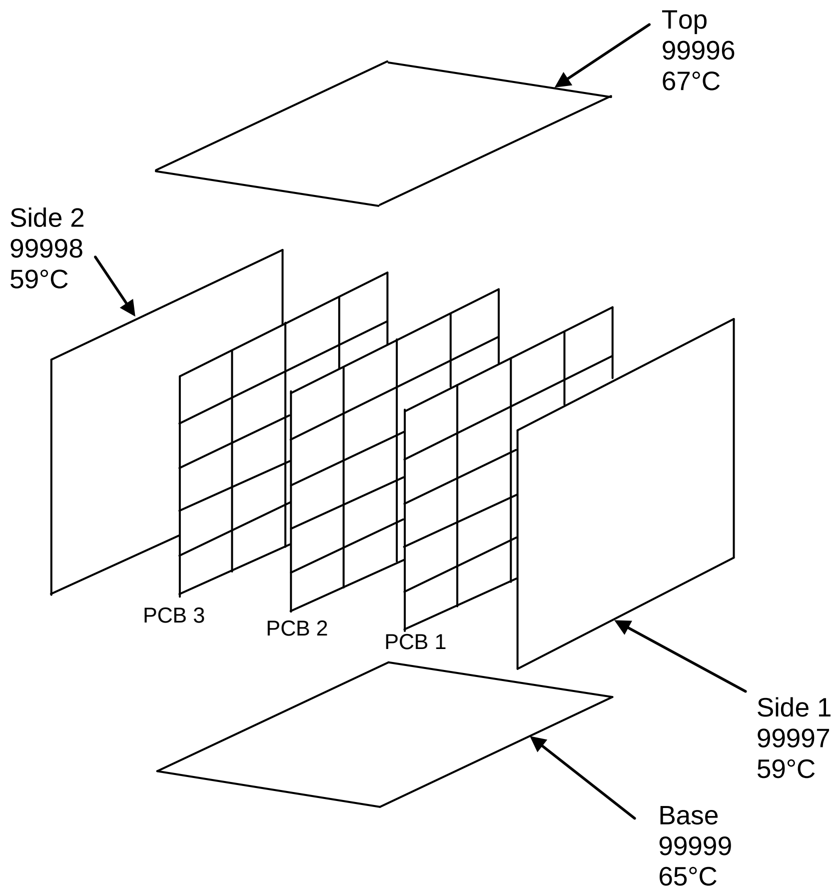

Figure 4-1 Electronics unit model

***

An ESATAN model of a single PCB was developed in Example 3. This is re-used here as a *submodel* of the electronics unit – or, rather, as three submodels. There are several ways to define a submodel in ESATAN, and they all involve nesting `$MODEL` and `$ENDMODEL` lines in the parent model as shown in Listing 4-1. The first submodel, `PCB1`, is defined *explicitly* and, as can be seen, is essentially a copy of the previous model. It should be noted, however, that the `$CONTROL`, `$EXCUTION` and `$OUTPUTS` blocks of a submodel are ignored; hence, they have been removed in this instance.

In the earlier PCB model the edges of the board were connected to a single boundary node. This has been slightly modified in the present version to connect the bottom edge to boundary node 99999 and the top edge to a different boundary node, 99996.

Two further submodels are then defined *implicitly* through the use of `$REPEAT`, which has the effect of making an exact copy of the named submodel.

Coming to the `$NODES` block of the main model, the boundary nodes of the base and top panel are defined as *supernodes* with the PCB boundaries as *constituents*. This has the effect of merging the specified nodes into one, with those in the submodels losing their separate identities: the nodal properties are as defined in the parent model. A supernode may be of boundary or diffusion type.

In the `$CONDUCTORS` block can be seen definitions of *inter-model links* – conductors for which at least one node lies in a submodel (the other node being in either the parent model, or another submodel, or even the same submodel). In this and other contexts, a node in a submodel is addressed from higher up using the syntax `MNAME:`*n* where `MNAME` is the name of the submodel and *n* is the node number (which may be given by a local constant).

Inter-model conductors can only be addressed from the model in which they are defined or further up the hierarchy, i.e. they do not exist within the submodels themselves. More generally, data-block items – nodes, conductors, arrays, etc. – defined in a submodel may be referenced from its parent, but the converse is not true. (Local constants can only be referenced within their own model.)

To enable the thermal engineer to understand how heat is rejected from the PCBs as a whole, the library functions `FLUXGL` and `FLUXGR` are used in the `$OUTPUTS` block to calculate heat flow to the boundary by conduction and radiation, respectively. These values are assigned to two real-valued *user constants*, `HFCOND` and `HFRAD`, defined in the `$CONSTANTS` block. User constants behave like global variables which can be modified in any operations block (thus, they in fact don't have to be constant at all!). The calculated heat flows are printed to standard output using standard FORTRAN `WRITE` and `FORMAT` statements.

Listing 4-1 Input for electronics unit model

```
$MODEL ELUNIT
#
# Model of an electronics unit containing 3 identical printed circuit boards.
# Each PCB has an evenly distributed dissipation and is mounted in an aluminium
# casing which acts as a thermal boundary.
#
# ****************************************************************************
#
#############
# Submodels #
#############
#
   $MODEL PCB1
   #
   #
   # Model of a Printed Circuit Board (PCB) with an evenly distributed power
   # dissipation. Each edge of the PCB is retained by clamps. The casing is
   # represented by two separate boundary nodes for the top and base.
   #
   ###############
   # Data Blocks #
   ###############
   #
   # ****************************************************************************
   $LOCALS
   # ****************************************************************************
   #
      $REAL
      k_copper        = 394.0;        # Thermal conductivity of copper
      cp_copper       = 386.0;        # Specific heat capacity of copper
```

Listing 4-1 Input for electronics unit model

```
   rho_copper      = 8900.0;       # Density of copper
   t_copper        = 0.000037;     # Thickness of a single copper layer
   pcb_length      = 0.32;         # Length of PCB
   pcb_width       = 0.27;         # Width of PCB
   pcb_thick       = 0.0016;       # Thickness of PCB
   cp_pcb          = 1800.0;       # Specific heat capacity of PCB material
   rho_pcb         = 1500.0;       # Density of PCB material
   kiface_clamp    = 7.0;          # Interface conductance of clamp per unit length
   pcb_power       = 20.0;         # PCB dissipation
#
   $INTEGER
   n_layers        = 4;            # Number of layers of copper in PCB
   n_length        = 4;            # Number of nodes along the length of the PCB
   n_width         = 5;            # Number of nodes across the width of the PCB
#
# ******************************************************************************
$NODES
# ******************************************************************************
#
# Define the PCB
#
FOR KL1 = 100 TO (n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO n_length DO
      KL3 = KL1 + KL2;
      DKL3 = 'PCB node',
         T = 0.0,
         C = ((pcb_length / n_length) * (pcb_width / n_width)
              * t_copper * n_layers * rho_copper * cp_copper)
             + ((pcb_length / n_length) * (pcb_width / n_width)
                * (pcb_thick - (n_layers * t_copper)) * rho_pcb * cp_pcb),
         QI = pcb_power / (n_length * n_width);
   END DO
END DO
#
# Define the casing
#
B99996 = 'Unit Top - boundary', T = 50.0;
B99999 = 'Unit Base - boundary', T = 50.0;
#
# ******************************************************************************
$CONDUCTORS
# ******************************************************************************
#
# CONDUCTORS ALONG THE LENGTH OF THE PCB
#
# First define the conductors along the length of the PCB
#   Only the copper layers are considered
#
FOR KL1 = 100 TO (n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO (n_length - 1) DO
      KL3 = KL1 + KL2;
      KL4 = KL3 + 1;
      GL(KL3, KL4) = k_copper * (pcb_width / n_width) * (t_copper * n_layers)
                     / (pcb_length / n_length);
   END DO
END DO
#
# ******************************************************************************
#
# CONDUCTORS ACROSS THE WIDTH OF THE PCB
#
# Now define the conductors across the width of the PCB
#   Only the copper layers are considered
#
FOR KL1 = 100 TO ((n_width - 1) * 100) STEP 100 DO
   FOR KL2 = 1 TO n_length DO
```

Listing 4-1 Input for electronics unit model

```
         KL3 = KL1 + KL2;
         KL4 = KL3 + 100;
         GL(KL3, KL4) = k_copper * (pcb_length / n_length) * (t_copper * n_layers)
                        / (pcb_width / n_width);
      END DO
   END DO
   #
   # ******************************************************************************
   #
   # INTERFACE CONDUCTORS
   #
   # Finally define the couplings at the clamped board edges to the unit base and top
   #
   FOR KL1 = 1 TO n_length DO
      KL2 = 100 + KL1;
      GL(KL2, 99999) = 1.0 / ((1.0 / (kiface_clamp  * (pcb_length / n_length)))
                       + (1.0 / (k_copper * (pcb_length / n_length) * (t_copper
                       * n_layers) / (pcb_width / (n_width * 2.0)))));
   #
      KL2 = (100 * n_width) + KL1;
      GL(KL2, 99996) = 1.0 / ((1.0 / (kiface_clamp  * (pcb_length / n_length)))
                       + (1.0 / (k_copper * (pcb_length / n_length) * (t_copper
                       * n_layers) / (pcb_width / (n_width * 2.0)))));
   END DO
   #
   $ENDMODEL PCB1
#
   $MODEL PCB2
      $REPEAT PCB1
   $ENDMODEL PCB2
#
   $MODEL PCB3
      $REPEAT PCB1
   $ENDMODEL PCB3
#
# ******************************************************************************
#
###############
# Data Blocks #
###############
#
# ******************************************************************************
$LOCALS
# ******************************************************************************
#
   $REAL
   l_pcb           = 0.320;    # Length of each PCB, m
   w_pcb           = 0.270;    # Width of each PCB, m
   emissivity_pcb  = 0.7;      # Infrared emissivity of PCB surface
   emissivity_Al   = 0.1;      # Infrared emissivity of inside of casing
#
   $INTEGER
   pcb_n_length    = 4;        # Number of nodes along the length of each PCB
   pcb_n_width     = 5;        # Number of nodes across the width of each PCB
#
# ******************************************************************************
$NODES
# ******************************************************************************
#
# Unit casing, boundary nodes
#
B99996 = 'Unit Top - boundary' = PCB1:99996 + PCB2:99996 + PCB3:99996, T = 67.0;
B99997 = 'Unit Side 1 - boundary', T = 59.0;
B99998 = 'Unit Side 2 - boundary', T = 59.0;
B99999 = 'Unit Base - boundary' = PCB1:99999 + PCB2:99999 + PCB3:99999, T = 65.0;
#
```

Listing 4-1 Input for electronics unit model

```
# *****************************************************************************
$CONDUCTORS
# *****************************************************************************
#
# INTERMODEL LINKS
#
# Internal Radiation PCB-to-PCB
#
FOR KL1 = 100 TO (pcb_n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO pcb_n_length DO
      KL3 = KL1 + KL2;
      GR(PCB1:KL3, PCB2:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                               1.0 / ((1.0 / emissivity_pcb) +
                               (1.0 / emissivity_pcb) - 1.0);
      GR(PCB2:KL3, PCB3:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                               1.0 / ((1.0 / emissivity_pcb) +
                               (1.0 / emissivity_pcb) - 1.0);
   END DO
END DO
#
# Internal Radiation PCB-to-side panels
#
FOR KL1 = 100 TO (pcb_n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO pcb_n_length DO
      KL3 = KL1 + KL2;
      GR(99997, PCB1:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                            1.0 / ((1.0 / emissivity_Al) +
                            (1.0 / emissivity_pcb) - 1.0);
      GR(99998, PCB3:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                            1.0 / ((1.0 / emissivity_Al) +
                            (1.0 / emissivity_pcb) - 1.0);
   END DO
END DO
#
#
# *****************************************************************************
$CONSTANTS
# *****************************************************************************
#
   $CONTROL
   RELXCA  = 0.001;        # Convergence criterion
   NLOOP   = 1000;         # Maximum number of iterations
   WIDTH   = 90;           # Width of output file
#
   $REAL
   HFCOND  = 0.0;          # Conductive heat flux from PCBs to casing
   HFRAD   = 0.0;          # Radiative heat flux from PCBs to casing
#
#####################
# Operations Blocks #
#####################
#
# *****************************************************************************
$EXECUTION
# *****************************************************************************
#
      HEADER = 'Electronics unit comprising 3 PCBs'
#
      CALL SOLVFM
#
# *****************************************************************************
$OUTPUTS
# *****************************************************************************
#
      CALL PRNDTB(' ', 'L, T, QI, C', CURRENT)
#
```

Listing 4-1 Input for electronics unit model

```
      HFCOND = FLUXGL(' ', CURRENT:ONLY, ' ', PCB1)
     &         + FLUXGL(' ', CURRENT:ONLY, ' ', PCB2)
     &         + FLUXGL(' ', CURRENT:ONLY, ' ', PCB3)
#
      HFRAD  = FLUXGR(' ', CURRENT:ONLY, ' ', PCB1)
     &         + FLUXGR(' ', CURRENT:ONLY, ' ', PCB2)
     &         + FLUXGR(' ', CURRENT:ONLY, ' ', PCB3)
#
      WRITE(*, 1001) HFCOND, HFRAD
#
 1001 FORMAT(' Heat flow by conduction to the casing = ', F8.3, ' W', /,
     &       ' Heat flow by radiation to the casing  = ', F8.3, ' W')
#
$ENDMODEL ELUNIT
```

***

The output (Listing 4-2) shows that some 54.5 W of heat is transferred to the casing by conduction and only 5.5 W by radiation.

Listing 4-2 Steady state results for electronics unit model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     1
 6 APRIL 2006                         16:03:10                                      ELUNIT

Electronics unit comprising 3 PCBs





 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =    12
ENBALA = 4.106E-04      ENBALR = 7.E-06


TABLE OUTPUT WITH ZENTS = 'L,T,QI,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

ELUNIT


         NODE   LABEL                              T             QI            C

       99996    Unit Top - boundary              67.00          0.00          0.00
       99997    Unit Side 1 - boundary           59.00          0.00          0.00
       99998    Unit Side 2 - boundary           59.00          0.00          0.00
       99999    Unit Base - boundary             65.00          0.00          0.00


==========================================================================================

ELUNIT:PCB1


         NODE   LABEL                              T             QI            C

         101    PCB node                         82.21          1.00         19.13
         102    PCB node                         82.21          1.00         19.13
```

Listing 4-2 Steady state results for electronics unit model

```
        103    PCB node                        82.21         1.00         19.13
        104    PCB node                        82.21         1.00         19.13
        201    PCB node                        97.76         1.00         19.13
        202    PCB node                        97.76         1.00         19.13
        203    PCB node                        97.76         1.00         19.13
        204    PCB node                        97.76         1.00         19.13
        301    PCB node                       103.11         1.00         19.13
        302    PCB node                       103.11         1.00         19.13
        303    PCB node                       103.11         1.00         19.13
        304    PCB node                       103.11         1.00         19.13
        401    PCB node                        98.48         1.00         19.13
        402    PCB node                        98.48         1.00         19.13
        403    PCB node                        98.48         1.00         19.13
        404    PCB node                        98.48         1.00         19.13
        501    PCB node                        83.68         1.00         19.13
        502    PCB node                        83.68         1.00         19.13
        503    PCB node                        83.68         1.00         19.13
        504    PCB node                        83.68         1.00         19.13
      99996    Unit Top - boundary             67.00         0.00          0.00
      99999    Unit Base - boundary            65.00         0.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     2
 6 APRIL 2006                         16:03:10                                       ELUNIT

Electronics unit comprising 3 PCBs



ELUNIT:PCB2


        NODE   LABEL                              T             QI            C

        101    PCB node                        82.95         1.00         19.13
        102    PCB node                        82.95         1.00         19.13
        103    PCB node                        82.95         1.00         19.13
        104    PCB node                        82.95         1.00         19.13
        201    PCB node                        99.21         1.00         19.13
        202    PCB node                        99.21         1.00         19.13
        203    PCB node                        99.21         1.00         19.13
        204    PCB node                        99.21         1.00         19.13
        301    PCB node                       104.81         1.00         19.13
        302    PCB node                       104.81         1.00         19.13
        303    PCB node                       104.81         1.00         19.13
        304    PCB node                       104.81         1.00         19.13
        401    PCB node                        99.95         1.00         19.13
        402    PCB node                        99.95         1.00         19.13
        403    PCB node                        99.95         1.00         19.13
        404    PCB node                        99.95         1.00         19.13
        501    PCB node                        84.44         1.00         19.13
        502    PCB node                        84.44         1.00         19.13
        503    PCB node                        84.44         1.00         19.13
        504    PCB node                        84.44         1.00         19.13
      99996    Unit Top - boundary             67.00         0.00          0.00
      99999    Unit Base - boundary            65.00         0.00          0.00


==========================================================================================

ELUNIT:PCB3


        NODE   LABEL                              T             QI            C

        101    PCB node                        82.21         1.00         19.13
```

Listing 4-2 Steady state results for electronics unit model

```
        102    PCB node                         82.21          1.00         19.13
        103    PCB node                         82.21          1.00         19.13
        104    PCB node                         82.21          1.00         19.13
        201    PCB node                         97.76          1.00         19.13
        202    PCB node                         97.76          1.00         19.13
        203    PCB node                         97.76          1.00         19.13
        204    PCB node                         97.76          1.00         19.13
        301    PCB node                        103.11          1.00         19.13
        302    PCB node                        103.11          1.00         19.13
        303    PCB node                        103.11          1.00         19.13
        304    PCB node                        103.11          1.00         19.13
        401    PCB node                         98.48          1.00         19.13
        402    PCB node                         98.48          1.00         19.13
        403    PCB node                         98.48          1.00         19.13
        404    PCB node                         98.48          1.00         19.13

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     3
 6 APRIL 2006                        16:03:10                                      ELUNIT

Electronics unit comprising 3 PCBs




        NODE   LABEL                              T             QI            C

        501    PCB node                         83.68          1.00         19.13
        502    PCB node                         83.68          1.00         19.13
        503    PCB node                         83.68          1.00         19.13
        504    PCB node                         83.68          1.00         19.13
      99996    Unit Top - boundary              67.00          0.00          0.00
      99999    Unit Base - boundary             65.00          0.00          0.00

Heat flow by conduction to the casing =   54.487 W
Heat flow by radiation to the casing  =    5.513 W
```

Example 5 An Air-Cooled Electronics Unit

In this example we show how a submodel can be parametrised for re-use (as an element), and introduce fluidic conductors.

The electronics unit of Example 4 now has a fan blowing air across the PCBs at 8 cm/s to provide cooling via forced convection. It can be assumed that there is negligible convective cooling of the base and top of the unit by the air. The power dissipations of the PCBs are now different: 20 W on the first PCB, 60 W on the second, and 40 W on the third.

***

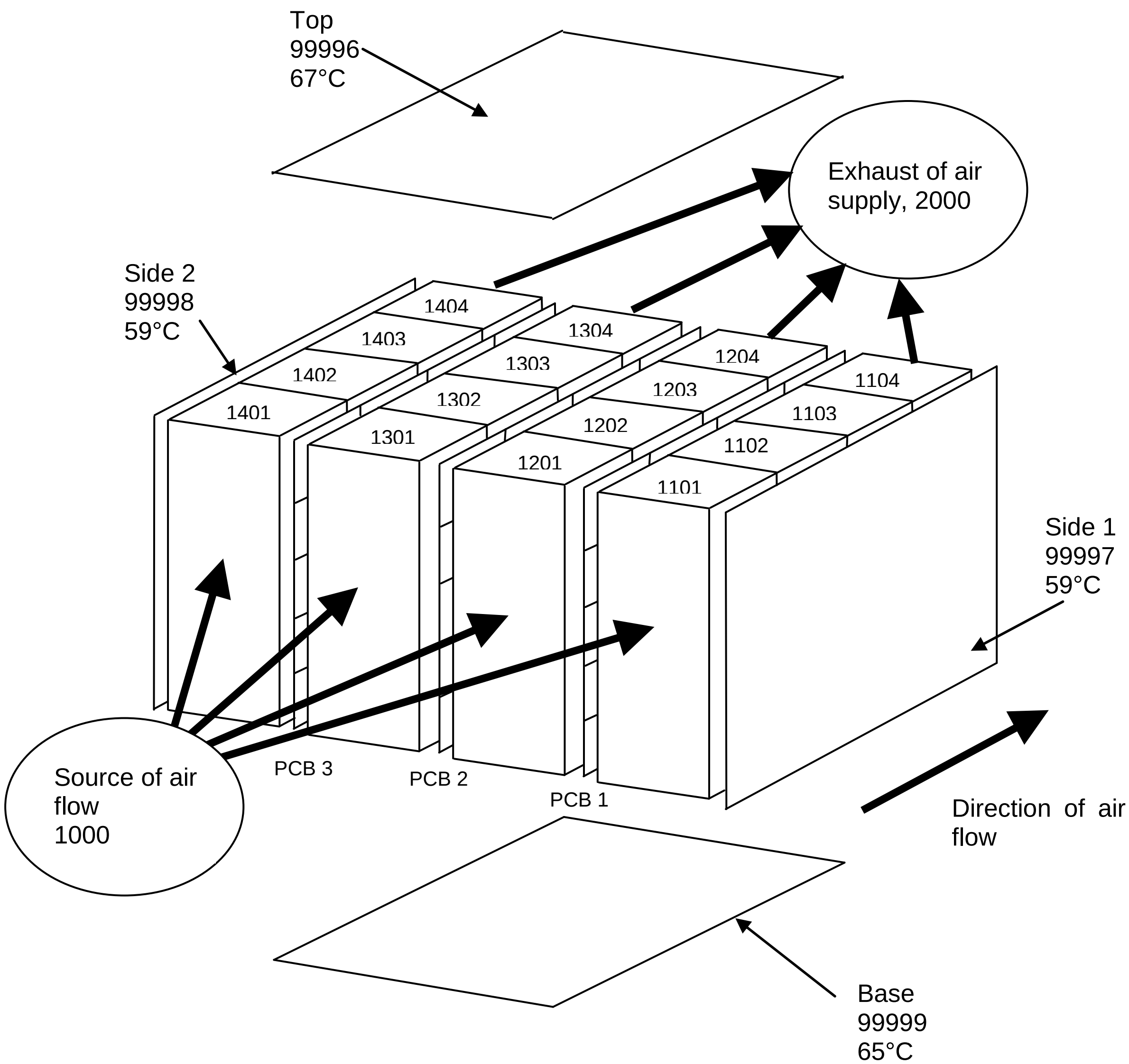

Figure 5-1 Air-cooled electronics unit

The model is shown schematically in Figure 5-1. Node 1000 represents the source of the cooling air which is blown in equal proportions either side of each PCB, exhausting to node 2000. Each flow path is discretised longitudinally into the same number of nodes as the PCBs, but we have assumed that there is no need to discretise transversely. Air nodes in each flow path are linked by *fluidic* or *one-way conductors* to model the transport of heat by advection. The conductance is

$$G_F = \dot{m} c_p$$

where $\dot{m}$ is the required mass flow rate and c_p is the specific heat of the air. The rate of heat transported along a fluidic conductor defined as going from node i to node j is

$$Q = G_F (T_i - T_j);$$

note, however, that there is *no* heat flow from node j to node i even if node j is hotter.

Convective heat transfer between the structure and the air is modelled by using linear conductors with the conductance given by

$$G_L = hA$$

where h is the *heat transfer coefficient* (HTC) and A is the surface area over which heat transfer takes place. There are many convective heat-transfer correlations in the literature; we shall use the well-known formula for laminar flow over a flat plate of length L:

$$h = \frac{0.664k \,\mathrm{Pr}^{1/3} \,\mathrm{Re}_L^{1/2}}{L}$$

where k is the conductivity, $\mathrm{Pr} = c_p \mu / k$ is the *Prandtl number*, $\mathrm{Re}_L = \rho u L / \mu$ is the *Reynolds number*, μ is the dynamic viscosity, ρ is the density, and u is the (free stream) velocity of the air. We will assume the following constant property values: c_p = 1004 J/kg K, k = 0.029 W/m K, $\mu = 2.0\times10^{-5}$ kg/m s, ρ = 1.1 kg/m^3.

***

As in the previous model, the PCBs are defined as submodels of the main electronics unit. This time, however, each submodel is specified implicitly using an *element* defined in the separate *global data file* (Listing 5-1). The element is written in the global file under the `$USER_ELEMENTS` keyword just like a normal model, except that certain quantities are denoted as *substitution data* by giving them a name enclosed in percent signs (‘%’). This means that their actual values do not have to be specified until the element is referenced in the parent model. Here, `PCB_LENGTH`, `PCB_WIDTH`, `PCB_DISS`, `NUM_LENGTH` and `NUM_WIDTH` are the substitution data for our PCB element. A default value can be supplied for each substitution data item in `$DEFAULTS`, a specialised block which is valid only in an element definition; otherwise, assignment in the parent model is mandatory.

Listing 5-1 Global file (*elunitc.gbl*) containing PCB element

```
$USER_ELEMENTS
#
# ****************************************************************************
#
$MODEL PCB
#
# Model of a Printed Circuit Board (PCB) with an evenly distributed power
# dissipation. Each edge of the PCB is retained by clamps. The casing is
# represented by two separate boundary nodes for the top and base.
#
# Substitution data:
#   PCB_LENGTH - Length of PCB
#   PCB_WIDTH  - Width of PCB
#   PCB_DISS   - Power dissipation (default 0.0)
#   NUM_LENGTH - Number of nodes along the length of the PCB
#   NUM_WIDTH  - Number of nodes across the width of the PCB
#
###############
# Data Blocks #
###############
#
# ****************************************************************************
$DEFAULTS
# ****************************************************************************
PCB_DISS   = 0.0;
#
# ****************************************************************************
$LOCALS
# ****************************************************************************
#
   $REAL
   k_copper        = 394.0;        # Thermal conductivity of copper
   cp_copper       = 386.0;        # Specific heat capacity of copper
   rho_copper      = 8900.0;       # Density of copper
   t_copper        = 0.000037;     # Thickness of a single copper layer
   pcb_length      = %PCB_LENGTH%; # Length of PCB
   pcb_width       = %PCB_WIDTH%;  # Width of PCB
   pcb_thick       = 0.0016;       # Thickness of PCB
   cp_pcb          = 1800.0;       # Specific heat capacity of PCB material
   rho_pcb         = 1500.0;       # Density of PCB material
   kiface_clamp    = 7.0;          # Interface conductance of clamp per unit length
   pcb_power       = %PCB_DISS%;   # PCB dissipation
#
   $INTEGER
   n_layers        = 4;            # Number of layers of copper in PCB
   n_length        = %NUM_LENGTH%; # Number of nodes along the length of the PCB
   n_width         = %NUM_WIDTH%;  # Number of nodes across the width of the PCB
#
# ****************************************************************************
$NODES
# ****************************************************************************
#
# Define the PCB
#
FOR KL1 = 100 TO (n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO n_length DO
      KL3 = KL1 + KL2;
      DKL3 = 'PCB node',
         T = 0.0,
         C = ((pcb_length / n_length) * (pcb_width / n_width)
              * t_copper * n_layers * rho_copper * cp_copper)
             + ((pcb_length / n_length) * (pcb_width / n_width)
                * (pcb_thick - (n_layers * t_copper)) * rho_pcb * cp_pcb),
         QI = pcb_power / (n_length * n_width);
   END DO
END DO
```

Listing 5-1 Global file (*elunitc.gbl*) containing PCB element

```
#
# Define the casing
#
B99996 = 'Unit Top - boundary', T = 50.0;
B99999 = 'Unit Base - boundary', T = 50.0;
#
# ****************************************************************************
$CONDUCTORS
# ****************************************************************************
#
# CONDUCTORS ALONG THE LENGTH OF THE PCB
#
# First define the conductors along the length of the PCB
#   Only the copper layers are considered
#
FOR KL1 = 100 TO (n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO (n_length - 1) DO
      KL3 = KL1 + KL2;
      KL4 = KL3 + 1;
      GL(KL3, KL4) = k_copper * (pcb_width / n_width) * (t_copper * n_layers)
                     / (pcb_length / n_length);
   END DO
END DO
#
# ****************************************************************************
#
# CONDUCTORS ACROSS THE WIDTH OF THE PCB
#
# Now define the conductors across the width of the PCB
#   Only the copper layers are considered
#
FOR KL1 = 100 TO ((n_width - 1) * 100) STEP 100 DO
   FOR KL2 = 1 TO n_length DO
      KL3 = KL1 + KL2;
      KL4 = KL3 + 100;
      GL(KL3, KL4) = k_copper * (pcb_length / n_length) * (t_copper * n_layers)
                     / (pcb_width / n_width);
   END DO
END DO
#
# ****************************************************************************
#
# INTERFACE CONDUCTORS
#
# Finally define the couplings at the clamped board edges to the unit base and top
#
FOR KL1 = 1 TO n_length DO
   KL2 = 100 + KL1;
   GL(KL2, 99999) = 1.0 / ((1.0 / (kiface_clamp  * (pcb_length / n_length)))
                    + (1.0 / (k_copper * (pcb_length / n_length) * (t_copper
                    * n_layers) / (pcb_width / (n_width * 2.0)))));
#
   KL2 = (100 * n_width) + KL1;
   GL(KL2, 99996) = 1.0 / ((1.0 / (kiface_clamp  * (pcb_length / n_length)))
                    + (1.0 / (k_copper * (pcb_length / n_length) * (t_copper
                    * n_layers) / (pcb_width / (n_width * 2.0)))));
END DO
#
$ENDMODEL PCB
#
# ****************************************************************************
#
```

The name of the global data file is specified on the main (top-level) `$MODEL` line of the input deck using the `GLOBALFILE` parameter (Listing 5-2). The element is invoked in a submodel definition via the `$ELEMENT` keyword, with the element name matching that on the `$MODEL` line of the element definition in the global file. Substitution data is then assigned in the `$SUBSTITUTIONS` block. Note that a different value is given for the power dissipation of each PCB (`PCB_DISS`).

In the `$OUTPUTS` block we again calculate the heat flows by different modes, this time including convection to the cooling air flow. Note how the `ZLABEL` arguments to the functions `FLUXGL` and `FLUXGR` are used to restrict the nodes included in the calculations.

Listing 5-2 Model file for air-cooled electronics unit

```
$MODEL ELUNITC, GLOBALFILE = elunitc.gbl
#
# Model of an electronics unit containing 3 printed circuit boards, each with its
# own evenly distributed power dissipation. The PCBs are mounted in an aluminium
# casing which acts as a thermal boundary. Cooling air is blown across the PCBs.
#
# ****************************************************************************
#
#############
# Submodels #
#############
#
   $MODEL PCB1
      $ELEMENT PCB
      $SUBSTITUTIONS
      PCB_LENGTH =  0.32;   # Length of PCB
      PCB_WIDTH  =  0.27;   # Width of PCB
      PCB_DISS   = 20.0;    # PCB dissipation
      NUM_LENGTH =  4;      # Number of nodes along the length of the PCB
      NUM_WIDTH  =  5;      # Number of nodes across the width of the PCB
   $ENDMODEL PCB1
#
   $MODEL PCB2
      $ELEMENT PCB
      $SUBSTITUTIONS
      PCB_LENGTH =  0.32;   # Length of PCB
      PCB_WIDTH  =  0.27;   # Width of PCB
      PCB_DISS   = 60.0;    # PCB dissipation
      NUM_LENGTH =  4;      # Number of nodes along the length of the PCB
      NUM_WIDTH  =  5;      # Number of nodes across the width of the PCB
   $ENDMODEL PCB2
#
   $MODEL PCB3
      $ELEMENT PCB
      $SUBSTITUTIONS
      PCB_LENGTH =  0.32;   # Length of PCB
      PCB_WIDTH  =  0.27;   # Width of PCB
      PCB_DISS   = 40.0;    # PCB dissipation
      NUM_LENGTH =  4;      # Number of nodes along the length of the PCB
      NUM_WIDTH  =  5;      # Number of nodes across the width of the PCB
   $ENDMODEL PCB3
#
# ****************************************************************************
#
###############
# Data Blocks #
###############
#
```

Listing 5-2 Model file for air-cooled electronics unit

```
# ******************************************************************************
$LOCALS
# ******************************************************************************
#
   $INTEGER
   pcb_n_length   = 4;        # Number of nodes along the length of each PCB
   pcb_n_width    = 5;        # Number of nodes across the width of each PCB
   num_pcbs       = 3;        # Number of PCBs in the unit
   num_flowpaths  =           # Number of air flow paths
      num_pcbs + 1;
#
   $REAL
   l_pcb          = 0.320;    # Length of each PCB, m
   w_pcb          = 0.270;    # Width of each PCB, m
   w_unit         = 0.225;    # Width of unit, m
   emissivity_pcb = 0.7;      # Infrared emissivity of PCB surface
   emissivity_Al  = 0.1;      # Infrared emissivity of inside of casing
   cond_air       = 0.029;    # Thermal conductivity of air, W/m/K
   density_air    = 1.1;      # Density of air, kg/m3
   specht_air     = 1004.0;   # Specific heat of air J/kg/K
   visc_air       = 2.0E-5;   # Viscosity of air, kg/m/s
   vel_air        = 0.08;     # Velocity of air, m/s
#
   prandtl        =           # Prandtl number
      specht_air * visc_air / cond_air;
   reynolds       =           # Reynolds number
      density_air * vel_air * l_pcb / visc_air;
   htc            =           # Heat transfer coefficient, forced convection, W/K/m2
      0.664 * cond_air * prandtl ** 0.333 * reynolds ** 0.5 / l_pcb;
   mdot_air       =           # Air mass flow rate through each flow path, kg/s
      (w_unit * w_pcb) / num_flowpaths * vel_air * density_air;
   ht_area        =           # Convective heat transfer area per node, m2
      (l_pcb * w_pcb) / pcb_n_length;
#
# ******************************************************************************
$NODES
# ******************************************************************************
#
# DEFINE AIR NODES
#
# Source and exhaust nodes
#
D1000 = 'Cooling Air Source', T = 40.0;
D2000 = 'Cooling Air Exhaust', T = 40.0;
#
# Flow-paths
#
FOR KL1 = 1100 TO (1000 + num_flowpaths * 100) STEP 100 DO
   FOR KL2 = 1 TO pcb_n_length DO
      KL3 = KL1 + KL2;
      DKL3 = 'Cooling Air',
         T = 40.0,
         C = (w_unit * w_pcb * l_pcb) / (num_flowpaths * pcb_n_length)
             * density_air * specht_air;
   END DO
END DO
#
# Unit casing, boundary nodes
#
B99996 = 'Unit Top - boundary' = PCB1:99996 + PCB2:99996 + PCB3:99996, T = 67.0;
B99997 = 'Unit Side 1 - boundary', T = 59.0;
B99998 = 'Unit Side 2 - boundary', T = 59.0;
B99999 = 'Unit Base - boundary' = PCB1:99999 + PCB2:99999 + PCB3:99999, T = 65.0;
#
# ******************************************************************************
$CONDUCTORS
```

Listing 5-2 Model file for air-cooled electronics unit

```
# ******************************************************************************
#
# INTERMODEL LINKS
#
# Internal Radiation PCB-to-PCB
#
FOR KL1 = 100 TO (pcb_n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO pcb_n_length DO
      KL3 = KL1 + KL2;
      GR(PCB1:KL3, PCB2:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                               1.0 / ((1.0 / emissivity_pcb) +
                               (1.0 / emissivity_pcb) - 1.0);
      GR(PCB2:KL3, PCB3:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                               1.0 / ((1.0 / emissivity_pcb) +
                               (1.0 / emissivity_pcb) - 1.0);
   END DO
END DO
#
# Internal Radiation PCB-to-side panels
#
FOR KL1 = 100 TO (pcb_n_width * 100) STEP 100 DO
   FOR KL2 = 1 TO pcb_n_length DO
      KL3 = KL1 + KL2;
      GR(99997, PCB1:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                            1.0 / ((1.0 / emissivity_Al) +
                            (1.0 / emissivity_pcb) - 1.0);
      GR(99998, PCB3:KL3) = (l_pcb * w_pcb / (pcb_n_length * pcb_n_width)) *
                            1.0 / ((1.0 / emissivity_Al) +
                            (1.0 / emissivity_pcb) - 1.0);
   END DO
END DO
#
# FLUIDIC LINKS
#
# Source to first node in each flow path
#
FOR KL1 = 1100 TO (1000 + num_flowpaths * 100) STEP 100 DO
   KL2 = KL1 + 1;
   GF(1000, KL2) = mdot_air * specht_air;
END DO
#
# Flow paths
#
FOR KL1 = 1100 TO (1000 + num_flowpaths * 100) STEP 100 DO
   FOR KL2 = 1 TO (pcb_n_length - 1) DO
      KL3 = KL1 + KL2;
      GF(KL3, KL3 + 1) = mdot_air * specht_air;
   END DO
END DO
#
# Last node in each flow path to exhaust
#
FOR KL1 = 1100 TO (1000 + num_flowpaths * 100) STEP 100 DO
   GF(KL1 + pcb_n_length, 2000) = mdot_air * specht_air;
END DO
#
# CONVECTIVE LINKS
#
# First flow path (between Side 1 and PCB 1)
#
FOR KL1 = 1 TO pcb_n_length DO
   KL3 = 1100 + KL1;
   GL(KL3, 99997) = htc * ht_area;
   FOR KL2 = 100 TO (pcb_n_width * 100) STEP 100 DO
      KL4 = KL2 + KL1;
      GL(KL3, PCB1:KL4) = htc * ht_area;
```

Listing 5-2 Model file for air-cooled electronics unit

```
   END DO
END DO
#
# Second flow path (between PCB 1 and PCB 2)
#
FOR KL1 = 1 TO pcb_n_length DO
   KL3 = 1200 + KL1;
   FOR KL2 = 100 TO (pcb_n_width * 100) STEP 100 DO
      KL4 = KL2 + KL1;
      GL(KL3, PCB1:KL4) = htc * ht_area;
      GL(KL3, PCB2:KL4) = htc * ht_area;
   END DO
END DO
#
# Third flow path (between PCB 2 and PCB 3)
#
FOR KL1 = 1 TO pcb_n_length DO
   KL3 = 1300 + KL1;
   FOR KL2 = 100 TO (pcb_n_width * 100) STEP 100 DO
      KL4 = KL2 + KL1;
      GL(KL3, PCB2:KL4) = htc * ht_area;
      GL(KL3, PCB3:KL4) = htc * ht_area;
   END DO
END DO
#
# Fourth flow path (between PCB 3 and Side 2)
#
FOR KL1 = 1 TO pcb_n_length DO
   KL3 = 1400 + KL1;
   GL(KL3, 99998) = htc * ht_area;
   FOR KL2 = 100 TO (pcb_n_width * 100) STEP 100 DO
      KL4 = KL2 + KL1;
      GL(KL3, PCB3:KL4) = htc * ht_area;
   END DO
END DO
#
# ******************************************************************************
$CONSTANTS
# ******************************************************************************
#
   $CONTROL
#
   RELXCA  = 0.001;        # Convergence criterion
   NLOOP   = 1000;         # Maximum number of iterations
   WIDTH   = 90;           # Width of output file
#
   $REAL
   HFCOND  = 0.0;          # Conductive heat flux from PCBs to casing
   HFRAD   = 0.0;          # Radiative heat flux from PCBs to casing
   HFCONV  = 0.0;          # Convective heat flux removed by cooling air
#
#####################
# Operations Blocks #
#####################
#
# ******************************************************************************
$EXECUTION
# ******************************************************************************
#
      HEADER = 'Electronics unit with air cooling'
#
      CALL SOLVFM
#
# ******************************************************************************
$OUTPUTS
# ******************************************************************************
```

Listing 5-2 Model file for air-cooled electronics unit

```
#
      CALL PRNDTB(' ', 'L, T, QI, C', CURRENT)
      CALL PRNDBL('Air', 'GL, GF', CURRENT)
#
      HFCOND = FLUXGL('#99996-99999', CURRENT, ' ', PCB1)
     &         + FLUXGL('#99996-99999', CURRENT, ' ', PCB2)
     &         + FLUXGL('#99996-99999', CURRENT, ' ', PCB3)
#
      HFRAD  = FLUXGR('#99996-99999', CURRENT, ' ', PCB1)
     &         + FLUXGR('#99996-99999', CURRENT, ' ', PCB2)
     &         + FLUXGR('#99996-99999', CURRENT, ' ', PCB3)
#
      HFCONV = FLUXGL('#1000-2000', CURRENT, 'PCB', CURRENT)
#
      WRITE(*, 1001) HFCOND, HFRAD, HFCONV
#
 1001 FORMAT(' Heat flow by conduction to the casing = ', F8.3, ' W',/,
     &       ' Heat flow by radiation to the casing  = ', F8.3, ' W',/,
     &       ' Heat flow by convection to the air    = ', F8.3, ' W')
#
$ENDMODEL ELUNITC
```

***

The results of a steady-state solution (Listing 5-3) show that the air-cooling has a very significant effect, with over 80% of the power dissipation being convected away.

Listing 5-3 Steady state results for air-cooled unit

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     1
 6 APRIL 2006                         16:04:40                                     ELUNITC

Electronics unit with air cooling




 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =    12
ENBALA = 1.917E-04      ENBALR = 1.E-06


TABLE OUTPUT WITH ZENTS = 'L,T,QI,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

ELUNITC


         NODE   LABEL                             T             QI            C

        1000    Cooling Air Source              40.00          0.00          0.00
        1101    Cooling Air                     43.56          0.00          1.34
        1102    Cooling Air                     46.89          0.00          1.34
        1103    Cooling Air                     50.05          0.00          1.34
        1104    Cooling Air                     52.99          0.00          1.34
        1201    Cooling Air                     47.02          0.00          1.34
        1202    Cooling Air                     53.03          0.00          1.34
```

Listing 5-3 Steady state results for air-cooled unit

```
       1203    Cooling Air                     58.31          0.00          1.34
       1204    Cooling Air                     62.88          0.00          1.34
       1301    Cooling Air                     47.91          0.00          1.34
       1302    Cooling Air                     54.63          0.00          1.34
       1303    Cooling Air                     60.48          0.00          1.34
       1304    Cooling Air                     65.52          0.00          1.34
       1401    Cooling Air                     44.54          0.00          1.34
       1402    Cooling Air                     48.74          0.00          1.34
       1403    Cooling Air                     52.67          0.00          1.34
       1404    Cooling Air                     56.29          0.00          1.34
       2000    Cooling Air Exhaust             59.42          0.00          0.00
      99996    Unit Top - boundary             67.00          0.00          0.00
      99997    Unit Side 1 - boundary          59.00          0.00          0.00
      99998    Unit Side 2 - boundary          59.00          0.00          0.00
      99999    Unit Base - boundary            65.00          0.00          0.00


==========================================================================================

ELUNITC:PCB1


         NODE   LABEL                            T             QI            C

         101    PCB node                       62.76          1.00         19.13
         102    PCB node                       64.68          1.00         19.13
         103    PCB node                       66.72          1.00         19.13
         104    PCB node                       68.33          1.00         19.13
         201    PCB node                       62.14          1.00         19.13
         202    PCB node                       65.02          1.00         19.13

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     2
 6 APRIL 2006                         16:04:40                                     ELUNITC

Electronics unit with air cooling




         NODE   LABEL                            T             QI            C

         203    PCB node                       68.13          1.00         19.13
         204    PCB node                       70.57          1.00         19.13
         301    PCB node                       62.15          1.00         19.13
         302    PCB node                       65.25          1.00         19.13
         303    PCB node                       68.63          1.00         19.13
         304    PCB node                       71.25          1.00         19.13
         401    PCB node                       62.45          1.00         19.13
         402    PCB node                       65.33          1.00         19.13
         403    PCB node                       68.45          1.00         19.13
         404    PCB node                       70.88          1.00         19.13
         501    PCB node                       63.71          1.00         19.13
         502    PCB node                       65.63          1.00         19.13
         503    PCB node                       67.67          1.00         19.13
         504    PCB node                       69.28          1.00         19.13
      99996    Unit Top - boundary             67.00          0.00          0.00
      99999    Unit Base - boundary            65.00          0.00          0.00


==========================================================================================

ELUNITC:PCB2


         NODE   LABEL                            T             QI            C
```

Listing 5-3 Steady state results for air-cooled unit

```
        101    PCB node                         72.40          3.00         19.13
        102    PCB node                         74.83          3.00         19.13
        103    PCB node                         77.33          3.00         19.13
        104    PCB node                         79.27          3.00         19.13
        201    PCB node                         76.15          3.00         19.13
        202    PCB node                         79.71          3.00         19.13
        203    PCB node                         83.45          3.00         19.13
        204    PCB node                         86.32          3.00         19.13
        301    PCB node                         77.11          3.00         19.13
        302    PCB node                         80.92          3.00         19.13
        303    PCB node                         84.95          3.00         19.13
        304    PCB node                         88.03          3.00         19.13
        401    PCB node                         76.46          3.00         19.13
        402    PCB node                         80.02          3.00         19.13
        403    PCB node                         83.76          3.00         19.13
        404    PCB node                         86.63          3.00         19.13
        501    PCB node                         73.35          3.00         19.13
        502    PCB node                         75.78          3.00         19.13
        503    PCB node                         78.27          3.00         19.13
        504    PCB node                         80.21          3.00         19.13
      99996    Unit Top - boundary              67.00          0.00          0.00
      99999    Unit Base - boundary             65.00          0.00          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.0)      PAGE     3
 6 APRIL 2006                        16:04:40                                      ELUNITC

Electronics unit with air cooling



ELUNITC:PCB3

         NODE   LABEL                              T             QI            C

        101    PCB node                         68.24          2.00         19.13
        102    PCB node                         70.43          2.00         19.13
        103    PCB node                         72.72          2.00         19.13
        104    PCB node                         74.53          2.00         19.13
        201    PCB node                         70.38          2.00         19.13
        202    PCB node                         73.63          2.00         19.13
        203    PCB node                         77.11          2.00         19.13
        204    PCB node                         79.82          2.00         19.13
        301    PCB node                         71.04          2.00         19.13
        302    PCB node                         74.52          2.00         19.13
        303    PCB node                         78.29          2.00         19.13
        304    PCB node                         81.21          2.00         19.13
        401    PCB node                         70.69          2.00         19.13
        402    PCB node                         73.94          2.00         19.13
        403    PCB node                         77.42          2.00         19.13
        404    PCB node                         80.13          2.00         19.13
        501    PCB node                         69.18          2.00         19.13
        502    PCB node                         71.38          2.00         19.13
        503    PCB node                         73.67          2.00         19.13
        504    PCB node                         75.48          2.00         19.13
      99996    Unit Top - boundary              67.00          0.00          0.00
      99999    Unit Base - boundary             65.00          0.00          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.0)      PAGE     4
 6 APRIL 2006                        16:04:40                                      ELUNITC

Electronics unit with air cooling
```

Listing 5-3 Steady state results for air-cooled unit

```
 TIMEN =      0.00      MODULE SOLVFM      LOOPCT =    12
ENBALA = 1.917E-04      ENBALR = 1.E-06


BLOCK OUTPUT WITH ZENTS = 'GL,GF'
FOR NODES OF ZLABEL = 'Air'


ELUNITC

VALUES FOR CONDUCTORS GL :
GL(1101,Z2:101) =       0.04      GL(1101,Z2:201) =       0.04
GL(1101,Z2:301) =       0.04      GL(1101,Z2:401) =       0.04
GL(1101,Z2:501) =       0.04      GL(1101,99997)  =       0.04
GL(1102,Z2:102) =       0.04      GL(1102,Z2:202) =       0.04
GL(1102,Z2:302) =       0.04      GL(1102,Z2:402) =       0.04
GL(1102,Z2:502) =       0.04      GL(1102,99997)  =       0.04
GL(1103,Z2:103) =       0.04      GL(1103,Z2:203) =       0.04
GL(1103,Z2:303) =       0.04      GL(1103,Z2:403) =       0.04
GL(1103,Z2:503) =       0.04      GL(1103,99997)  =       0.04
GL(1104,Z2:104) =       0.04      GL(1104,Z2:204) =       0.04
GL(1104,Z2:304) =       0.04      GL(1104,Z2:404) =       0.04
GL(1104,Z2:504) =       0.04      GL(1104,99997)  =       0.04
GL(1201,Z2:101) =       0.04      GL(1201,Z2:201) =       0.04
GL(1201,Z2:301) =       0.04      GL(1201,Z2:401) =       0.04
GL(1201,Z2:501) =       0.04      GL(1201,Z3:101) =       0.04
GL(1201,Z3:201) =       0.04      GL(1201,Z3:301) =       0.04
GL(1201,Z3:401) =       0.04      GL(1201,Z3:501) =       0.04
GL(1202,Z2:102) =       0.04      GL(1202,Z2:202) =       0.04
GL(1202,Z2:302) =       0.04      GL(1202,Z2:402) =       0.04
GL(1202,Z2:502) =       0.04      GL(1202,Z3:102) =       0.04
GL(1202,Z3:202) =       0.04      GL(1202,Z3:302) =       0.04
GL(1202,Z3:402) =       0.04      GL(1202,Z3:502) =       0.04
GL(1203,Z2:103) =       0.04      GL(1203,Z2:203) =       0.04
GL(1203,Z2:303) =       0.04      GL(1203,Z2:403) =       0.04
GL(1203,Z2:503) =       0.04      GL(1203,Z3:103) =       0.04
GL(1203,Z3:203) =       0.04      GL(1203,Z3:303) =       0.04
GL(1203,Z3:403) =       0.04      GL(1203,Z3:503) =       0.04
GL(1204,Z2:104) =       0.04      GL(1204,Z2:204) =       0.04
GL(1204,Z2:304) =       0.04      GL(1204,Z2:404) =       0.04
GL(1204,Z2:504) =       0.04      GL(1204,Z3:104) =       0.04
GL(1204,Z3:204) =       0.04      GL(1204,Z3:304) =       0.04
GL(1204,Z3:404) =       0.04      GL(1204,Z3:504) =       0.04
GL(1301,Z3:101) =       0.04      GL(1301,Z3:201) =       0.04
GL(1301,Z3:301) =       0.04      GL(1301,Z3:401) =       0.04
GL(1301,Z3:501) =       0.04      GL(1301,Z4:101) =       0.04
GL(1301,Z4:201) =       0.04      GL(1301,Z4:301) =       0.04
GL(1301,Z4:401) =       0.04      GL(1301,Z4:501) =       0.04
GL(1302,Z3:102) =       0.04      GL(1302,Z3:202) =       0.04

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     5
 6 APRIL 2006                        16:04:40                                      ELUNITC

Electronics unit with air cooling




GL(1302,Z3:302) =       0.04      GL(1302,Z3:402) =       0.04
GL(1302,Z3:502) =       0.04      GL(1302,Z4:102) =       0.04
GL(1302,Z4:202) =       0.04      GL(1302,Z4:302) =       0.04
GL(1302,Z4:402) =       0.04      GL(1302,Z4:502) =       0.04
```

Listing 5-3 Steady state results for air-cooled unit

```
GL(1303,Z3:103) =       0.04      GL(1303,Z3:203) =       0.04
GL(1303,Z3:303) =       0.04      GL(1303,Z3:403) =       0.04
GL(1303,Z3:503) =       0.04      GL(1303,Z4:103) =       0.04
GL(1303,Z4:203) =       0.04      GL(1303,Z4:303) =       0.04
GL(1303,Z4:403) =       0.04      GL(1303,Z4:503) =       0.04
GL(1304,Z3:104) =       0.04      GL(1304,Z3:204) =       0.04
GL(1304,Z3:304) =       0.04      GL(1304,Z3:404) =       0.04
GL(1304,Z3:504) =       0.04      GL(1304,Z4:104) =       0.04
GL(1304,Z4:204) =       0.04      GL(1304,Z4:304) =       0.04
GL(1304,Z4:404) =       0.04      GL(1304,Z4:504) =       0.04
GL(1401,Z4:101) =       0.04      GL(1401,Z4:201) =       0.04
GL(1401,Z4:301) =       0.04      GL(1401,Z4:401) =       0.04
GL(1401,Z4:501) =       0.04      GL(1401,99998)  =       0.04
GL(1402,Z4:102) =       0.04      GL(1402,Z4:202) =       0.04
GL(1402,Z4:302) =       0.04      GL(1402,Z4:402) =       0.04
GL(1402,Z4:502) =       0.04      GL(1402,99998)  =       0.04
GL(1403,Z4:103) =       0.04      GL(1403,Z4:203) =       0.04
GL(1403,Z4:303) =       0.04      GL(1403,Z4:403) =       0.04
GL(1403,Z4:503) =       0.04      GL(1403,99998)  =       0.04
GL(1404,Z4:104) =       0.04      GL(1404,Z4:204) =       0.04
GL(1404,Z4:304) =       0.04      GL(1404,Z4:404) =       0.04
GL(1404,Z4:504) =       0.04      GL(1404,99998)  =       0.04

VALUES FOR CONDUCTORS GF :
GF(1000,1101) =       1.34      GF(1000,1201) =       1.34
GF(1000,1301) =       1.34      GF(1000,1401) =       1.34
GF(1000,1101) =       1.34      GF(1101,1102) =       1.34
GF(1101,1102) =       1.34      GF(1102,1103) =       1.34
GF(1102,1103) =       1.34      GF(1103,1104) =       1.34
GF(1103,1104) =       1.34      GF(1104,2000) =       1.34
GF(1000,1201) =       1.34      GF(1201,1202) =       1.34
GF(1201,1202) =       1.34      GF(1202,1203) =       1.34
GF(1202,1203) =       1.34      GF(1203,1204) =       1.34
GF(1203,1204) =       1.34      GF(1204,2000) =       1.34
GF(1000,1301) =       1.34      GF(1301,1302) =       1.34
GF(1301,1302) =       1.34      GF(1302,1303) =       1.34
GF(1302,1303) =       1.34      GF(1303,1304) =       1.34
GF(1303,1304) =       1.34      GF(1304,2000) =       1.34
GF(1000,1401) =       1.34      GF(1401,1402) =       1.34
GF(1401,1402) =       1.34      GF(1402,1403) =       1.34
GF(1402,1403) =       1.34      GF(1403,1404) =       1.34
GF(1403,1404) =       1.34      GF(1404,2000) =       1.34
GF(1104,2000) =       1.34      GF(1204,2000) =       1.34
GF(1304,2000) =       1.34      GF(1404,2000) =       1.34

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.0)       PAGE     6
 6 APRIL 2006                        16:04:40                                      ELUNITC

Electronics unit with air cooling




 KEY FOR SUB-MODEL CODE :


Z2 = ELUNITC:PCB1


Z3 = ELUNITC:PCB2


Z4 = ELUNITC:PCB3
Heat flow by conduction to the casing =   17.408 W
Heat flow by radiation to the casing  =    1.657 W
Heat flow by convection to the air    =  100.934 W
```

***

As well as the user being able to define their own elements, a system library of parametrised component models is supplied with ESATAN in the file *ELEMSYS.DAT*. Predominantly for fluid-loop modelling with FHTS, these include elements for pumps, heat exchangers, valves, PID controllers and Peltier-effect heaters. When using a system element, *ELEMSYS.DAT* does not need to be specified as the global file.

Example 6 A Cryogenically Cooled Instrument

This example introduces the concept of user-written control logic and subroutines; it also demonstrates the modelling of components at cryogenic temperatures.

A conceptual study is being performed to assess the viability of the proposed design for a new space-borne multi-spectral imaging instrument in a Sun-synchronised orbit.

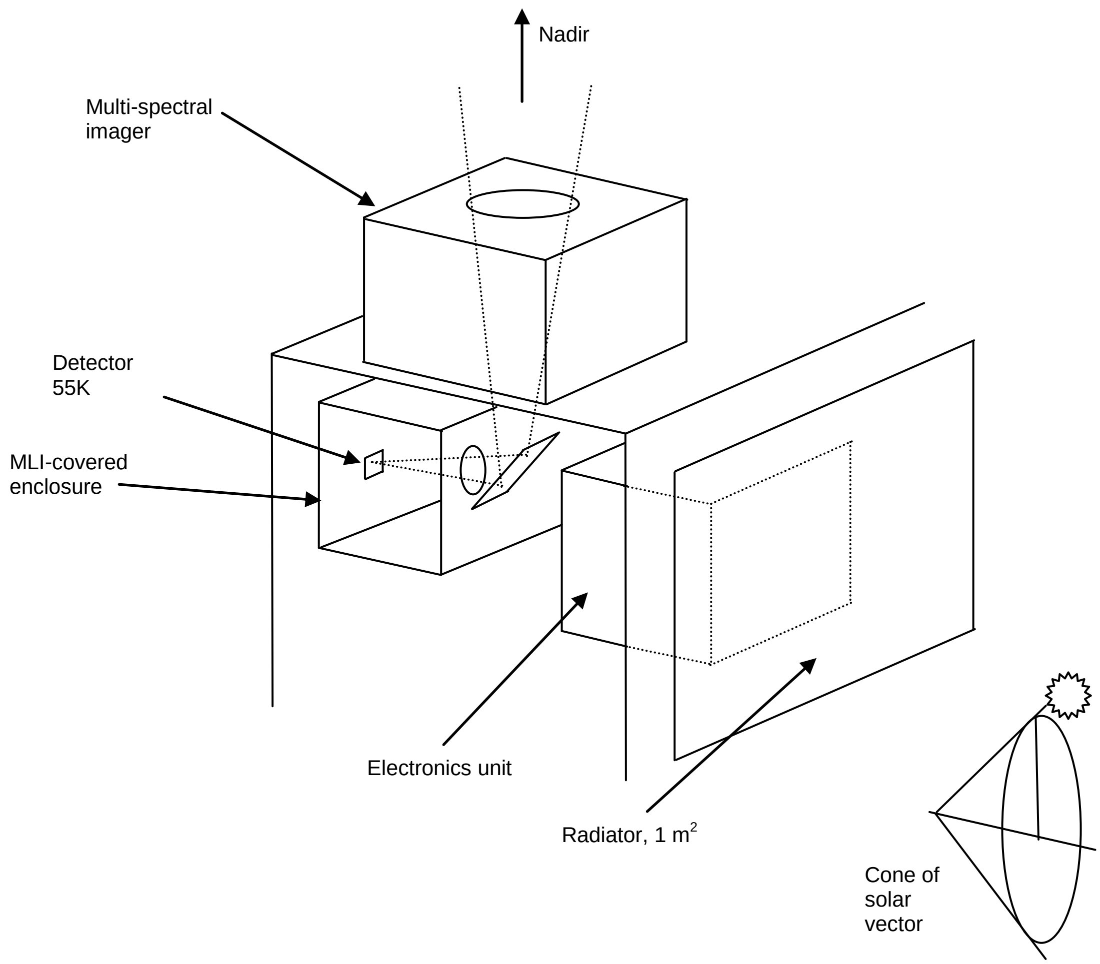

Figure 6-1 Accommodation of instrument on spacecraft

The structure is somewhat integrated (Figure 6-1), and the instrument detector (Figure 6-2) is housed within its own enclosure, acting as a cryogenic shield, inside the host spacecraft. Inside this enclosure the detector, which is mounted on a 0.2 kg molybdenum substrate, has to be kept at or below –218 °C (55 K), and its enclosure at around –193 °C (80 K). The detector, which dissipates 0.8 W of heat, is supported on four G10 (carbon fibre) struts and has an electrical harness (manganin) which also thermally links it to the enclosure. The enclosure itself is supported on six G10 struts which connect it to the spacecraft structure, as does another electrical harness. Multi-layer insulation (MLI) is applied around the outside of the enclosure body to reduce the heat load. A two-stage cryo-cooler is used to maintain the desired temperatures; the first stage of the cooler is applied to the enclosure walls and the second stage to the detector.

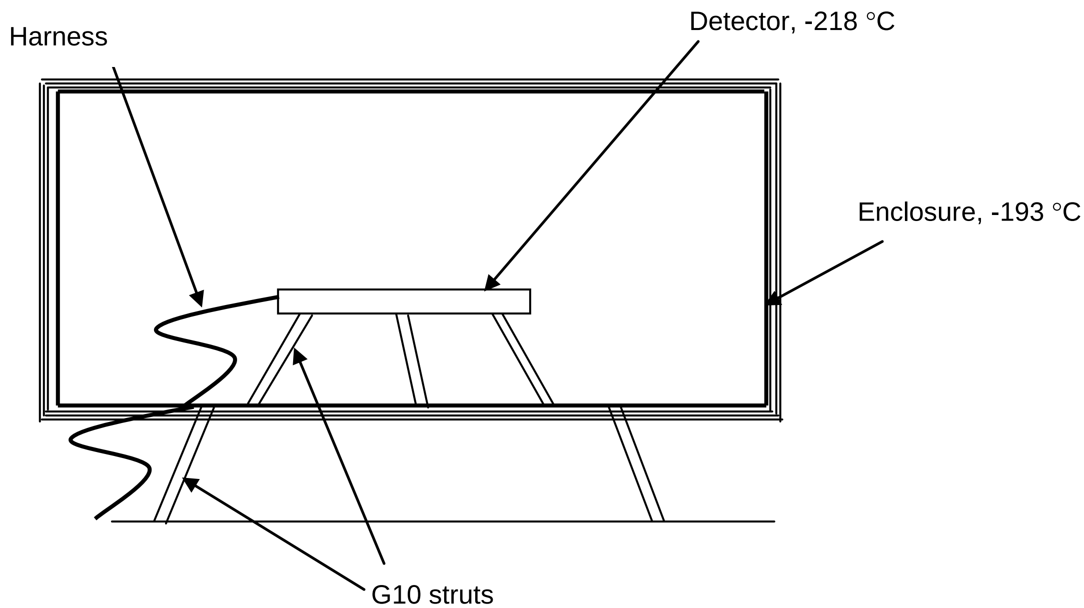

Figure 6-2 Schematic of detector enclosure

The electronics to process the detector signals and to drive the cooler are housed in a single unit whose operation is intermittent and only lasts for a total of 20 minutes per orbit. After switch-on the unit enters a warming-up phase for five minutes, the dissipation being 200 W, and then, for the remaining fifteen minutes, the unit is operational and the dissipation is 400 W. This electronics unit is mounted on the inside of a radiator panel on the sun-facing side of the spacecraft. At all times there is a 500 W heater enabled to maintain the unit at a minimum temperature of 20 °C, the heater being controlled using a thermostat with high/low set-points of 25/20 °C. Due to its large thermal dissipation inside the spacecraft the temperature of the electronics is assumed to determine the internal radiative and conductive boundaries.

Deep space at –270 °C forms the boundary for the radiator.

***

As this is a conceptual study, the model discretisation is relatively simple. The radiator is assumed to be very efficient at spreading heat away from the base of the unit and can therefore be modelled as a single node. Similarly the electronics unit can be assumed to be isothermal on its outer surface and can also be modelled as a single node.

The detector is mounted integral with its molybdenum substrate and it also requires only one node. The thermal capacity of the detector will vary with temperature, and it is important for this to be calculated accurately, particularly for cool-down analyses; the specific heat is therefore calculated from a fifth-degree polynomial expression:

$$c = 252.3353 + 0.269392T - 0.00882T^2 - 0.00016T^3 - 1.08\times10^{-6}T^4 - 2.10\times10^{-9}T^5$$

(here T is temperature in °C).

The mounting struts and electrical harness are not explicitly included as nodes, rather there are conductors that represent the heat path through them. As the material properties of the G10 struts and the manganin harness vary significantly with temperature, an average conductivity is calculated by integrating over the temperature range:

$$\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} k\,dT\,.$$

The conductivity for each material is given as a polynomial in T.

As stated above, the cryo-cooler is a two-stage device. The cooler performance map is shown in Figure 6-3. Sometimes known as a carpet graph, this presents the cooler performance as a relation between four variables: first stage temperature and heat lift, and second stage temperature and heat lift. Given the temperature of each stage the heat lifts can be determined, and vice versa.

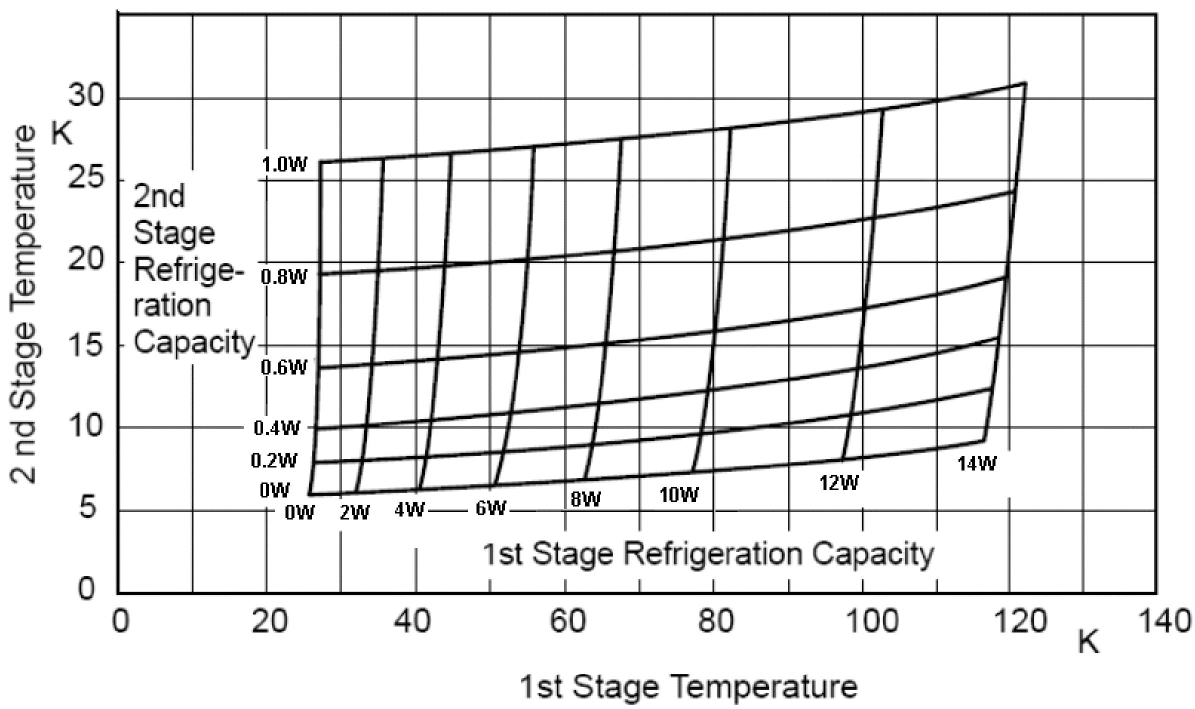

Figure 6-3 Cooler performance map

***

Consider the model definition in Listing 6-1. The cooled detector assembly and the electronics unit are defined as submodels.

Submodel DETECTOR

In the `$NODES` block, the thermal capacitance of the detector is defined by use of the library function `NODFNC`, type 2. This directs ESATAN to evaluate the user-defined function `SPHTMO` at the current nodal temperature during solution:

```
D1 = 'Detector', T = -218.0, QI = 0.8, C = 0.200 * NODFNC(2, SPHTMO);
```

Note that the use of `NODFNC` will cause MORTRAN to be generated and 'invisibly' placed in the `$VARIABLES1` block of this submodel. Therefore, to avoid a FORTRAN compilation error, **it is necessary to declare the user-defined function `SPHTMO` as `EXTERNAL` at the start of the `$VARIABLES1` block.** The cryo-cooler is modelled by means of two boundary nodes, the temperatures of which are directly modified as described below.

Turning to `$CONDUCTORS`, the temperature-dependent conductances of the G10 support rods are simulated using the library function `CNDFNC`, type 4, like so:

```
GL(2, 99999) = CNDFNC(4, k_G10) * (6.0 * csa2) / len2;
```

This calculates an average value via integration of conductivity with respect to temperature, assuming the conductivity to be represented as a polynomial with the polynomial coefficients being supplied in array `k_G10`. The manganin harness conductances are similarly defined.

Two *table arrays*, `CC_T1` and `CC_T2`, represent the data in the cryo-cooler performance map, giving the first- and second-stage temperatures, respectively, as a function of both heat lifts. This performance map is applied in a control algorithm encoded in `$VARIABLES1`, which is executed during the main part of both steady-state and transient solutions. The algorithm involves computing the heat lifts, updating the cryo-cooler temperatures accordingly, and iterating until convergence is reached. To ensure convergence a simple damping scheme is used when modifying the temperatures:

```
T11 = T11 + 0.5 * (T11NEW - T11)
```

and similarly for `T12`. Note that the heat lifts are assigned to the nodal entities `QI11` and `QI12` rather than using local FORTRAN variables. This is done for convenience: since these nodes are boundaries the heat sources (`QI`) will have no direct effect on the solution, but their values can be easily reported by calling `PRNDTB`, for instance (as in the `$OUTPUTS` block of the main model).

Submodel ELUNIT

This comprises a single diffusion node for the electronics unit and a boundary node for the spacecraft structure, radiatively coupled.

Main model

The detector boundary node is supernoded together with that of the electronics unit to represent the internal spacecraft structure. The internal temperature of the spacecraft is strongly influenced by the electronics unit (node `ELUNIT:10`) so this is used to define the internal boundary temperature:

```
B99997 = 'Structure' = ELUNIT:99997 + DETECTOR:99999, T = T:ELUNIT:10;
```

The effect of this is to continually update the temperature of `B99997` during solution, via generated Mortran in `$VARIABLES1`.

We need to ensure that there are time steps that coincide exactly with the start and finish times of the electronics operations. In order to achieve this we define *events*:

```
$EVENTS
...
   $OUTPUT
#
   Unit_warmup = 300.0;
   Unit_operational = 600.0;
   Unit_off = 1500.0;
```

(This type, *output events*, have the additional property of ensuring the `$OUTPUTS` block is executed at the specified time; *timestep events* do not do this.)

The first operations block is `$SUBROUTINES`, in which user subroutine `HEATSW` (see below) is placed. **This block, if present, must come before any other operations blocks.**

We then place code in `$VARIABLES2` (which, for a transient, is called at the end of each time step) to test if the solution is currently at the point of occurrence of one of these events, using the library function `AT`. If so, the electronics unit heat source is set accordingly:

```
IF (AT(Unit_warmup, 0)) THEN
   QI:ELUNIT:10 = 200.0
ELSE ...
```

The user subroutine `HEATSW` is also called from `$VARIABLES2` to check the status of the electronics unit temperature. It returns a value of 0 or 1, here assigned to the user constant `IUNITSW`, depending on whether a controlling thermostat would be opened or closed. This is used as a switch to apply the installed heater power to the unit:

```
QR:ELUNIT:10 = HTUNIT * IUNITSW
```

`HEATSW` also writes a line to the user-defined output file *heater.dat* to record the heater switching on and off. Finally in `$VARIABLES2` we call the library routine `PRNCSV` to record the temperature history of the detector and enclosure in comma-separated-value format in the file *temp.csv*.

External fluxes on the radiator panel are applied in the `$INITIAL` block, which is called at run-time prior to `$EXECUTION`. Since this is a conceptual study, these heat fluxes are averaged values obtained by a separate, first-order analysis.

Listing 6-1 Model file for cryogenic instrument

```
$MODEL CRYOINST
#
# Model of a space-borne instrument comprising an electronics unit and a
# mechanically cooled detector operating at cryogenic temperatures
#
# ***************************************************************************
#
#############
# Submodels #
#############
#
   $MODEL DETECTOR
   #
   # A detector mounted within a cryogenic enclosure using 4 G10 rods each of
   # length 100mm and cross-sectional area 30 mm2. The enclosure is covered in
   # MLI and is itself supported using 6 G10 rods each of length 50 mm and
   # cross-sectional area 60 mm2. Both the detector and the enclosure are
   # cooled by a 2-stage cryo-cooler, and there is an electrical harness
   # running from the detector to the supporting structure via the enclosure
   # which provides further thermal coupling.
   #
   ###############
   # Data Blocks #
   ###############
   #
   # ***************************************************************************
   $LOCALS
   # ***************************************************************************
   #
      $REAL
      csa1            = 30.0E-06; # CSA of each strut supporting detector, m2
      len1            = 0.1;      # Length of each strut supporting detector, m
      csa2            = 60.0E-06; # CSA of each strut supporting enclosure, m2
      len2            = 0.05;     # Length of each strut supporting enclosure, m
      encl_surfarea   = 0.15;     # Surface area of cryogenic enclosure, m2
      eff_emittance   = 0.02;     # Effective emittance through MLI
   #
   # ***************************************************************************
   $NODES
   # ***************************************************************************
      D1 = 'Detector', T = -218.0, QI = 0.8, C = 0.2 * NODFNC(2, SPHTMO);
      D2 = 'Enclosure wall', T = -193.0, C = 29.0;
      D3 = 'Enclosure MLI', T = -193.0, C = encl_surfarea * 360.0;
   #
      B11 = 'Cooler 1st stage', T = -200.0;
      B12 = 'Cooler 2nd stage', T = -250.0;
      B99999 = 'Structure', T = 20.0;
   #
   # ***************************************************************************
   $CONDUCTORS
   # ***************************************************************************
   #
      GL(1, 2) = CNDFNC(4, k_G10) * (4.0 * csa1) / len1;   # Struts
      GL(1, 2) = CNDFNC(4, k_Manganin) * (30E-06) / 0.25;  # Electrical harness
      GR(2, 3) = encl_surfarea * eff_emittance;
```

Listing 6-1 Model file for cryogenic instrument

```
   GL(2, 99999) = CNDFNC(4, k_G10) * (6.0 * csa2) / len2;  # Struts
   GL(2, 99999) = CNDFNC(4, k_Manganin) * (30E-06) / 0.1;  # Electr. harness
   GR(3, 99999) = encl_surfarea * 0.05;
#
# Thermal straps to cooler:
# - Thermal enclosure to first stage
   GL(2, 11) = 0.08;
# - Detector to second stage
   GL(1, 12) = 0.03;
#
# ***************************************************************************
$ARRAYS
# ***************************************************************************
   $REAL
   #
   # Material conductivity polynomial coefficients
   #
      k_G10(3)      =     0.15816653,
                         -0.0002877247,
                          1.1282121E-07;

      k_Manganin(6) =    10.718621,
                          0.00239395,
                          0.0002385,
                          3.176757E-06,
                          4.620897E-08,
                          4.06997E-11;
   #
   $TABLE
   #
   # Cryo-cooler performance map
   #
   CC_T1(Q1, Q2)
            Q2 =    0.0,    0.2,    0.4,    0.6,    0.8,    1.0,
      Q1 =  0.0, -247.6, -247.0, -246.7, -246.3, -246.0, -245.9,
      Q1 =  2.0, -241.1, -240.5, -239.9, -239.2, -238.3, -237.7,
      Q1 =  4.0, -232.5, -231.8, -231.2, -230.3, -229.4, -228.4,
      Q1 =  6.0, -222.6, -221.3, -220.4, -219.5, -218.3, -217.3,
      Q1 =  8.0, -210.5, -209.6, -208.7, -207.8, -206.5, -205.6,
      Q1 = 10.0, -196.0, -194.8, -193.9, -193.0, -192.0, -190.8,
      Q1 = 12.0, -176.0, -174.7, -173.8, -172.9, -171.7, -170.4,
      Q1 = 14.0, -156.8, -155.6, -155.0, -154.1, -152.8, -151.3;

   CC_T2(Q1, Q2)
            Q2 =    0.0,    0.2,    0.4,    0.6,    0.8,    1.0,
      Q1 =  0.0, -267.2, -265.3, -263.2, -259.4, -253.8, -246.9,
      Q1 =  2.0, -267.1, -265.1, -263.1, -259.3, -253.6, -246.8,
      Q1 =  4.0, -266.8, -264.9, -262.6, -259.0, -253.3, -246.4,
      Q1 =  6.0, -266.7, -264.6, -262.2, -258.6, -252.9, -246.1,
      Q1 =  8.0, -266.3, -264.2, -261.7, -258.1, -252.4, -245.6,
      Q1 = 10.0, -265.8, -263.5, -260.8, -257.2, -251.7, -244.9,
      Q1 = 12.0, -265.0, -262.2, -259.4, -255.8, -250.3, -243.8,
      Q1 = 14.0, -263.9, -260.7, -257.6, -253.9, -248.8, -242.1;
#
#####################
# Operations Blocks #
#####################
#
# ***************************************************************************
$SUBROUTINES
# ***************************************************************************
#
      DOUBLE PRECISION FUNCTION SPHTMO(TC)   # TC  - temperature in deg C
#
# Routine to calculate temperature-dependent specific heat capacity of
# molybdenum (Mo)
```

Listing 6-1 Model file for cryogenic instrument

```
   #
         DOUBLE PRECISION TC
   #
         SPHTMO = 252.3353 - 0.269392 * TC - 0.00882 * TC**2
     &             -0.00016 * TC**3 - 1.08E-06 * TC**4 - 2.10E-09 * TC**5
   #
         RETURN
         END
   #
   # ***************************************************************************
   $VARIABLES1
   # ***************************************************************************
      EXTERNAL SPHTMO    # Needed for NODFNC
   #
      DOUBLE PRECISION T11DIF, T11NEW, T12DIF, T12NEW
   #
   # Cryo-cooler control:
   # - Calculate heat lift required by each stage given current temperatures.
   # - Interpolate table arrays to get operating temperatures of cooler.
   # - Iterate until convergence.
   #
      REPEAT
         QI11 = GL(2, 11) * (T2 - T11)
         QI12 = GL(1, 12) * (T1 - T12)
         T11NEW = INTRP2(QI11, QI12, CC_T1, 1)
         T12NEW = INTRP2(QI11, QI12, CC_T2, 1)
         T11DIF = T11NEW - T11
         T12DIF = T12NEW - T12
         T11 = T11 + 0.5 * (T11NEW - T11)
         T12 = T12 + 0.5 * (T12NEW - T12)
      UNTIL (ABS(T11DIF) .LT. 0.01 .AND. ABS(T12DIF) .LT. 0.01)
   #
   $ENDMODEL DETECTOR
   #
   ###############
   #
   $MODEL ELUNIT
   #
   # Electronics unit attached to spacecraft structure.
   #
   ###############
   # Data Blocks #
   ###############
   #
   # ***************************************************************************
   $NODES
   # ***************************************************************************
   D10 = 'Electronics Unit', T = 20.0, C = 17000.0;
   B99997 = 'Structure', T = 0.0;
   #
   # ***************************************************************************
   $CONDUCTORS
   # ***************************************************************************
   GR(10, 99997) = 0.0055 ;
   #
   $ENDMODEL ELUNIT
#
###############
# Data Blocks #
###############
#
# ******************************************************************************
$NODES
# ******************************************************************************
D100 = 'Panel', T = 0.0, C = 650.0, A = 1.0, ALP = 0.08, EPS = 0.83;
B99999 =  'Deep Space', T = -270.0;
```

Listing 6-1 Model file for cryogenic instrument

```
#
# Couple detector & unit structure nodes via a supernode
B99997 = 'Structure' = ELUNIT:99997 + DETECTOR:99999, T = T:ELUNIT:10;
#
# ******************************************************************************
$CONDUCTORS
# ******************************************************************************
GL(ELUNIT:10, 100) = 100.0;
GR(100, 99999) = 0.83;
#
# ******************************************************************************
$CONSTANTS
# ******************************************************************************
#
   $REAL
   HTUNIT = 500.0;         # Heater power installed in electronics unit
#
   $INTEGER
   IUNITSW = 0;    # Switch for electronics unit heater
#
   $CONTROL
   NLOOP = 100;
   RELXCA = 0.01;
   TIMEND = 3000;
   DTIMEI = 10.0;
   WIDTH = 90;
#
# ******************************************************************************
$EVENTS
# ******************************************************************************
#
   $OUTPUT
#
   Unit_warmup = 300.0;
   Unit_operational = 600.0;
   Unit_off = 1500.0;
#
# ******************************************************************************
$SUBROUTINES
# ******************************************************************************
      SUBROUTINE HEATSW (TIME, TEMPER, HPOWER, TLOW, THIGH, OPS, ISTATE)
#
# Heater switch control (thermostat)
#
      DOUBLE PRECISION TIME, TEMPER, HPOWER, TLOW, THIGH
      INTEGER ISTATE, OPS
#
# Test ISTATE first then check on temperature and update ISTATE.
# Write to output file if ISTATE changes
#
      IF (ISTATE .EQ. 0) THEN
         IF (TEMPER .LE. TLOW) THEN
            ISTATE = 1
            WRITE (OPS, 9001) HPOWER, TIME
         END IF
      ELSE
         IF (TEMPER .GE. THIGH) THEN
            ISTATE = 0
            WRITE (OPS, 9002) HPOWER, TIME
         END IF
      END IF
      RETURN
#
 9001 FORMAT ('Heater power ', F8.2, ' switched ON  at time ',
     &        F10.2)
 9002 FORMAT ('Heater power ', F8.2, ' switched OFF at time ',
```

Listing 6-1 Model file for cryogenic instrument

```
     &        F10.2)
#
      END
#
# ****************************************************************************
$INITIAL
# ****************************************************************************
#
      QS100 = 47.5
      QA100 = 2.0
      QE100 = 44.3
#
# ****************************************************************************
$VARIABLES2
# ****************************************************************************
#
# Set electronics unit dissipation
#
      IF (AT(Unit_warmup, 0)) THEN
         QI:ELUNIT:10 = 200.0
      ELSE IF (AT(Unit_operational, 0)) THEN
         QI:ELUNIT:10 = 400.0
      ELSE IF (AT(Unit_off, 0)) THEN
         QI:ELUNIT:10 = 0.0
      END IF
#
# Operate heater thermostat and record operation.
#
      CALL HEATSW(TIMEN, T:ELUNIT:10, HTUNIT, 20.0D0, 25.0D0, 91, IUNITSW)
      QR:ELUNIT:10 = HTUNIT * IUNITSW
#
# Record detector & enclosure temperatures in CSV format
#
      CALL PRNCSV('#1, 2', 'T', DETECTOR, 'NODE', 'temp.csv')
#
# ****************************************************************************
$EXECUTION
# ****************************************************************************
#
# Open heater data file
#
      OPEN(UNIT = 91, FILE = 'heater.dat', STATUS='UNKNOWN')
#
# Transient solution
#
      CALL SLFWBK
#
      CLOSE (91)
#
# ****************************************************************************
$OUTPUTS
# ****************************************************************************
#
      CALL PRNDTB(' ', 'L,T,QS,QE,QA,QI,QR,C', CURRENT)
#
$ENDMODEL CRYOINST
```

***

The results of the transient solution (Listing 6-2) indicate that the detector and enclosure (nodes `DETECTOR:1` and `DETECTOR:2`, respectively) remain within the desired limits. An examination of the more complete data in the CSV file *temp.dat* () confirms this.

Listing 6-2 Standard output for cryogenic instrument model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.1)      PAGE     1
25 AUGUST 2006                          17:20:53                                 CRYOINST




 TIMEN =      0.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =    6.4376  AT NODE 100 IN SUB-MODEL  CRYOINST


TABLE OUTPUT WITH ZENTS = 'L,T,QS,QE,QA,QI,QR,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

CRYOINST


         NODE   LABEL                             T             QS            QE

          100    Panel                            0.00         47.50         44.30
        99997    Structure                       20.00          0.00          0.00
        99999    Deep Space                    -270.00          0.00          0.00



         NODE          QA            QI            QR            C

          100         2.00          0.00          0.00        650.00
        99997         0.00          0.00          0.00          0.00
        99999         0.00          0.00          0.00          0.00


==========================================================================================

CRYOINST:DETECTOR


         NODE   LABEL                             T             QS            QE

            1    Detector                      -218.00          0.00          0.00
            2    Enclosure wall                -193.00          0.00          0.00
            3    Enclosure MLI                 -193.00          0.00          0.00
           11    Cooler 1st stage              -232.57          0.00          0.00
           12    Cooler 2nd stage              -248.98          0.00          0.00
        99999    Structure                       20.00          0.00          0.00



         NODE          QA            QI            QR            C

            1         0.00          0.80          0.00         28.86
            2         0.00          0.00          0.00         29.00
            3         0.00          0.00          0.00         54.00
           11         0.00          3.17          0.00          0.00
           12         0.00          0.93          0.00          0.00
        99999         0.00          0.00          0.00          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK      (VERSION 9.6.1)      PAGE     2
25 AUGUST 2006                          17:20:53                                 CRYOINST
```

Listing 6-2 Standard output for cryogenic instrument model

```
CRYOINST:ELUNIT


         NODE   LABEL                              T              QS             QE

          10    Electronics Unit                 20.00           0.00           0.00
       99997    Structure                        20.00           0.00           0.00



         NODE          QA            QI             QR             C

          10          0.00          0.00           0.00      17000.00
       99997          0.00          0.00           0.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     3
25 AUGUST 2006                        17:20:53                                   CRYOINST





 TIMEN =    300.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =    6.4226  AT NODE 100 IN SUB-MODEL  CRYOINST


TABLE OUTPUT WITH ZENTS = 'L,T,QS,QE,QA,QI,QR,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

CRYOINST


         NODE   LABEL                              T              QS             QE

         100    Panel                            20.73          47.50          44.30
       99997    Structure                        23.25           0.00           0.00
       99999    Deep Space                     -270.00           0.00           0.00



         NODE          QA            QI             QR             C

         100          2.00          0.00           0.00        650.00
       99997          0.00          0.00           0.00          0.00
       99999          0.00          0.00           0.00          0.00


==========================================================================================

CRYOINST:DETECTOR


         NODE   LABEL                              T              QS             QE

           1    Detector                       -217.95           0.00           0.00
           2    Enclosure wall                 -206.22           0.00           0.00
           3    Enclosure MLI                  -175.44           0.00           0.00
          11    Cooler 1st stage               -236.04           0.00           0.00
          12    Cooler 2nd stage               -249.02           0.00           0.00
       99999    Structure                        23.25           0.00           0.00
```

Listing 6-2 Standard output for cryogenic instrument model

```
         NODE          QA           QI           QR           C

            1         0.00         0.80         0.00        28.88
            2         0.00         0.00         0.00        29.00
            3         0.00         0.00         0.00        54.00
           11         0.00         2.41         0.00         0.00
           12         0.00         0.93         0.00         0.00
        99999         0.00         0.00         0.00         0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     4
25 AUGUST 2006                        17:20:53                                    CRYOINST



CRYOINST:ELUNIT


         NODE   LABEL                            T             QS            QE

           10    Electronics Unit               23.39          0.00          0.00
        99997    Structure                      23.25          0.00          0.00



         NODE          QA           QI           QR           C

           10         0.00       200.00       500.00     17000.00
        99997         0.00         0.00         0.00         0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     5
25 AUGUST 2006                        17:20:53                                    CRYOINST




 TIMEN =    600.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =    6.4217  AT NODE 100 IN SUB-MODEL  CRYOINST


TABLE OUTPUT WITH ZENTS = 'L,T,QS,QE,QA,QI,QR,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

CRYOINST


         NODE   LABEL                            T             QS            QE

          100    Panel                          21.70         47.50         44.30
        99997    Structure                      24.34          0.00          0.00
        99999    Deep Space                   -270.00          0.00          0.00



         NODE          QA           QI           QR           C

          100         2.00         0.00         0.00       650.00
        99997         0.00         0.00         0.00         0.00
        99999         0.00         0.00         0.00         0.00


==========================================================================================
```

Listing 6-2 Standard output for cryogenic instrument model

```
CRYOINST:DETECTOR


        NODE   LABEL                              T             QS            QE

          1    Detector                      -218.51          0.00          0.00
          2    Enclosure wall                -211.53          0.00          0.00
          3    Enclosure MLI                 -157.30          0.00          0.00
         11    Cooler 1st stage              -237.52          0.00          0.00
         12    Cooler 2nd stage              -249.33          0.00          0.00
      99999    Structure                       24.34          0.00          0.00



        NODE         QA           QI            QR            C

          1         0.00         0.80          0.00         28.68
          2         0.00         0.00          0.00         29.00
          3         0.00         0.00          0.00         54.00
         11         0.00         2.09          0.00          0.00
         12         0.00         0.93          0.00          0.00
      99999         0.00         0.00          0.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     6
25 AUGUST 2006                        17:20:53                                     CRYOINST



CRYOINST:ELUNIT


        NODE   LABEL                              T             QS            QE

         10    Electronics Unit                24.30          0.00          0.00
      99997    Structure                       24.34          0.00          0.00



        NODE         QA           QI            QR            C

         10         0.00       400.00          0.00      17000.00
      99997         0.00         0.00          0.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     7
25 AUGUST 2006                        17:20:53                                     CRYOINST




 TIMEN =   1500.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =    6.4170  AT NODE 100 IN SUB-MODEL  CRYOINST


TABLE OUTPUT WITH ZENTS = 'L,T,QS,QE,QA,QI,QR,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

CRYOINST


        NODE   LABEL                              T             QS            QE
```

Listing 6-2 Standard output for cryogenic instrument model

```
        100    Panel                        27.64         47.50         44.30
      99997    Structure                    30.53          0.00          0.00
      99999    Deep Space                 -270.00          0.00          0.00



        NODE          QA            QI            QR            C

        100          2.00          0.00          0.00        650.00
      99997          0.00          0.00          0.00          0.00
      99999          0.00          0.00          0.00          0.00


==========================================================================================

CRYOINST:DETECTOR


         NODE   LABEL                             T             QS            QE

          1    Detector                   -220.35          0.00          0.00
          2    Enclosure wall             -214.05          0.00          0.00
          3    Enclosure MLI              -103.74          0.00          0.00
         11    Cooler 1st stage           -238.26          0.00          0.00
         12    Cooler 2nd stage           -250.27          0.00          0.00
      99999    Structure                    30.53          0.00          0.00



        NODE          QA            QI            QR            C

          1          0.00          0.80          0.00         28.02
          2          0.00          0.00          0.00         29.00
          3          0.00          0.00          0.00         54.00
         11          0.00          1.94          0.00          0.00
         12          0.00          0.90          0.00          0.00
      99999          0.00          0.00          0.00          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     8
25 AUGUST 2006                        17:20:53                                   CRYOINST


CRYOINST:ELUNIT


         NODE   LABEL                             T             QS            QE

         10    Electronics Unit             30.59          0.00          0.00
      99997    Structure                    30.53          0.00          0.00



        NODE          QA            QI            QR            C

         10          0.00          0.00          0.00      17000.00
      99997          0.00          0.00          0.00          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE     9
25 AUGUST 2006                        17:20:53                                   CRYOINST
```

Listing 6-2 Standard output for cryogenic instrument model

```
 TIMEN =   3000.00      MODULE SLFWBK      DTIMEU =   10.0000
CSGMIN =    6.4245  AT NODE 100 IN SUB-MODEL  CRYOINST


TABLE OUTPUT WITH ZENTS = 'L,T,QS,QE,QA,QI,QR,C'
FOR NODES OF ZLABEL = ' '

==========================================================================================

CRYOINST


         NODE   LABEL                             T             QS             QE

          100    Panel                          18.21          47.50          44.30
        99997    Structure                      20.61           0.00           0.00
        99999    Deep Space                   -270.00           0.00           0.00



         NODE          QA            QI            QR            C

          100         2.00          0.00          0.00        650.00
        99997         0.00          0.00          0.00          0.00
        99999         0.00          0.00          0.00          0.00


==========================================================================================

CRYOINST:DETECTOR


         NODE   LABEL                             T             QS             QE

            1    Detector                     -221.23           0.00           0.00
            2    Enclosure wall               -211.27           0.00           0.00
            3    Enclosure MLI                 -41.87           0.00           0.00
           11    Cooler 1st stage             -237.58           0.00           0.00
           12    Cooler 2nd stage             -250.71           0.00           0.00
        99999    Structure                      20.61           0.00           0.00



         NODE          QA            QI            QR            C

            1         0.00          0.80          0.00         27.70
            2         0.00          0.00          0.00         29.00
            3         0.00          0.00          0.00         54.00
           11         0.00          2.10          0.00          0.00
           12         0.00          0.88          0.00          0.00
        99999         0.00          0.00          0.00          0.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.6.1)       PAGE    10
25 AUGUST 2006                        17:20:53                                   CRYOINST



CRYOINST:ELUNIT


         NODE   LABEL                             T             QS             QE

           10    Electronics Unit               20.75           0.00           0.00
```

Listing 6-2 Standard output for cryogenic instrument model

```
      99997    Structure                       20.61          0.00          0.00



        NODE          QA            QI            QR            C

          10          0.00          0.00        500.00      17000.00
       99997          0.00          0.00          0.00          0.00
```

Listing 6-3 CSV output of temperatures

```
ESATAN v9.6.1;  MODEL CRYOINST;  TIME 25 AUGUST 2006  17:20:53

TIME,T:DETECTOR:1,T:DETECTOR:2,
     10.00,-2.179806E+02,-1.936518E+02,
     20.00,-2.179628E+02,-1.942870E+02,
     30.00,-2.179465E+02,-1.949036E+02,
     40.00,-2.179317E+02,-1.955027E+02,
     50.00,-2.179184E+02,-1.960846E+02,
     60.00,-2.179065E+02,-1.966500E+02,
     70.00,-2.178959E+02,-1.971991E+02,
     80.00,-2.178867E+02,-1.977324E+02,
     90.00,-2.178789E+02,-1.982504E+02,
    100.00,-2.178722E+02,-1.987534E+02,
    110.00,-2.178669E+02,-1.992419E+02,
    120.00,-2.178627E+02,-1.997162E+02,
    . . .
   1800.00,-2.207325E+02,-2.137285E+02,
   1810.00,-2.207430E+02,-2.137165E+02,
   1820.00,-2.207534E+02,-2.137044E+02,
   1830.00,-2.207637E+02,-2.136922E+02,
   1840.00,-2.207738E+02,-2.136799E+02,
   1850.00,-2.207839E+02,-2.136675E+02,
   1860.00,-2.207938E+02,-2.136550E+02,
   . . .
   2930.00,-2.212391E+02,-2.114400E+02,
   2940.00,-2.212384E+02,-2.114170E+02,
   2950.00,-2.212375E+02,-2.113941E+02,
   2960.00,-2.212366E+02,-2.113706E+02,
   2970.00,-2.212357E+02,-2.113468E+02,
   2980.00,-2.212347E+02,-2.113228E+02,
   2990.00,-2.212336E+02,-2.112984E+02,
   3000.00,-2.212325E+02,-2.112738E+02,
```

Example 7   Radiator Sizing

This example shows how the ESATAN parameter-case facility may be used to perform a parametric analysis, in this case to determine the optimum size for a radiator. It also demonstrates features for determining minimum and maximum values during a solution.

As part of a preliminary sizing exercise we are required to determine the optimum size of a radiator dedicated to cooling a single electronics unit which is contained in an aluminium box, 150 mm × 200 mm × 150 mm and 3 mm thick. The electronics unit gives rise to a constant heat load of 12 W which is to be rejected by the radiator. The heat rejection capability of the radiator is affected by the albedo and earthshine heat fluxes it receives whilst orbiting the earth (no flux is received from the sun in this case). Whilst the earthshine is constant, the albedo heat flux varies with the orbital position, and our task is to size the radiator in order to maintain the electronics payload in the range 10–20 °C throughout the orbit. The electronics unit has a thermal capacity of 500 J/K and is coupled to two sides of the box by conductances of 1.50 W/K.

***

As this is a preliminary sizing exercise the model is relatively simple, as shown in Figure 7-1.

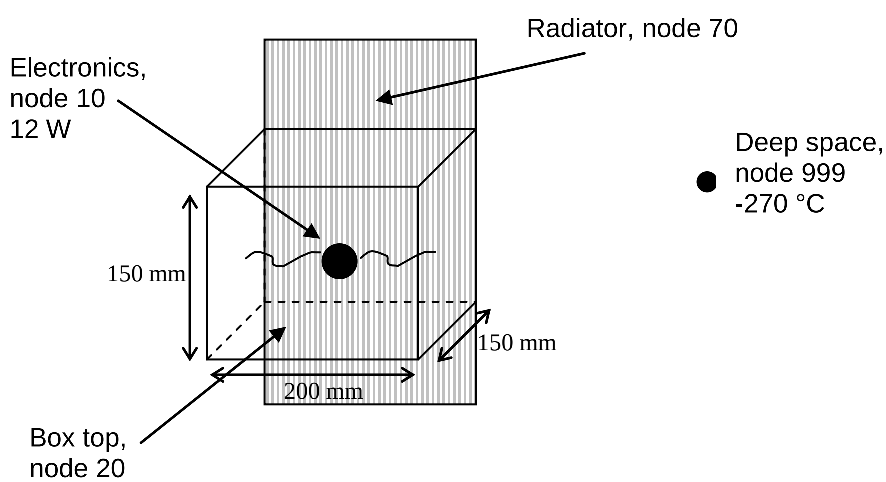

Figure 7-1   Electronics unit with radiator

As can be seen the model consists of a six-sided box with a single internal node representing the electronics payload. The box is perfectly insulated, and by treating the base of the box and the radiator as a single node we assume that there is perfect contact between the two. We also assume that the thermal conductivity of the radiator is such that the temperature through the radiator is effectively uniform and thus we can model it with a single node. The radiator is the same width as the box (200 mm), but its length is to be determined by running successive solutions with different lengths, until the temperature of the payload remains within the permitted range. Deep space forms the boundary.

***

The ESATAN model file is shown in Listing 7-1. Quantities such as the capacitance of the radiator or its radiative coupling with deep space are defined in terms of the user constant `RadLen` representing the radiator length. This allows them to be recalculated during parametric analysis as described below. Our first guess for the length is 0.5 m.

The absorbed albedo flux density (i.e. per unit area) on the radiator varies as the satellite orbits the earth. This time-dependent, periodic value is given at a number of orbit positions in array `ALBFLUX`, with the corresponding orbit times in array `ORBTIM`. (This data has been obtained from the radiative analysis of a simple geometric model with a radiator of unit area using ESATAN-TMS Workbench.) The absorbed flux is calculated at each time step within `$VARIABLES1` by cyclically interpolating on these arrays, using the library routine `INTCYC`, and multiplying by the surface area of the radiator, `w_box * RadLen`. Even though constant in this example, the absorbed earthshine (planet) flux is calculated in the same manner; this would permit straightforward updating of the model by redefining array `PLFLUX` should this flux become time-varying.

```
$VARIABLES1
. . .
      QA70 = INTCYC (TIMEM, ORBTIM, ALBFLUX, 1, Period, 0.0D0)
             * w_box * RadLen
      QE70 = INTCYC (TIMEM, ORBTIM, PLFLUX, 1, Period, 0.0D0)
             * w_box * RadLen
```

Now, a satellite in orbit with cyclically varying heat loads or boundary conditions will, after a few orbits, settle down into a periodic response; i.e. it will eventually experience cyclically varying temperatures. Hence, starting from arbitrary initial conditions – here we set all the temperatures to 20 °C in the `$NODES` block – we need to run a transient solution on our model for long enough until it too achieves periodicity. In ESATAN this is made simple with the aid of the meta-solver `SOLCYC`. This will call a named solution routine repeatedly, simulating one complete period each time, and detect when cyclic conditions are obtained to the desired accuracy. It is usual to suppress the output of results during these intermediate cycles via the last argument to `SOLCYC` and then call the specified transient solver one more time (with output enabled):

```
$EXECUTION
. . .
      CALL SOLCYC('SLFWBK', 0.1D0, 0.1D0, Period, 99, ' ', 'NONE')
. . .
      CALL SLFWBK
```

Note that control constants `TIMEO` and `TIMEND` are automatically restored to their original values at the beginning of each `SOLCYC` cycle and before the routine exits.

In order to record maximum and minimum temperatures for each node (and the time at which each one occurs) we call the library routine `STORMM` in `$VARIABLES2` for the final orbit (when user constant `IRESULT = 1`). This stores the values in user-defined nodal entities, thus allowing them to be reported using all the standard output routines such as `PRNDTB`. The minimum/maximum values are initialised via calls to `SETNDR` in the `$INITIAL` block. The user-defined nodal entities (`T_MIN`, `TIM_MIN`, `T_MAX` and `TIM_MAX`) are made available at solution time by declaring them to the preprocessor in the global file (Listing 7-2).

Listing 7-1 ESATAN definition for radiator model

```
$MODEL RADIATOR, GLOBALFILE = radiator.gbl
#
# Model of an electronics unit with a variable-size radiator.
#
# ****************************************************************************
$LOCALS
# ****************************************************************************
#
   $REAL
   k_Al    = 180.0;    # Thermal conductivity of aluminium, W/m/K
   cp_Al   = 920.0;    # Specific thermal heat capacity of aluminium, J/kg/K
   rho_Al  = 2800.0;   # Density of aluminium, kg/m3
   t_box   = 0.003;    # Thickness of box sides, m
   l_box   = 0.150;    # Length of box, m
   w_box   = 0.200;    # Width of box, m
   h_box   = 0.150;    # Height of box, m
   temp    = 20.0;     # Initial temperature, deg C
#
# ****************************************************************************
$NODES
# ****************************************************************************
#
D10 = 'Internal Electronics', T = temp, C = 500.0, QI = 12.0;
D20 = 'Unit top', T = temp, C = w_box * l_box * t_box * rho_Al * cp_Al;
D30 = 'Unit side 1', T = temp, C = h_box * l_box * t_box * rho_Al * cp_Al;
D40 = 'Unit side 2', T = temp, C = h_box * w_box * t_box * rho_Al * cp_Al;
D50 = 'Unit side 3', T = temp, C = h_box * l_box * t_box * rho_Al * cp_Al;
D60 = 'Unit side 4', T = temp, C = h_box * w_box * t_box * rho_Al * cp_Al;
D70 = 'Radiator', T = temp, C = w_box * RadLen * t_box * rho_Al * cp_Al,
                  EPS = 0.9, A = w_box * RadLen;
B999= 'Deep Space', T = -270.0;
#
#
# ****************************************************************************
$CONDUCTORS
# ****************************************************************************
#
GR(70,999) = w_box * RadLen * 0.9;
#
GL(10, 30) = 1.50;
GL(10, 50) = 1.50;
GL(30, 40) = h_box * t_box / ((w_box + l_box) / 2.0) * k_Al;
GL(40, 50) = h_box * t_box / ((w_box + l_box) / 2.0) * k_Al;
GL(50, 60) = h_box * t_box / ((w_box + l_box) / 2.0) * k_Al;
GL(60, 30) = h_box * t_box / ((w_box + l_box) / 2.0) * k_Al;
GL(20, 30) = l_box * t_box / ((w_box + h_box) / 2.0) * k_Al;
GL(20, 40) = w_box * t_box / ((l_box + h_box) / 2.0) * k_Al;
GL(20, 50) = l_box * t_box / ((w_box + h_box) / 2.0) * k_Al;
GL(20, 60) = w_box * t_box / ((l_box + h_box) / 2.0) * k_Al;
GL(70, 30) = l_box * t_box / ((w_box + h_box) / 2.0) * k_Al;
GL(70, 40) = w_box * t_box / ((l_box + h_box) / 2.0) * k_Al;
GL(70, 50) = l_box * t_box / ((w_box + h_box) / 2.0) * k_Al;
GL(70, 60) = w_box * t_box / ((l_box + h_box) / 2.0) * k_Al;
#
# ****************************************************************************
$CONSTANTS
# ****************************************************************************
#
   $REAL
   RadLen  = 0.5;          # Radiator length
```

Listing 7-1 ESATAN definition for radiator model

```
   Period  = 6047.80;      # Orbital period
#
   $INTEGER
   IRESULT = 0;            # Flag to control recording of results
#
   $CONTROL
   WIDTH = 90;           # Width of output file
#
# ******************************************************************************
$ARRAYS
# ******************************************************************************
#
   $REAL
   ORBTIM(12) =  # orbit times
             0.0,  377.98, 2645.83, 3023.80, 3401.78, 3779.76,
         4157.73, 4535.71, 4913.68, 5291.66, 5669.63, 6047.80;
#
   ALBFLUX(12) = # Absorbed albedo flux density
          4.47,   0.0,   0.0,  3.76, 36.31, 68.04,
         89.42, 97.18, 90.15, 69.36, 38.07,  4.71;
#
   PLFLUX(12) = # Absorbed planet flux density
         94.61, 94.61, 94.61, 94.61, 94.61, 94.61,
         94.61, 94.61, 94.61, 94.61, 94.61, 94.61;
#
# ******************************************************************************
$INITIAL
# ******************************************************************************
      CALL SETNDR(' ', 'T_MIN', 1.0D10, CURRENT)
      CALL SETNDR(' ', 'T_MAX', -1.0D10, CURRENT)
#
# ******************************************************************************
$VARIABLES1
# ******************************************************************************
#
# Set radiator fluxes
#
       QA70 = INTCYC (TIMEM, ORBTIM, ALBFLUX, 1, Period, 0.0D0) * w_box * RadLen
       QE70 = INTCYC (TIMEM, ORBTIM, PLFLUX, 1, Period, 0.0D0) * w_box * RadLen
#
# ******************************************************************************
$VARIABLES2
# ******************************************************************************
#
      IF (IRESULT .EQ. 1) THEN
         CALL STORMM('T', 'T_MIN', 'TIM_MIN', 'T_MAX', 'TIM_MAX')
      END IF
#
# ******************************************************************************
$EXECUTION
# ******************************************************************************
#
      HEADER = 'Radiator Sizing Model'
#
      NLOOP = 100
      RELXCA = 0.01
      TIMEND = Period
      OUTINT = TIMEND / 10.0
      DTIMEI = 20.0
#
      IRESULT = 0
      CALL SOLCYC('SLFWBK', 0.1D0, 0.1D0, Period, 99, ' ', 'NONE')
#
      IRESULT = 1
      CALL SLFWBK
#
```

Listing 7-1 ESATAN definition for radiator model

```
# ******************************************************************************
$OUTPUTS
# ******************************************************************************
#
      IF (TIMEN .EQ. TIMEND) THEN
         CALL PRNDTB(' ', 'T_MIN, TIM_MIN, T_MAX, TIM_MAX', CURRENT)
      END IF
#
$ENDMODEL RADIATOR
```

Listing 7-2 Global file (*radiator.gbl*) with user-defined nodal entities

```
$USER_NODE_ENTITIES
   $REAL
   T_MIN;
   TIM_MIN;
   T_MAX;
   TIM_MAX;
```

***

The output from this model is shown in Listing 7-3. The summary report from `SOLCYC` is given for each cycle, followed by the maximum and minimum temperatures and the times at which they occurred. As can be seen, our first-guess value for the radiator length is not sufficient: node 10 does not stay within the required temperature range of 10–20 °C.

Listing 7-3 Results for radiator sizing

```
SOLCYC cycle number: 1
  Max delta T =  2.0169E+01
    at node 70
    in submodel RADIATOR
  Max delta dT/dt =  3.1738E-02
    at node 70
    in submodel RADIATOR

SOLCYC cycle number: 2
  Max delta T =  5.6508E+00
    at node 10
    in submodel RADIATOR
  Max delta dT/dt =  9.1751E-04
    at node 10
    in submodel RADIATOR

SOLCYC cycle number: 3
  Max delta T =  2.1948E+00
    at node 10
    in submodel RADIATOR
  Max delta dT/dt =  3.4432E-04
    at node 10
    in submodel RADIATOR
```

Listing 7-3 Results for radiator sizing

```
SOLCYC cycle number: 4
  Max delta T =  8.8307E-01
    at node 10
    in submodel RADIATOR
  Max delta dT/dt =  1.3649E-04
    at node 10
    in submodel RADIATOR

SOLCYC cycle number: 5
  Max delta T =  3.5856E-01
    at node 10
    in submodel RADIATOR
  Max delta dT/dt =  5.5113E-05
    at node 10
    in submodel RADIATOR

SOLCYC cycle number: 6
  Max delta T =  1.4589E-01
    at node 10
    in submodel RADIATOR
  Max delta dT/dt =  2.2348E-05
    at node 10
    in submodel RADIATOR

SOLCYC cycle number: 7
  Max delta T =  5.9656E-02
    at node 10
    in submodel RADIATOR
  Max delta dT/dt =  9.1442E-06
    at node 10
    in submodel RADIATOR

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK       (VERSION 9.7.1)       PAGE     1
31 AUGUST 2006                        18:04:31                                    RADIATOR

Radiator Sizing Model




 TIMEN =   6047.80      MODULE SLFWBK      DTIMEU =   12.3900
CSGMIN =   51.8824  AT NODE 30 IN SUB-MODEL  RADIATOR


TABLE OUTPUT WITH ZENTS = 'T_MIN,TIM_MIN,T_MAX,TIM_MAX'
FOR NODES OF ZLABEL = ' '

==========================================================================================

RADIATOR


         NODE        T_MIN       TIM_MIN         T_MAX       TIM_MAX

          10         -0.93       3583.90          2.78         20.00
          20         -6.48       3483.90         -2.66       5883.02
          30         -4.97       3423.90         -1.20       5863.02
          40         -7.49       3363.90         -3.56       5763.02
          50         -4.97       3423.90         -1.20       5863.02
          60         -7.49       3363.90         -3.56       5743.02
          70        -12.01       3083.90         -6.99       5318.24
         999       -270.00         20.00       -270.00         20.00
```

***

At this stage we can re-run the solution on our model for a series of different radiator lengths without having to modify the model file and preprocess it again — an important consideration for large models especially. We use the *parameter case* feature of ESATAN, whereby certain modifications to a model can be made at solution time via an auxiliary file (Listing 7-4).

Listing 7-4 Parameter-case file for radiator sizing model

```
$PARAMETERS, PARMONLY, CSV_ENTITIES = (RadLen, T:*)
#
!INITIAL = 'Sizing-1'
CHANGE RadLen = 0.2
#
!INITIAL = 'Sizing-2'
CHANGE RadLen = 0.3
#
!INITIAL = 'Sizing-3'
CHANGE RadLen = 0.4
```

The file starts with the `$PARAMETERS` line. The `PARMONLY` option specifies that only parameter cases defined here will be run, i.e. not the nominal case as defined in the model file. The `CSV_ENTITIES` option requests the values of user constant `RadLen` and all temperatures to be recorded in CSV format; by default, this data will be output to a single file, named *RADIATOR_PAR.csv*. If desired, a separate CSV file per parameter case may be requested with `CSV_OUTPUT = MULTIPLE`, each one being given a four-digit numeric suffix.

Here we are using *initial* parameter cases, whereby the model is returned to its initial state before each one is commenced. (Alternatively, *final* parameter cases commence with the model's state as it was at the end of the previous run.) For each case we simply assign a different value to `RadLen` (other commands are available, including scaling and activating/deactivating conductors, and there is no limit to the number of commands in a parameter case).

The resulting CSV file can be loaded into a spreadsheet, for instance, for postprocessing. (An alternative is to request GFF output and use the ThermNV application supplied in the ESATAN Thermal Suite.) This has been done and the results plotted as shown in Figure 7-2. It is evident that a radiator length of about 0.35 m will satisfy the requirements.

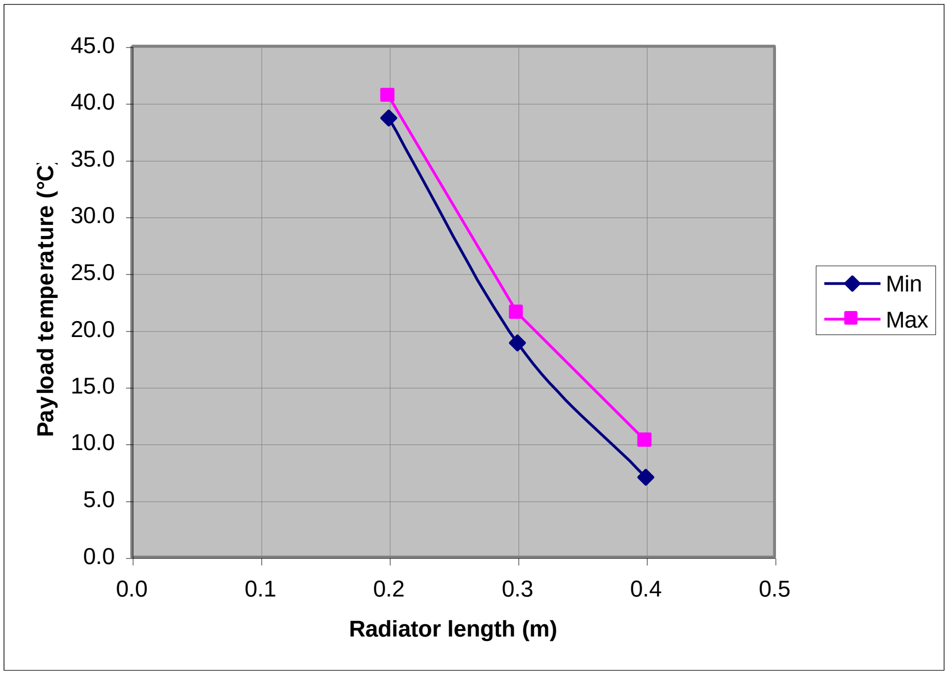

Figure 7-2 Payload temperature vs. radiator length

Example 8   A Simple Fluid Loop

This example models a very simple fluid loop. It contains a length of pipe, which is modelled using 4 fluid nodes, and a pump.

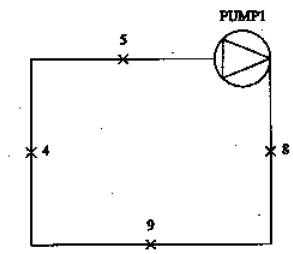

Figure 8-1   A simple fluid loop

Pump data is often supplied by the manufacturer in the form of characteristic curves. This example uses the centrifugal pump element, `PUMP_CF`, with the characteristic curves represented by polynomial coefficients. The pump element data is contained in the system elements file, `ELEMSYS.DAT`.

The topology of the fluid network is described in terms of nodes in a similar way to standard ESATAN models. Fluid nodes can be of five different types. That is,

"F" type node where both pressure and temperature are unknown.
"J" type node where pressure is fixed.
"K" type node where temperature (or enthalpy) is fixed.
"R" type node where both pressure and temperature (or enthalpy) is fixed.
"H" type node representing an arithmetic node.

To define a fluid node various new nodal entities have been introduced, the complete list is,

i.   *Heat transfer area (A),*
ii.   *Hydraulic diameter (FD),*
iii.   *Node length (FL),*
iv.   *Static pressure (P),*
v.   *Node specific enthalpy (FE),*
vi.   *Temperature (T),*
vii.   *Wall surface roughness (FF),*
viii.   *Internal heat source (FQ),*
ix.   *Nodal mass source or sink (FM),*
x.   *Specific enthalpy of the source/sink (FH),*
xi.   *Temperature of the source/sink (FR),*
xii.   *Vapour quality (specific humidity for air/vapour) of mass source/sink (FW).*
xiii.   *Cartesian coordinates (FX,FY and FZ),*

- *xiv. Fluid type (FT),*
- *xv. Vapour quality (VQ).*
- *xvi. Predicted flow regime (FRG).*
- *xvii. Flow area (FLA).*
- *xviii. Node volume (VOL).*
- *xix. Compliance (CMP).*
- *xx. Change in volume with time (VDT).*
- *xxi. Relative humidity (PHI).*
- xxii. *Fluid state descriptor (FST).*

The fluid type must also be defined and this can be done through the nodal entity FT or as a parameter on the `$MODEL` card. The state of the fluid is defined by the appropriate entities from pressure (P), temperature (T), enthalpy (FE) and vapour quality (VQ). The choice of entities used depends on the definition of the fluid state descriptor (FST), which has the default value 'P&T'.

In addition to these, FD and FL must be defined. The nodal entity FD represents the hydraulic diameter, therefore for non-circular sections the flow area must also be defined via the nodal entity FLA. FLA defaults to be

$$FLA = PI/4 * FD^2,$$

appropriate for circular cross-section. This default value can only be set by the preprocessor if FD is defined explicitly. If FD is given via MORTRAN then FLA must be defined, otherwise failure at solution time will occur. Note that the dimensions, and hence volume, of a node should only be changed via the compliance entity (CMP), which is the rate of change of volume with pressure, and/or the change in volume with time entity (VDT). The volume of a node is updated by the solution and should only be referenced. In this example the main model contains 4 fluid nodes, that is 3 "F" type nodes and 1 "J" type node. The fluid type used is WATER and is defined on the `$MODEL` card.

The single phase routines require a fixed pressure boundary within each independent fluid loop in the model. The boundary pressure is defined using a "J" type node and is set to be at the default atmospheric pressure (zero gauge pressure). The surface roughness of the pipe is defined using the nodal entity FF, and is set equal to 1.0E-7 metres.

Two new conductor types have been introduced and are defined within the `$CONDUCTORS` block. These are mass flow links, M(n1,n2) and flow conductance GP(n1,n2). Mass flow links describe the connections between the fluid nodes. The value associated with the mass flow link provides an initial estimate for a steady-state solution and a starting condition for a transient. The node ordering does not imply a direction of flow but defines the positive direction of flow.

Flow conductance values are used to define the conductance of flow between two nodes. Note that flow conductance is the inverse of resistance. If no flow conductance is defined for a mass flow link a default large value (1.0E10) is used.

In this example a flow conductance of 1.2 has been defined to represent the irreversible pressure loss at the entry and the exit of the pump. Similarly a flow resistance has been defined between fluid nodes 8 and 9, and fluid nodes 4 and 5.

Standard ESATAN conductors (GL, GR and GF) can be used to describe the thermal links between fluid nodes and thermal nodes. The most common form of heat transfer between fluid and thermal nodes is convection and therefore, a special conductor definition has been introduced to be used in conjunction with GL conductors. That is, GL(n1,n2) = *. The correlation used within this definition is described in document UM Appendix K. This form of definition has been used in this example to define the convective heat transfer coefficient between fluid node 5 and thermal node 3 and also between fluid node 4 and the thermal boundary node 10.

Listing 8-1 Model file for a simple fluid loop

```
$MODEL FLOOP, FLUID = WATER
#
#
#   Simple loop with centrifugal pump
#
#   ***Single phase solution***
#
#   Features:
#       1.Simple test of pumped flow around loop
#       2.Contains limited heat transfer via GL conductors
#       3.Fluid = Water
#       4.Thermal boundary = 20.0 deg C
#       5.Heat input = 5.0 W
#
   $MODEL PUMP1, FLUID = WATER
#
#   Pump element
#
   $ELEMENT PUMP_CF
#
   $SUBSTITUTIONS
      CHAR_TYPE = 'POLY';
      DIAM = 0.005 ;
      PRESS = 0.0 ;
      TEMP = 14.0 ;
      VOL = 3.92699E-6 ;
      DP_ARRAY = 5.5E4, 0.0, 5.0E-8;
      EFF_ARRAY = 0.9, 0.0001;
      MFLOW = 0.08;
#
   $ENDMODEL PUMP1
#
$NODES
#
#   Main model
#
B10, T = 20.0;
D3, T = 26.80, QI = 5.0;
#
F4, A = 0.001, FD = 0.005, FL = 0.1, P = -9677.26, T = 14.0,
FF = 5.0E-07;
#
F5, A = 0.001, FD = 0.005, FL = 0.1, P = -20347.83, T = 14.0,
FF = 5.0E-07;
#
F8, A = 0.001, FD = 0.005, FL = 0.1, P = 8950.56, T = 14.0,
FF = 5.0E-07;
#
J9, A = 0.001, FD = 0.005, FL = 0.1, P = -.00, T = 14.0,
FF = 5.0E-07;
#
$CONDUCTORS
#
#   Mass flow links
#
M(5, PUMP1:1) = 0.08;
M(PUMP1:2, 8) = 0.08;
M(4, 5) = 0.08;
M(8, 9) = 0.08;
M(9, 4) = 0.08;
#
#   Fitting losses
#
GP(5, PUMP1:1) = 1.2;
GP(PUMP1:2, 8) = 1.2;
```

Listing 8-1 Model file for a simple fluid loop

```
GP(8, 9) = 1.2;
GP(4, 5) = 1.2;
#
#   Fluid = thermal links
#
GL(10, 4) = *;
GL(3, 5) = *;
#
$CONSTANTS
#
$CONTROL
#
RELXCA = 0.01;
FRLXCA = 0.01;
NLOOP = 1000;
RELXMA = 0.01;
TIMEO = 0.0;
TIMEND = 5.0;
OUTINT = 5.0;
#
PABS = 1.01E5;
GRAVZ = 9.81;
#
$OUTPUTS
#
      FORMAT='F10.5'
#
      CALL PRNDTB(' ', 'T,P', CURRENT)
#
      CALL PRNDBL(' ', 'M,GL', CURRENT)
#
$EXECUTION
#
      HEADER = 'Simple loop with centrifugal pump'
#
      CALL FLTNTF
#
$ENDMODEL FLOOP
```

Listing 8-2 Output for simple fluid loop model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     1
21 AUGUST 2006                   12:11:40                                  FLOOP

Simple loop with centrifugal pump





 TIMEN =      0.00      MODULE FLTNTF      RELXMC = 8.643E-04
DTIMEU = 1.114E-02      DTCOUR = 2.229E-02
CSGMIN = 2.338E-02  AT NODE 5 IN SUB-MODEL  FLOOP


TABLE OUTPUT WITH ZENTS = 'T,P'
FOR NODES OF ZLABEL = ' '

================================================================================

FLOOP


         NODE          T             P

           3         26.80
          10         20.00

           4         14.00      -5371.00
           5         14.00     -19121.00
           8         14.00      13749.87
           9         14.00          0.00

================================================================================

FLOOP:PUMP1


         NODE          T             P


           1         14.00     -30185.54
           2         14.00      24814.20

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     2
21 AUGUST 2006                   12:11:40                                  FLOOP

Simple loop with centrifugal pump





 TIMEN =      0.00      MODULE FLTNTF      RELXMC = 8.643E-04
DTIMEU = 1.114E-02      DTCOUR = 2.229E-02
CSGMIN = 2.338E-02  AT NODE 5 IN SUB-MODEL  FLOOP


BLOCK OUTPUT WITH ZENTS = 'M,GL'
FOR NODES OF ZLABEL = ' '


FLOOP

VALUES FOR CONDUCTORS M  :
M (4,5)    =    0.08800      M (4,9)    =   -0.08800
```

Listing 8-2 Output for simple fluid loop model

```
M (5,4)    =   -0.08800      M (5,Z2:1) =    0.08800
M (8,9)    =    0.08800      M (8,Z2:2) =   -0.08800
M (9,8)    =   -0.08800      M (9,4)    =    0.08800

VALUES FOR CONDUCTORS GL :
GL(3,5)  =   16.33673      GL(10,4) =   16.33673


FLOOP:PUMP1

VALUES FOR CONDUCTORS M  :
M (1,2)    =    0.08801      M (1,Z1:5) =   -0.08800
M (2,1)    =   -0.08801      M (2,Z1:8) =    0.08800



 KEY FOR SUB-MODEL CODE :


Z1 = FLOOP


Z2 = FLOOP:PUMP1

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     3
21 AUGUST 2006                   12:11:40                                  FLOOP

Simple loop with centrifugal pump





 TIMEN =      5.00      MODULE FLTNTF      RELXMC = 2.985E-07
DTIMEU = 9.332E-03      DTCOUR = 2.214E-02
CSGMIN = 2.106E-02  AT NODE 5 IN SUB-MODEL  FLOOP


TABLE OUTPUT WITH ZENTS = 'T,P'
FOR NODES OF ZLABEL = ' '

================================================================================

FLOOP


         NODE          T             P

           3         19.81
          10         20.00

           4         19.54      -5249.98
           5         19.55     -18986.14
           8         19.54      13736.36
           9         19.53          0.00

================================================================================

FLOOP:PUMP1


         NODE          T             P


           1         19.54     -30097.47
           2         19.54      24847.63

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     4
```

Listing 8-2 Output for simple fluid loop model

```
21 AUGUST 2006                  12:11:40                                  FLOOP

Simple loop with centrifugal pump





 TIMEN =      5.00      MODULE FLTNTF      RELXMC = 2.985E-07
DTIMEU = 9.332E-03      DTCOUR = 2.214E-02
CSGMIN = 2.106E-02  AT NODE 5 IN SUB-MODEL  FLOOP


BLOCK OUTPUT WITH ZENTS = 'M,GL'
FOR NODES OF ZLABEL = ' '


FLOOP

VALUES FOR CONDUCTORS M  :
M (4,5)    =    0.08852      M (4,9)    =   -0.08852
M (5,4)    =   -0.08852      M (5,Z2:1) =    0.08852
M (8,9)    =    0.08852      M (8,Z2:2) =   -0.08852
M (9,8)    =   -0.08852      M (9,4)    =    0.08852

VALUES FOR CONDUCTORS GL :
GL(3,5)  =   18.90264      GL(10,4) =   18.90159


FLOOP:PUMP1

VALUES FOR CONDUCTORS M  :
M (1,2)    =    0.08852      M (1,Z1:5) =   -0.08852
M (2,1)    =   -0.08852      M (2,Z1:8) =    0.08852



 KEY FOR SUB-MODEL CODE :


Z1 = FLOOP


Z2 = FLOOP:PUMP1
```

Example 9 A Single-Phase Steady State Fluid Loop

This model demonstrates the use of the single-phase steady state solution routine. The model also contains various interesting features, such as,

- i. Variable mass source.
- ii. Use of user-defined elements.
- iii. Temperature control valve.
- iv. Multiple links to a node.

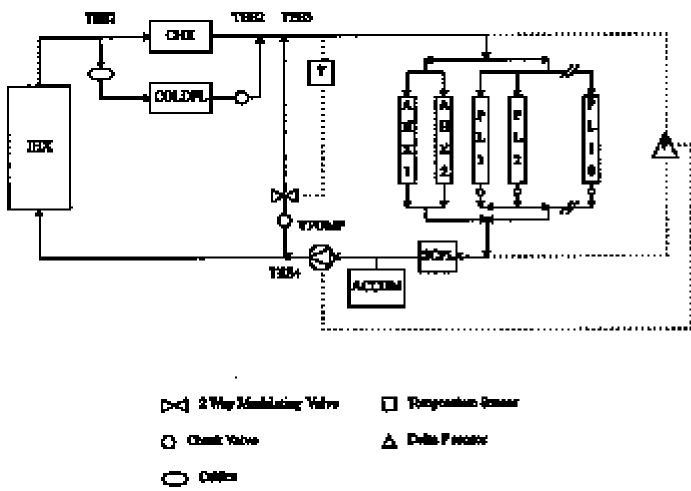

Figure 9-1 A single-phase steady state fluid loop

- i. 1 condensing heat exchanger (CHX),
- ii. 1 cold payload by-passing the CHX heat exchanger,
- iii. 2 Avionic heat exchangers (AHX1 and AHX2) and 7 payload heat exchangers in parallel,
- iv. 1 subsystems cold plate (SCPL) and
- v. 1 station interloop heat exchanger which rejects the heat to a fixed thermal boundary node at 2 ° C.

The heat exchangers are modelled using the user defined element facility. The user defined element is stored within the global file. Values which are to be parametrised are enclosed within the percent sign (%). For example the fluid node number 1 within the element `STNHTX`,

F1 = 'INLET',A=%HTXA%,FD=%HTXD%,FL=%HTXL%,P=10.0E5,T=20.0,FF=0.0;

requires the substitution data HTXA, HTXD and HTXL.

To represent the heat input to the heat exchangers, heat sources are specified within the heat exchanger wall using the `$SUBSTITUTIONS` facility. The IHX heat exchanger wall is linked to the thermal boundary node via linear intermodel conductances. The convective heat transfer coefficient between the fluid and the wall of each heat exchanger is specified using fixed GL values, and is input using the `$SUBSTITUTIONS` facility. The convective heat transfer coefficient from the fluid to the pipe wall in the main loop is defined using the GL(n1,n2)=* definition.

Fluid nodes 7 and 26 form the headers to the 9 heat exchangers in parallel. Due to the assumption that all mass flow links are in the same direction (except tee piece elements) no momentum losses are taken into account due to the change in direction at these nodes.

The model definition requires the pressure drop across the payloads to be kept at 0.4 +/- 0.01 bar. However, a dead band of +/- 100 Pa is used where no control action is taken. The pressure drop is regulated by modulating the mass flow rate in the network using a variable mass source. The network is therefore defined as an open loop, with a source and sink applied within the submodel `VPUMP`. The sink and source temperatures are set equal to the temperature of the upstream node to simulate a closed network. Note that the temperature of the source must be specified otherwise it defaults to zero. The control algorithm used to calculate the required mass flow rate is,

$$W_{new} = \sqrt{(0.4 \times 10^5 \times W^2_{old} / \Delta P_{old})}$$

where

W_{new} is the new mass flow rate,
W_{old} is the current mass flow rate,
ΔP_{old} is the current pressure drop across the payloads.

The pump mass source and sink is updated within the `$VARIABLES1` block using the definition,

```
FM:VPUMP:2 = PUMPM()
FM:VPUMP:1 = -1.0 * FM:VPUMP:2
```

where `PUMPM` is a user-defined function. The pump control logic is a function of pressure only, therefore to improve efficiency it is only executed if `SOLTYP = 'FLUID'`.

Only 3 of the payloads (PL1, PL7 and PL10) have heat input, and therefore, the mass flow rate through the 4 remaining payloads, and the CHX by-pass heat exchanger, is required to be zero. However, fluid nodes cannot be set inactive and hence will always remain in the hydraulic solution. Due to `RELXMA` being a relative change in mass flow rate, convergence problems can occur if nodes contain links which have mass flow rates of greatly differing magnitudes. This situation arises if closed valves are modelled using either very small flow conductance values or by setting the valve link inactive. One method is to switch "OFF" all the mass flow links within the branch containing zero mass flow rate.

Using this method the pressure of the isolated nodes and the mass flow rates of the inactive links remain unchanged. Within the example the user defined subroutine `SETINL` uses `STATST` to switch 'OFF' all the links in the branches with no heat input.

The mass flow rate down the IHX by-pass is regulated to force the temperature of node 7 to lie between 17 °C and 22 °C. The definition of the valve is such that it is fully open when the temperature of node 7 is at 17 °C and fully closed at 22 °C. A linear variation of the valve opening fraction is assumed between these two extremes. The temperature control valve produces a strong link between the thermal and hydraulic solution. The steady state solution carries out a hydraulic and thermal steady state solution independently and repeats this until convergence. Low thermal and hydraulic loop counters (`NLOOPT` and `NLOOPH`) have been used to avoid the solution converging to steady state before the modulating valve has stabilised. Steady state is achieved when only one iteration is performed within the hydraulic and thermal solutions to achieve convergence to `RELXMA`, `FRLXCA` and `RELXCA`.

For stability purposes the control algorithm is damped using a damping factor of 0.25. The control algorithm is purely a function of temperature and therefore does not change during the hydraulic solution. For this reason the control logic is only executed if `SOLTYP = ' '`.

The single-phase steady state routine `FLTNSS` requires `RELXCA`, `FRLXCA`, `RELXMA` and `NLOOP` to be specified. In this case the `NLOOPT` and `NLOOPH` have also been set in order to limit the number of hydraulic or thermal iterations per outer iteration. In addition to these `DAMPT` and/or `DAMPM` can be defined to damp the thermal and hydraulic solution respectively.

It has been found that in most cases it is advantageous to damp the thermal solution using the control constant `DAMPT`. In this example `DAMPT` is set to 0.5.

Listing 9-1 Model file for single-phase steady state fluid loop

```
$MODEL COLSS, FLUID=WATER, GLOBALFILE=colss.gbl
#
#
#  Single phase columbus model
#
#  Cabin heat exchanger
#
   $MODEL CHX, FLUID = WATER
#
#  Use standard heat exchanger model
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.1818;    # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 5.261;     # length of each node (m)
   HTXC = 2500.0;    # Capacitance of wall (J/K)
   HTXQ = 1400.0;    # Heat source at wall node
   HTXCD = 250.0;    # Conductance value between fluid and wall (W/K)
   CONGP = 0.08684;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL CHX
#
   $MODEL COLDPL, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;   # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 2.631;     # length of each node (m)
   HTXC = 1250.0;    # Capacitance of wall (J/K)
   HTXQ = 0.0;       # Heat source at wall node
   HTXCD = 175.0;    # Conductance value (W/K)
   CONGP = 0.2613;   # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL COLDPL
#
# Generate parallel payloads PL1, PL2, PL3, PL4, PL7, PL9 & PL10
#
   $MODEL PL1, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 210.0;      # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL1
#
   $MODEL PL2 , FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 0.0;        # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL2
#
   $MODEL PL3, FLUID = WATER
#
      $REPEAT PL2
#
   $ENDMODEL PL3
#
   $MODEL PL4, FLUID = WATER
#
      $REPEAT PL2
#
   $ENDMODEL PL4
#
   $MODEL PL7, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 900.0;      # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL7
#
   $MODEL PL9, FLUID = WATER
#
      $REPEAT PL2
#
   $ENDMODEL PL9
#
   $MODEL PL10, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 380.0;      # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL10
#
   $MODEL SCPL, FLUID = WATER
#
# SCPL has the same pressure drop - flow rate curve as COLDPL
# and also the same U*A value. Heat source constant
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
#
   HTXA = 0.09091;   # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 2.631;     # length of each node (m)
   HTXC = 1250.0;    # Capacitance of wall (J/K)
   HTXQ = 75.0;      # Heat source at wall node
   HTXCD = 175.0;    # Conductance value (W/K)
   CONGP = 0.2613;   # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL SCPL
#
   $MODEL IHX, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.3636;    # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 10.523;    # length of each node (m)
   HTXC = 7500.0;    # Capacitance of wall (J/K)
   HTXQ = 0.0;       # Heat source at wall node
   HTXCD = 380.0;    # Conductance value (W/K)
   CONGP = 0.08684;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL IHX
#
   $MODEL AHX1, FLUID = WATER
#
# Uses standard elements STNAHX - 4 nodes per model
#
   $ELEMENT STNAHX
#
   $SUBSTITUTIONS
#
   AHTXA = 0.09091;   # Heat transfer area per fluid node (sq m)
   AHTXD = 0.011;     # Pipe diameter (m)
   AHTXL = 2.631;     # Length of node (m)
   AHTXC = 1250.0;    # Wall capacitance (J/K)
   AHTXQ = 800.0;     # Heat source per node (W)
   AHTXCD = 125.0;    # Coductivity from fluid to wall (W/K)
   ACONGP = 0.26052;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL AHX1
#
   $MODEL AHX2, FLUID = WATER
#
   $ELEMENT STNAHX
#
   $SUBSTITUTIONS
#
   AHTXA = 0.09091;   # Heat transfer area per fluid node (sq m)
   AHTXD = 0.011;     # Pipe diameter (m)
   AHTXL = 2.631;     # Length of node (m)
   AHTXC = 1250.0;    # Wall capacitance (J/K)
   AHTXQ = 150.0;     # Heat source per node (W)
   AHTXCD = 125.0;    # Coductivity from fluid to wall (W/K)
   ACONGP = 0.26052;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL AHX2
#
   $MODEL VPUMP, FLUID = WATER
#
# Variable speed pump modelled as a mass source and sink
# Used to regulate pressure drop over payloads to 0.39 - 0.41 bar
#
   $NODES
#
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
   F1 = 'MASS SINK', A = 0.03456, FD = 0.011, FL = 5.621,
   P = 10.0E5, T = 20.0, FF = 0.0, FM = -0.1, FR = T1 ;
#
   F2 = 'MASS SOURCE', A = 0.03456, FD = 0.011, FL = 5.621,
   P = 10.0E5, T = 20.0, FF = 0.0, FM = 0.1, FR = T1 ;
#
   D3 = 'PUMP WALL', T =20.0, C = 750.0 ;
   D4 = 'PUMP WALL', T =20.0, C = 750.0 ;
#
   $CONDUCTORS
#
# Conduction links to pipe wall
#
   GL(1, 3) = *;
   GL(2, 4) = *;
#
   $ENDMODEL VPUMP
#
   $MODEL TEE1, FLUID = WATER
#
# Use library tee piece element to model momentum
# losses due to a 90 degree bend
#
   $ELEMENT TEE
#
   $SUBSTITUTIONS
#
   TA1 = 0.03456 ; TFD1 = 0.011 ; TFL1 = 1.0 ; TP1 = 10.0E5 ;
   TFE1 = 83.6E3 ; TT1 = 20.0 ; TFF1 = 0.1E-3 ;
#
   TA2 = 0.03456 ; TFD2 = 0.011 ; TFL2 = 1.0 ; TP2 = 10.0E5;
   TFE2 = 83.6E3 ; TT2 = 20.0 ; TFF2 = 0.1E-3;
#
   MFLOW = 0.01;
#
   TGP = 1.0E10;
#
   $ENDMODEL TEE1
#
   $MODEL TEE2, FLUID = WATER
#
   $REPEAT TEE1
#
   $ENDMODEL TEE2
#
   $MODEL TEE3, FLUID = WATER
#
   $REPEAT TEE1
#
   $ENDMODEL TEE3
#
   $MODEL TEE4, FLUID = WATER
#
   $REPEAT TEE1
#
   $ENDMODEL TEE4
#
# Main model
#
$LOCALS
#
$REAL
#
# Initialisation values for GP's of orifice payloads
#
# GP = 0.5 * RO * (MAXFR / A) ** 2 / DELTAP
#
# These used if density assumed constant = 1000 Kg/m**3
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
#
RL1 = 3.86E-4 ;  # GP for orifice for payload 1 MAXFR = 1.67 E-5
RL2 = 3.86E-4  ; # GP for orifice for payload 2 MAXFR = 1.67 E-5
RL3 = 3.86E-4 ;  # GP for orifice for payload 3 MAXFR = 1.67 E-5
RL4 = 9.6E-5 ;   # GP for orifice for payload 4 MAXFR = 8.33 E -6
RL7 = 1.54E-3 ;  # GP for orifice for payload 7 MAXFR = 3.34 E-5
RL9 = 1.54E-3 ;  # GP for orifice for payload 9 MAXFR = 3.34 E-5
RL10 = 3.86E-4 ; # GP for orifice for payload 10 MAXFR = 1.67 E-5
#
# Heat transfer area for nodes
#
RL20 = 0.03456 ;      # HTA for pipe nodes 1m long
#
# Thermal node pipe capacitance
#
RL30 = 107.973 ;      #Capacitance of pipe wall V*RHO*Cp - 1m pipes
#
$NODES
#
##########################################
# Generate fluid nodes along the pipe work
##########################################
#
F1 = 'AFTER IHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F2 = 'BEFORE CHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F3 = 'AFTER CHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F4 = 'BEFORE COLDPL',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F5 = 'AFTER COLDPL',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F6 = 'BEFORE BY-PASS',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F7 = 'TOP HEADER',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F8 = 'BEFORE AHX1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F9 = 'AFTER AHX1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F10 = 'BEFORE AHX2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F11 = 'AFTER AHX2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F12 = 'BEFORE PL1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F13 = 'AFTER PL1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F14 = 'BEFORE PL2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F15 = 'AFTER PL2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F16 = 'BEFORE PL3',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F17 = 'AFTER PL3',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F18 = 'BEFORE PL4',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F19 = 'AFTER PL4',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F20 = 'BEFORE PL7',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F21 = 'AFTER PL7',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F22 = 'BEFORE PL9',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F23 = 'AFTER PL9',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
#
F24 = 'BEFORE PL10',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F25 = 'AFTER PL10',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F26 = 'BOTTOM HEADER',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
J27 = 'BEFORE PUMP',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F28 = 'AFTER PUMP',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F29 = 'BEFORE IHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F30 = 'BY-PASS',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
##################################
# Generate nodes along the pipe wall
##################################
#
#  Node length 1.0 m
#
FOR KL1 = 1001 TO 1030 DO
   DKL1 = 'PIPE WALL', T = 20.0, C = RL30;
END DO
#
# Thermal boundary node for the IHX heat exchanger
#
B9999 = 'IHX B/NODE', T = 2.0;
#
$CONDUCTORS
#
#######################################
# Generate mass flow links along the pipe
#######################################
#
M(1, TEE1:1) = 0.1;
M(TEE1:1, 2) = 0.1;
M(2, CHX:1) = 0.1;
M(CHX:2, 3) = 0.1;
M(3, TEE2:1) = 0.1;
M(TEE2:1, 6) = 0.1;
M(TEE1:2, 4) = 0.1;
M(4, COLDPL:1) = 0.1;
M(COLDPL:2, 5) = 0.1;
M(5, TEE2:2) = 0.1;
M(6, TEE3:1) = 0.1;
M(TEE3:1, 7) = 0.1;
#
# Top header links
#
M(7, 8) = 0.01;
M(7, 10) = 0.01;
M(7, 12) = 0.01;
M(7, 14) = 0.01;
M(7, 16) = 0.01;
M(7, 18) = 0.01;
M(7, 20) = 0.01;
M(7, 22) = 0.01;
M(7, 24) = 0.01;
#
M(8, AHX1:1) = 0.01;
M(AHX1:4, 9) = 0.01;
M(10, AHX2:1) = 0.01;
M(AHX2:4, 11) = 0.01;
M(12, PL1:1) = 0.01;
M(PL1:2, 13) = 0.01;
M(14, PL2:1) = 0.01;
M(PL2:2, 15) = 0.01;
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
M(16, PL3:1) = 0.01;
M(PL3:2, 17) = 0.01;
M(18, PL4:1) = 0.01;
M(PL4:2, 19) = 0.01;
M(20, PL7:1) = 0.01;
M(PL7:2, 21) = 0.01;
M(22, PL9:1) = 0.01;
M(PL9:2, 23) = 0.01;
M(24, PL10:1) = 0.01;
M(PL10:2, 25) = 0.01;
#
# Bottom header links
#
M(9, 26) = 0.01;
M(11, 26) = 0.01;
M(13, 26) = 0.01;
M(15, 26) = 0.01;
M(17, 26) = 0.01;
M(19, 26) = 0.01;
M(21, 26) = 0.01;
M(23, 26) = 0.01;
M(25, 26) = 0.01;
#
M(26, SCPL:1) = 0.1;
M(SCPL:2, 27) = 0.1;
M(27, VPUMP:1) = 0.1;
M(VPUMP:2, 28) = 0.1;
M(28, TEE4:1) = 0.1;
M(TEE4:1, 29) = 0.1;
M(29, IHX:1) = 0.1;
M(IHX:2, 1) = 0.1;
#
M(TEE4:2, 30) = 0.1;
M(30, TEE3:2) = 0.1;
#
#################################################################
# Generate conduction links from the fluid nodes to the pipe wall
#################################################################
#
FOR KL1 = 1 TO 30 DO
   KL2 = KL1 + 1000;
   GL(KL1, KL2) = *;
END DO
#
###################################################
# IHX intermodel links to the thermal boundary node
###################################################
#
GL(IHX:3, 9999) = 4550.0;
GL(IHX:4, 9999) = 4550.0;
#
GP(TEE1:2, 4) = 0.01140;    # Orifice within by-pass for CHX
#
#########################
# Set up payload orifices
#########################
#
# pipe length before (PL1)
#
GP(7, 12) = RL1;
#
# pipe length before (PL2)
#
GP(7, 14) = RL2;
#
# Pipe length before (PL3)
#
GP(7, 16) = RL3;
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
#
# Pipe length before (PL4)
#
GP(7, 18) = RL4;
#
# Pipe length before (PL7)
#
GP(7, 20) = RL7;
#
# Pipe length before (PL9)
#
GP(7, 22) = RL9;
#
# Pipe length before (PL10)
#
GP(7, 24) = RL10;
#
########################
# AHX1 and AHX2 orifices
########################
#
GP(7, 8) = 3.38E-3;
GP(7, 10) = 5.393E-4;
#
############################
# BY-PASS V2WM control valve
############################
#
GP(TEE4:2, 30) = 4.429E-4;      # Set at valve opening of 0.2
#
$CONSTANTS
#
$INTEGER
#
COUNT = 0;                      # Counter for solution number
#
$REAL
#
XNEW = 0.2;                     # New valve opening fraction before damping
XBYP = 0.2;                     # Opening fraction of bypass valve used
LBPD = 0.399E5;                 # Lower pressure where no pump action taken
UBPD = 0.401E5;                 # Upper pressure where no pump action taken
#
$CONTROL
#
DAMPT = 0.5;
RELXCA = 0.001;
RELXMA = 0.005;
FRLXCA = 0.001;
NLOOP = 500;
NLOOPH=40;
NLOOPT=40;
#
PABS = 1.01E5;
GRAVZ = 9.81;
#
$SUBROUTINES
#
      SUBROUTINE SETINL
C
      IF (QI:COLDPL:3 .LT. 1.0E-3) THEN
         M:TEE1:(1, 2) = MINFLO
C
         CALL STATST('M:TEE1:(1, 2)' , 'OFF')
C
         M(TEE1:2, 4) = MINFLO
C
         CALL STATST('M(TEE1:2, 4)' , 'OFF')
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
C
         M(4, COLDPL:1) = MINFLO
C
         CALL STATST('M(4, COLDPL:1)','OFF')
C
         M:COLDPL:(1, 2) = MINFLO
C
         CALL STATST('M:COLDPL:(1, 2)','OFF')
C
         M(COLDPL:2, 5) = MINFLO
C
         CALL STATST('M(COLDPL:2, 5)','OFF')
C
         M(5, TEE2:2) = MINFLO
C
         CALL STATST('M(5, TEE2:2)','OFF')
C
         M:TEE2:(1, 2) = MINFLO
C
         CALL STATST('M:TEE2:(1, 2)','OFF')
C
      END IF
C
      IF (QI:PL1:3 .LT. 1.0E-3) THEN
         M(7, 12) = MINFLO
         CALL STATST('M(7, 12)','OFF')
C
         M(12, PL1:1) = MINFLO
C
         CALL STATST('M(12, PL1:1)','OFF')
C
         M:PL1:(1, 2) = MINFLO
C
         CALL STATST('M:PL1:(1, 2)','OFF')
C
         M(PL1:2, 13) = MINFLO
C
         CALL STATST('M(PL1:2, 13)','OFF')
C
         M(13, 26) = MINFLO
C
         CALL STATST('M(13, 26)','OFF')
C
      END IF
C
      IF(QI:PL2:3 .LT. 1.0E-3)THEN
         M(7, 14) = MINFLO
C
         CALL STATST('M(7, 14)' , 'OFF')
C
         M(14, PL2:1) = MINFLO
C
         CALL STATST('M(14, PL2:1)' , 'OFF')
C
         M:PL2:(1, 2) = MINFLO
C
         CALL STATST('M:PL2:(1, 2)' , 'OFF')
C
         M(PL2:2, 15) = MINFLO
C
         CALL STATST('M(PL2:2, 15)' , 'OFF')
C
         M(15, 26) = MINFLO
C
         CALL STATST('M(15, 26)' , 'OFF')
C
      END IF
C
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
      IF(QI:PL3:3 .LT. 1.0E-3)THEN
         M(7, 16) = MINFLO
C
         CALL STATST('M(7, 16)','OFF')
C
         M(16, PL3:1) = MINFLO
C
         CALL STATST('M(16, PL3:1)','OFF')
C
         M:PL3:(1, 2) = MINFLO
C
         CALL STATST('M:PL3:(1, 2)','OFF')
C
         M(PL3:2, 17) = MINFLO
C
         CALL STATST('M(PL3:2, 17)','OFF')
C
         M(17, 26) = MINFLO
C
         CALL STATST('M(17, 26)','OFF')
C
      END IF
C
      IF (QI:PL4:3 .LT. 1.0E-3) THEN
         M(7, 18) = MINFLO
C
         CALL STATST('M(7, 18)','OFF')
C
         M(18, PL4:1) = MINFLO
C
         CALL STATST('M(18, PL4:1)','OFF')
C
         M:PL4:(1, 2) = MINFLO
C
         CALL STATST('M:PL4:(1, 2)','OFF')
C
         M(PL4:2, 19) = MINFLO
C
         CALL STATST('M(PL4:2, 19)','OFF')
C
         M(19, 26) = MINFLO
C
         CALL STATST('M(19, 26)','OFF')
C
      END IF
C
      IF(QI:PL7:3 .LT. 1.0E-3)THEN
         M(7, 20) = MINFLO
C
         CALL STATST('M(7, 20)','OFF')
C
         M(20, PL7:1) = MINFLO
C
         CALL STATST('M(20, PL7:1)','OFF')
C
         M:PL7:(1, 2) = MINFLO
C
         CALL STATST('M:PL7:(1, 2)','OFF')
C
         M(PL7:2, 21) = MINFLO
C
         CALL STATST('M(PL7:2, 21)','OFF')
C
         M(21, 26) = MINFLO
C
         CALL STATST('M(21, 26)','OFF')
C
      END IF
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
C
      IF(QI:PL9:3 .LT. 1.0E-3)THEN
         M(7, 22) = MINFLO
C
         CALL STATST('M(7, 22)','OFF')
C
         M(22, PL9:1) = MINFLO
C
         CALL STATST('M(22, PL9:1)','OFF')
C
         M:PL9:(1, 2) = MINFLO
C
         CALL STATST('M:PL9:(1, 2)','OFF')
C
         M(PL9:2, 23) = MINFLO
C
         CALL STATST('M(PL9:2, 23)','OFF')
C
         M(23, 26) = MINFLO
C
         CALL STATST('M(23, 26)','OFF')
C
      END IF
C
      IF(QI:PL10:3 .LT. 1.0E-3)THEN
         M(7, 24) = MINFLO
C
         CALL STATST('M(7, 24)','OFF')
C
         M(24, PL10:1) = MINFLO
C
         CALL STATST('M(24, PL10:1)','OFF')
C
         M:PL10:(1, 2) = MINFLO
C
         CALL STATST('M:PL10:(1, 2)','OFF')
C
         M(PL10:2, 25) = MINFLO
C
         CALL STATST('M(PL10:2, 25)','OFF')
C
         M(25, 26) = MINFLO
C
         CALL STATST('M(25, 26)','OFF')
       END IF
C
C=======================================================================
C
       RETURN
C
C=======================================================================
C
       END
C
C=======================================================================
C
       DOUBLE PRECISION FUNCTION PUMPM()
C
C=======================================================================
C
C LOCALS
C   PDIFF  DOUBLE PRECISION Pressure difference accross Payloads
C   DAMP   DOUBLE PRECISION Damping factor to be used
C   MNEW   DOUBLE PRECISION New mass source
C
C=======================================================================
C
       DOUBLE PRECISION PDIFF , DAMP , MNEW
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
C
C=========================================================================
C
       PARAMETER (DAMP = 1.D0)
C
C Calculate pressure differnce accross payloads
C
       PDIFF = P7 - P26
C
       IF(PDIFF .LT. 1.0E-10) THEN
C
C No pressure difference
C
          PUMPM = FM:VPUMP:2
C
       ELSE
          IF(PDIFF .GT. LBPD .AND. PDIFF .LT. UBPD)THEN
C
C Do not adjust pump speed
C
             PUMPM = FM:VPUMP:2
C
          ELSE
C
             MNEW = SQRT(M(TEE3:1 , 7) ** 2 * 0.4E5 / PDIFF)
             PUMPM = FM:VPUMP:2 + (MNEW - FM:VPUMP:2) / DAMP
C
          END IF
C
       END IF
C
C=========================================================================
C
       RETURN
C
C=========================================================================
C
       END
C
$VARIABLES1
C
C Update pump speed during hydraulic solution
C
      IF (SOLTYP .EQ. 'FLUID') THEN
C
C Calculate mass flow of pump
C
         FM:VPUMP:2 = PUMPM()
         FM:VPUMP:1 = -1.0 * FM:VPUMP:2
      END IF
C
      IF (SOLTYP .EQ. ' ') THEN
C
C Calculate valve char of by-pass valve
C
         IF(T7 .LT. 17.0) THEN
            XNEW = 1.0
         ELSE IF(T7 .GT. 22.0) THEN
            XNEW = 0.001
         ELSE
            XNEW = -1 * 0.1998 * T7 + 4.3966
         END IF
C
C Use GP = RHO * XOPEN ** 2 / (2 * E * A ** 2)  E = 5.0E12 RHO = 1000
C note RHO /(2 * E * A ** 2) = constant = 0.011073
C
         XBYP = XBYP + 0.25 * (XNEW - XBYP)
C
```

Listing 9-1 Model file for single-phase steady state fluid loop

```
         GP(TEE4:2 , 30) = 0.011073 * XBYP ** 2
C
      END IF
C
$EXECUTION DYSTOR = 100000
C
      FORMAT = 'F10.4'
      HEADER = 'Single phase columbus model'
C
C Call subroutine SETINL to set mass flow links inactive to represent
C closed valves (Test for no heat input)
C
      CALL SETINL
C
      CALL FLTNSS
C
$OUTPUTS
      WRITE(6, 9000)
      WRITE(6, 9050) ' '
      WRITE(6, 9050) ' Summary of Operating Conditions - COLSS'
      WRITE(6, 9050) ' ****************************************'
      WRITE(6, 9050) ' '
      WRITE(6, 9100) ' Mass flow through AHX1 = ',M(7,8)
      WRITE(6, 9100) ' Temperature increase over AHX1 = ',T9 - T8
      WRITE(6, 9050) ' '
      WRITE(6, 9100) ' Mass flow through AHX2 = ',M(7,10)
      WRITE(6, 9100) ' Temperature increase over AHX2 = ',T11 - T10
      WRITE(6, 9050) ' '
      WRITE(6, 9100) ' Temperature of by-pass node = ',T7
      WRITE(6, 9100) ' Opening fraction for by-pass valve = ',XBYP
      WRITE(6, 9100) ' GP value for by-pass valve = ',GP(TEE4:2 , 30)
      WRITE(6, 9100) ' Mass flow down by-pass = ',M(TEE4:2 , 30)
      WRITE(6, 9050) ' '
      WRITE(6, 9100) ' Mass flow of pump',FM:VPUMP:2
      WRITE(6, 9100) ' Pressure drop over payloads = ',P7 - P26
C
      CALL PRNDTB(' ','L , T , P , QI' , CURRENT)
      CALL PRNDBL(' ' , 'M , GL',CURRENT)
C
 9000 FORMAT('1')
 9050 FORMAT(1X , A)
 9100 FORMAT(1X , A , E14.4)
C
$ENDMODEL COLSS
```

Listing 9-2 Global file for single-phase steady state fluid loop

```
$USER_ELEMENTS
$MODEL STNHTX


$NODES
F1 = 'INLET',A = %HTXA%,FD=%HTXD%,FL=%HTXL%,P=10.0E5,T=20.0,FF=0.0;
F2 = 'OUTLET',A = %HTXA%,FD=%HTXD%,FL=%HTXL%,P=10.0E5,T=20.0,FF=0.0;
D3 = 'WALL',T=20.0,C=%HTXC%,QI=%HTXQ%;
D4 = 'WALL',T=20.0,C=%HTXC%,QI=%HTXQ%;
$CONDUCTORS
#
# Mass flow links
#
M(1,2)=0.1;
#
```

Listing 9-2 Global file for single-phase steady state fluid loop

```
# Conduction links to the wall
#
GL(1,3) = %HTXCD% ;
GL(2,4) = %HTXCD% ;
#
# Fluid conductance
#
# Constant value taking RHO = 1000 KG/M**3
#
GP(1,2) = %CONGP% ;
#
$ENDMODEL STNHTX
#
$MODEL STNAHX
$NODES
F1='AHX INLET',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0,FF=0.0;
F2='AHX NODE',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0,FF=0.0;
F3='AHX NODE',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0,FF=0.0;
F4='AHX OUTLET',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0, FF=0.0;
#
D5='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
D6='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
D7='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
D8='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
#
$CONDUCTORS
#
# Mass flow links
#
M(1,2) = 0.1 ;
M(2,3) = 0.1 ;
M(3,4) = 0.1 ;
#
# Conduction links to the wall
#
GL(1,5) = %AHTXCD% ;
GL(2,6) = %AHTXCD% ;
GL(3,7) = %AHTXCD% ;
GL(4,8) = %AHTXCD% ;
#
# Fluid conductance - Assuming density = 1000Kg/m**3
#
GP(1,2) = %ACONGP% ;
GP(2,3) = %ACONGP% ;
GP(3,4) = %ACONGP% ;
#
$ENDMODEL STNAHX
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
 Summary of Operating Conditions - COLSS
 ****************************************

 Mass flow through AHX1 =     0.4750E-01
 Temperature increase over AHX1 =     0.1610E+02

 Mass flow through AHX2 =     0.1961E-01
 Temperature increase over AHX2 =     0.7315E+01

 Temperature of by-pass node =     0.2065E+02
 Opening fraction for by-pass valve =     0.2696E+00
 GP value for by-pass valve =     0.8049E-03
 Mass flow down by-pass =     0.2253E-01

 Mass flow of pump    0.1333E+00
 Pressure drop over payloads =     0.4001E+05

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     1
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model




 TIMEN =      0.00      MODULE FLTNSS      LOOPCT =    13
ENBALA =   15.9407      ENBALR = 0.0007    DTCOUR =     0.0000


TABLE OUTPUT WITH ZENTS = 'L,T,P,QI'
FOR NODES OF ZLABEL = ' '

================================================================================

COLSS


         NODE   LABEL                              T             P

        1001    PIPE WALL                        12.09
        1002    PIPE WALL                        12.09
        1003    PIPE WALL                        18.13
        1004    PIPE WALL                        20.00
        1005    PIPE WALL                        20.00
        1006    PIPE WALL                        18.13
        1007    PIPE WALL                        20.65
        1008    PIPE WALL                        20.65
          1009    PIPE WALL                        36.75
        1010    PIPE WALL                        20.65
        1011    PIPE WALL                        27.97
        1012    PIPE WALL                        20.65
        1013    PIPE WALL                        26.69
        1014    PIPE WALL                        20.00
        1015    PIPE WALL                        20.00
        1016    PIPE WALL                        20.00
        1017    PIPE WALL                        20.00
        1018    PIPE WALL                        20.00
        1019    PIPE WALL                        20.00
        1020    PIPE WALL                        20.65
        1021    PIPE WALL                        33.73
        1022    PIPE WALL                        20.00
        1023    PIPE WALL                        20.00
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
        1024    PIPE WALL                        20.65
        1025    PIPE WALL                        31.57
        1026    PIPE WALL                        32.81
        1027    PIPE WALL                        33.08
        1028    PIPE WALL                        33.09
        1029    PIPE WALL                        33.09
        1030    PIPE WALL                        33.09
        9999    IHX B/NODE                        2.00

           1    AFTER IHX                        12.09    1074925.69
           2    BEFORE CHX                       12.09    1069719.68
           3    AFTER CHX                        18.13    1059308.02
           4    BEFORE COLDPL                    20.00    1000000.00
           5    AFTER COLDPL                     20.00    1000000.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     2
21 AUGUST 2006                   12:29:44                                 COLSS

Single phase columbus model




         NODE   LABEL                              T             P

           6    BEFORE BY-PASS                   18.13    1054192.53
           7    TOP HEADER                       20.65    1047376.09
           8    BEFORE AHX1                      20.65    1009825.22
           9    AFTER AHX1                       36.75    1007867.76
          10    BEFORE AHX2                      20.65    1007759.17
          11    AFTER AHX2                       27.97    1007442.72
          12    BEFORE PL1                       20.65    1007521.39
          13    AFTER PL1                        26.69    1007415.76
          14    BEFORE PL2                       20.00    1000000.00
          15    AFTER PL2                        20.00    1000000.00
          16    BEFORE PL3                       20.00    1000000.00
          17    AFTER PL3                        20.00    1000000.00
          18    BEFORE PL4                       20.00    1000000.00
          19    AFTER PL4                        20.00    1000000.00
          20    BEFORE PL7                       20.65    1008112.00
          21    AFTER PL7                        33.72    1007622.66
          22    BEFORE PL9                       20.00    1000000.00
          23    AFTER PL9                        20.00    1000000.00
          24    BEFORE PL10                      20.65    1007524.43
          25    AFTER PL10                       31.57    1007417.22
          26    BOTTOM HEADER                    32.81    1007366.10
          27    BEFORE PUMP                      33.08    1000000.00
          28    AFTER PUMP                       33.09    1090793.18
          29    BEFORE IHX                       33.09    1085313.00
          30    BY-PASS                          33.09    1051805.18


         NODE          QI

        1001          0.00
        1002          0.00
        1003          0.00
        1004          0.00
        1005          0.00
        1006          0.00
        1007          0.00
        1008          0.00
        1009          0.00
        1010          0.00
        1011          0.00
        1012          0.00
        1013          0.00
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
        1014          0.00
        1015          0.00
        1016          0.00
        1017          0.00
        1018          0.00
        1019          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     3
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model




         NODE          QI

        1020          0.00
        1021          0.00
        1022          0.00
        1023          0.00
        1024          0.00
        1025          0.00
        1026          0.00
        1027          0.00
        1028          0.00
        1029          0.00
        1030          0.00
        9999          0.00

           1
           2
           3
           4
           5
           6
           7
           8
           9
          10
          11
          12
          13
          14
          15
          16
          17
          18
          19
          20
          21
          22
          23
          24
          25
          26
          27
          28
          29
          30

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     4
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
COLSS:CHX


        NODE   LABEL                           T             P

          3    WALL                         20.71
          4    WALL                         23.73

          1    INLET                        15.11    1068417.49
          2    OUTLET                       18.13    1060586.97


        NODE          QI

          3       1400.00
          4       1400.00

          1
          2

================================================================================

COLSS:COLDPL


        NODE   LABEL                           T             P

          3    WALL                         20.00
          4    WALL                         20.00

          1    INLET                        20.00    1000000.00
          2    OUTLET                       20.00    1000000.00


        NODE          QI

          3          0.00
          4          0.00

          1
          2

================================================================================

COLSS:PL1


        NODE   LABEL                           T             P

          3    WALL                         24.51
          4    WALL                         27.53

          1    INLET                        23.67    1007498.48
          2    OUTLET                       26.69    1007439.61


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     5
21 AUGUST 2006                  12:29:44                                  COLSS

Single phase columbus model




        NODE          QI
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
           3        210.00
           4        210.00

           1
           2

================================================================================

COLSS:PL2


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1000000.00
           2    OUTLET                           20.00    1000000.00


         NODE          QI

           3          0.00
           4          0.00

           1
           2

================================================================================

COLSS:PL3


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1000000.00
           2    OUTLET                           20.00    1000000.00


         NODE          QI

           3          0.00
           4          0.00

           1
           2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     6
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



COLSS:PL4


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1000000.00
           2    OUTLET                           20.00    1000000.00
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
        NODE          QI

          3         0.00
          4         0.00

          1
          2

================================================================================

COLSS:PL7


        NODE   LABEL                             T             P

          3    WALL                            30.79
          4    WALL                            37.32

          1    INLET                           27.19    1007981.25
          2    OUTLET                          33.72    1007750.77


        NODE          QI

          3       900.00
          4       900.00

          1
          2

================================================================================

COLSS:PL9


        NODE   LABEL                             T             P

          3    WALL                            20.00
          4    WALL                            20.00

          1    INLET                           20.00    1000000.00
          2    OUTLET                          20.00    1000000.00


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     7
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model





        NODE          QI

          3         0.00
          4         0.00

          1
          2

================================================================================

COLSS:PL10


        NODE   LABEL                             T             P
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
          3    WALL                             27.63
          4    WALL                             33.09

          1    INLET                            26.11    1007501.50
          2    OUTLET                           31.57    1007442.57


        NODE          QI

          3       380.00
          4       380.00

          1
          2

================================================================================

COLSS:SCPL


        NODE   LABEL                              T             P

          3    WALL                             33.38
          4    WALL                             33.51

          1    INLET                            32.95    1005575.13
          2    OUTLET                           33.08    1001790.24


        NODE          QI

          3        75.00
          4        75.00

          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     8
21 AUGUST 2006                  12:29:44                                  COLSS

Single phase columbus model



COLSS:IHX


        NODE   LABEL                              T             P

          3    WALL                              3.36
          4    WALL                              2.78

          1    INLET                            19.70    1084061.94
          2    OUTLET                           12.08    1076227.27


        NODE          QI

          3         0.00
          4         0.00

          1
          2

================================================================================

COLSS:AHX1
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
        NODE   LABEL                          T             P

          5    AHX WALL                     31.07
          6    AHX WALL                     35.10
          7    AHX WALL                     39.12
          8    AHX WALL                     43.15

          1    AHX INLET                    24.68    1009562.56
          2    AHX NODE                     28.70    1009081.45
          3    AHX NODE                     32.72    1008599.78
          4    AHX OUTLET                   36.75    1008117.48


        NODE         QI

          5       800.00
          6       800.00
          7       800.00
          8       800.00

          1
          2
          3
          4

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     9
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



COLSS:AHX2


        NODE   LABEL                          T             P

          5    AHX WALL                     23.68
          6    AHX WALL                     25.51
          7    AHX WALL                     27.34
          8    AHX WALL                     29.17

          1    AHX INLET                    22.48    1007725.65
          2    AHX NODE                     24.31    1007643.72
          3    AHX NODE                     26.14    1007561.76
          4    AHX OUTLET                   27.97    1007479.75


        NODE         QI

          5       150.00
          6       150.00
          7       150.00
          8       150.00

          1
          2
          3
          4

================================================================================

COLSS:VPUMP


        NODE   LABEL                          T             P
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
          3    PUMP WALL                         33.09
          4    PUMP WALL                         33.09

          1    MASS SINK                         33.08     998209.76
          2    MASS SOURCE                       33.09    1092583.34


        NODE          QI

          3         0.00
          4         0.00

          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    10
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



COLSS:TEE1


        NODE   LABEL                               T             P


          1                                      12.09    1072322.53
          2                                      20.00    1000000.00


        NODE          QI


          1
          2

================================================================================

COLSS:TEE2


        NODE   LABEL                               T             P


          1                                      18.13    1056750.13
          2                                      20.00    1000000.00


        NODE          QI


          1
          2

================================================================================

COLSS:TEE3


        NODE   LABEL                               T             P


          1                                      20.66    1051641.98
          2                                      33.09    1051690.67
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
         NODE          QI


           1
           2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    11
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



COLSS:TEE4


         NODE   LABEL                             T             P


           1                                    33.09    1087212.87
           2                                    33.09    1087041.87


         NODE          QI


           1
           2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    12
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model





 TIMEN =      0.00      MODULE FLTNSS      LOOPCT =    13
ENBALA =   15.9407      ENBALR = 0.0007    DTCOUR =     0.0000


BLOCK OUTPUT WITH ZENTS = 'M,GL'
FOR NODES OF ZLABEL = ' '


COLSS

VALUES FOR CONDUCTORS M  :
M (1,Z12:2)  =    -0.1108      M (1,Z16:1)  =     0.1108
M (2,Z2:1)   =     0.1108      M (2,Z16:1)  =    -0.1108
M (3,Z2:2)   =    -0.1108      M (3,Z17:1)  =     0.1108
M (4,Z3:1)   =     0.0000 X    M (4,Z16:2)  =     0.0000 X
M (5,Z3:2)   =     0.0000 X    M (5,Z17:2)  =     0.0000 X
M (6,Z17:1)  =    -0.1108      M (6,Z18:1)  =     0.1108
M (7,8)      =     0.0475      M (7,10)     =     0.0196
M (7,12)     =     0.0166      M (7,14)     =     0.0000 X
M (7,16)     =     0.0000 X    M (7,18)     =     0.0000 X
M (7,20)     =     0.0329      M (7,22)     =     0.0000 X
M (7,24)     =     0.0166      M (7,Z18:1)  =    -0.1333
M (8,7)      =    -0.0475      M (8,Z13:1)  =     0.0475
M (9,26)     =     0.0475      M (9,Z13:4)  =    -0.0475
M (10,7)     =    -0.0196      M (10,Z14:1) =     0.0196
M (11,26)    =     0.0196      M (11,Z14:4) =    -0.0196
M (12,7)     =    -0.0166      M (12,Z4:1)  =     0.0166
M (13,26)    =     0.0166      M (13,Z4:2)  =    -0.0166
M (14,7)     =     0.0000 X    M (14,Z5:1)  =     0.0000 X
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
M (15,26)    =     0.0000 X    M (15,Z5:2)  =     0.0000 X
M (16,7)     =     0.0000 X    M (16,Z6:1)  =     0.0000 X
M (17,26)    =     0.0000 X    M (17,Z6:2)  =     0.0000 X
M (18,7)     =     0.0000 X    M (18,Z7:1)  =     0.0000 X
M (19,26)    =     0.0000 X    M (19,Z7:2)  =     0.0000 X
M (20,7)     =    -0.0329      M (20,Z8:1)  =     0.0329
M (21,26)    =     0.0329      M (21,Z8:2)  =    -0.0329
M (22,7)     =     0.0000 X    M (22,Z9:1)  =     0.0000 X
M (23,26)    =     0.0000 X    M (23,Z9:2)  =     0.0000 X
M (24,7)     =    -0.0166      M (24,Z10:1) =     0.0166
M (25,26)    =     0.0166      M (25,Z10:2) =    -0.0166
M (26,9)     =    -0.0475      M (26,11)    =    -0.0196
M (26,13)    =    -0.0166      M (26,15)    =     0.0000 X
M (26,17)    =     0.0000 X    M (26,19)    =     0.0000 X
M (26,21)    =    -0.0329      M (26,23)    =     0.0000 X
M (26,25)    =    -0.0166      M (26,Z11:1) =     0.1333
M (27,Z11:2) =    -0.1333      M (27,Z15:1) =     0.1333
M (28,Z15:2) =    -0.1333      M (28,Z19:1) =     0.1333
M (29,Z12:1) =     0.1108      M (29,Z19:1) =    -0.1108
M (30,Z18:2) =     0.0225      M (30,Z19:2) =    -0.0225

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    13
21 AUGUST 2006                   12:29:44                                 COLSS

Single phase columbus model




VALUES FOR CONDUCTORS GL :
GL(1001,1)     =   173.0376      GL(1002,2)     =   173.0446
GL(1003,3)     =   186.0695      GL(1004,4)     =     6.8968
GL(1005,5)     =     6.8968      GL(1006,6)     =   186.0715
GL(1007,7)     =   198.3546      GL(1008,8)     =    86.8792
GL(1009,9)     =   114.1867      GL(1010,10)    =    12.3094
GL(1011,11)    =    23.1628      GL(1012,12)    =     6.9077
GL(1013,13)    =    11.6650      GL(1014,14)    =     6.8968
GL(1015,15)    =     6.8968      GL(1016,16)    =     6.8968
GL(1017,17)    =     6.8968      GL(1018,18)    =     6.8968
GL(1019,19)    =     6.8968      GL(1020,20)    =    60.7564
GL(1021,21)    =    82.8017      GL(1022,22)    =     6.8968
GL(1023,23)    =     6.8968      GL(1024,24)    =     6.9077
GL(1025,25)    =    16.9480      GL(1026,26)    =   251.3951
GL(1027,27)    =   252.0369      GL(1028,28)    =   252.0517
GL(1029,29)    =   217.3630      GL(1030,30)    =    46.9250
GL(9999,Z12:3) =  4550.0000      GL(9999,Z12:4) =  4550.0000


COLSS:CHX

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.1108      M (1,Z1:2) =    -0.1108
M (2,1)    =    -0.1108      M (2,Z1:3) =     0.1108

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000


COLSS:COLDPL

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:4) =     0.0000 X
M (2,1)    =     0.0000 X    M (2,Z1:5) =     0.0000 X

VALUES FOR CONDUCTORS GL :
GL(3,1) =   175.0000      GL(4,2) =   175.0000
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
COLSS:PL1

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0166      M (1,Z1:12) =    -0.0166
M (2,1)     =    -0.0166      M (2,Z1:13) =     0.0166

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    14
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



COLSS:PL2

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0000 X    M (1,Z1:14) =     0.0000 X
M (2,1)     =     0.0000 X    M (2,Z1:15) =     0.0000 X

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000


COLSS:PL3

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0000 X    M (1,Z1:16) =     0.0000 X
M (2,1)     =     0.0000 X    M (2,Z1:17) =     0.0000 X

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000


COLSS:PL4

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0000 X    M (1,Z1:18) =     0.0000 X
M (2,1)     =     0.0000 X    M (2,Z1:19) =     0.0000 X

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000


COLSS:PL7

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0329      M (1,Z1:20) =    -0.0329
M (2,1)     =    -0.0329      M (2,Z1:21) =     0.0329

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000


COLSS:PL9

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0000 X    M (1,Z1:22) =     0.0000 X
M (2,1)     =     0.0000 X    M (2,Z1:23) =     0.0000 X

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    15
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model





COLSS:PL10

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0166      M (1,Z1:24) =    -0.0166
M (2,1)     =    -0.0166      M (2,Z1:25) =     0.0166

VALUES FOR CONDUCTORS GL :
GL(3,1) =   250.0000      GL(4,2) =   250.0000


COLSS:SCPL

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.1333      M (1,Z1:26) =    -0.1333
M (2,1)     =    -0.1333      M (2,Z1:27) =     0.1333

VALUES FOR CONDUCTORS GL :
GL(3,1) =   175.0000      GL(4,2) =   175.0000


COLSS:IHX

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.1108      M (1,Z1:29) =    -0.1108
M (2,1)     =    -0.1108      M (2,Z1:1)  =     0.1108

VALUES FOR CONDUCTORS GL :
GL(3,Z1:9999) =  4550.0000      GL(3,1)       =   380.0000
GL(4,Z1:9999) =  4550.0000      GL(4,2)       =   380.0000


COLSS:AHX1

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0475      M (1,Z1:8) =    -0.0475
M (2,1)    =    -0.0475      M (2,3)    =     0.0475
M (3,2)    =    -0.0475      M (3,4)    =     0.0475
M (4,3)    =    -0.0475      M (4,Z1:9) =     0.0475

VALUES FOR CONDUCTORS GL :
GL(5,1) =   125.0000      GL(6,2) =   125.0000      GL(7,3) =   125.0000
GL(8,4) =   125.0000


COLSS:AHX2

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0196      M (1,Z1:10) =    -0.0196
M (2,1)     =    -0.0196      M (2,3)     =     0.0196

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    16
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
M (3,2)     =    -0.0196      M (3,4)     =     0.0196
M (4,3)     =    -0.0196      M (4,Z1:11) =     0.0196

VALUES FOR CONDUCTORS GL :
GL(5,1) =   125.0000      GL(6,2) =   125.0000      GL(7,3) =   125.0000
GL(8,4) =   125.0000


COLSS:VPUMP

VALUES FOR CONDUCTORS M  :
M (1,Z1:27) =    -0.1333      M (2,Z1:28) =     0.1333

VALUES FOR CONDUCTORS GL :
GL(3,1) =   252.0407      GL(4,2) =   252.0461


COLSS:TEE1

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:1) =    -0.1108
M (1,Z1:2) =     0.1108      M (2,1)    =     0.0000 X
M (2,Z1:4) =     0.0000 X


COLSS:TEE2

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:3) =    -0.1108
M (1,Z1:6) =     0.1108      M (2,1)    =     0.0000 X
M (2,Z1:5) =     0.0000 X


COLSS:TEE3

VALUES FOR CONDUCTORS M  :
M (1,2)     =    -0.0225      M (1,Z1:6)  =    -0.1108
M (1,Z1:7)  =     0.1333      M (2,1)     =     0.0225
M (2,Z1:30) =    -0.0225


COLSS:TEE4

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0225      M (1,Z1:28) =    -0.1333
M (1,Z1:29) =     0.1108      M (2,1)     =    -0.0225
M (2,Z1:30) =     0.0225

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    17
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



 KEY FOR SUB-MODEL CODE :


Z1 = COLSS


Z2 = COLSS:CHX


Z3 = COLSS:COLDPL
```

Listing 9-3 Output for single-phase steady state fluid loop model

```
Z4 = COLSS:PL1

Z5 = COLSS:PL2

Z6 = COLSS:PL3

Z7 = COLSS:PL4

Z8 = COLSS:PL7

Z9 = COLSS:PL9

Z10 = COLSS:PL10

Z11 = COLSS:SCPL

Z12 = COLSS:IHX

Z13 = COLSS:AHX1

Z14 = COLSS:AHX2

Z15 = COLSS:VPUMP

Z16 = COLSS:TEE1



EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    18
21 AUGUST 2006                   12:29:44                                  COLSS

Single phase columbus model



Z17 = COLSS:TEE2

Z18 = COLSS:TEE3

Z19 = COLSS:TEE4
```

Example 10 A Single-Phase Transient Fluid Loop

This example illustrates the use of the single phase transient routine `FLTNTS`. The fluid network is identical to the single-phase steady state model. The heat loads to the heat exchangers are modified prior to the transient. As heat loads are now added to payloads PL2, PL3, PL4 and PL9 the user defined subroutine `SETINL` is called to switch the links within these branches active.

Due to more heat exchangers within the bank of payloads now being active, the mass flow rate increases to maintain a pressure drop of 0.4 bar over these components. To avoid the change in mass flow rate in the system occurring immediately, a damping factor of 15 seconds is used for the pump response.

The function `ACLOSS` is called to model the expansion and contraction losses at the entry and exit of the pump. Also, the function `NUVRE` is called to model the heat transfer from the fluid to the pipe wall. This function interpolates on the user defined array `NRHT` containing Reynold number versus Nusselt number pairs.

The solution routine `FLTNTS` allows the user to define the time step to be used by setting the control constant `DTIMEI`. In this example an initial time step of 1.0 second is used but for subsequent steps the time step length is set equal to the Courant limiting time step. This is carried out by setting `DTIMEI` equal to `DTCOUR` within the `$VARIABLES2` block.

The control constants `DTIMEI`, `TIMEND`, `OUTINT, NLOOP, NLOOPT, NLOOPH, RELXCA,` `FRLXCA` and `RELXMA` need to be defined. In addition `TIMEO` can be specified if different from zero and also `DTMIN, DTMAX` and `DTPMAX` to impose further restrictions upon the time step. During the transient the property output routine `PRNDPT` is called to output the volumetric flow rate (VFLO), the fluid velocity (U), the Reynolds number (RE) and the fluid density (RHO).

Listing 10-1 Model file for single-phase transient fluid loop

```
$MODEL COLTR, FLUID = WATER, GLOBALFILE=coltr.gbl
#
#
# Single phase columbus model
# Starting from steady state case 9 - change heat loads to
# payloads and run transient
#
# Cabin heat exchanger
#
   $MODEL CHX,FLUID=WATER
#
# Use standard heat exchanger model
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.1818;    # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 5.261;     # length of each node (m)
   HTXC = 2500.0;    # Capacitance of wall (J/K)
   HTXQ = 1400.0;    # Heat source at wall node
   HTXCD = 250.0;    # Conductance value between fluid and wall (W/K)
   CONGP = 0.08684;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL CHX
#
   $MODEL COLDPL, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;  # Heat transfer area (sq m)
   HTXD = 0.011;    # Pipe diameter (m)
   HTXL = 2.631;    # length of each node (m)
   HTXC = 1250.0;   # Capacitance of wall (J/K)
   HTXQ = 0.0;      # Heat source at wall node
   HTXCD = 175.0;   # Conductance value (W/K)
   CONGP = 0.2613;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL COLDPL
#
# Generate parallel payloads PL1, PL2, PL3, PL4, PL7, PL9 & PL10
#
   $MODEL PL1, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 210.0;      # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL1
#
   $MODEL PL2, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
```

Listing 10-1 Model file for single-phase transient fluid loop

```
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 0.0;        # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL2
#
   $MODEL PL3, FLUID = WATER
#
      $REPEAT PL2
#
   $ENDMODEL PL3
#
   $MODEL PL4, FLUID = WATER
#
      $REPEAT PL2
#
   $ENDMODEL PL4
#
   $MODEL PL7, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 900.0;      # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL7
#
   $MODEL PL9, FLUID = WATER
#
      $REPEAT PL2
#
   $ENDMODEL PL9
#
   $MODEL PL10, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.09091;    # Heat transfer area (sq m)
   HTXD = 0.011;      # Pipe diameter (m)
   HTXL = 2.631;      # length of each node (m)
   HTXC = 1250.0;     # Capacitance of wall (J/K)
   HTXQ = 380.0;      # Heat source at wall node
   HTXCD = 250.0;     # Conductance value (W/K)
   CONGP = 0.2613;    # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL PL10
#
   $MODEL SCPL, FLUID = WATER
#
# SCPL has the same pressure drop - flow rate curve as COLDPL
# and also the same U*A value. Heat source constant
#
   $ELEMENT STNHTX
#
```

Listing 10-1 Model file for single-phase transient fluid loop

```
   $SUBSTITUTIONS
#
   HTXA = 0.09091;   # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 2.631;     # length of each node (m)
   HTXC = 1250.0;    # Capacitance of wall (J/K)
   HTXQ = 75.0;      # Heat source at wall node
   HTXCD = 175.0;    # Conductance value (W/K)
   CONGP = 0.2613;   # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL SCPL
#
   $MODEL IHX, FLUID = WATER
#
   $ELEMENT STNHTX
#
   $SUBSTITUTIONS
#
   HTXA = 0.3636;    # Heat transfer area (sq m)
   HTXD = 0.011;     # Pipe diameter (m)
   HTXL = 10.523;    # length of each node (m)
   HTXC = 7500.0;    # Capacitance of wall (J/K)
   HTXQ = 0.0;       # Heat source at wall node
   HTXCD = 380.0;    # Conductance value (W/K)
   CONGP = 0.08684;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL IHX
#
   $MODEL AHX1, FLUID = WATER
#
# Uses standard elements STNAHX - 4 nodes per model
#
   $ELEMENT STNAHX
#
   $SUBSTITUTIONS
#
   AHTXA = 0.09091;   # Heat transfer area per fluid node (sq m)
   AHTXD = 0.011;     # Pipe diameter (m)
   AHTXL = 2.631;     # Length of node (m)
   AHTXC = 1250.0;    # Wall capacitance (J/K)
   AHTXQ = 800.0;     # Heat source per node (W)
   AHTXCD = 125.0;    # Coductivity from fluid to wall (W/K)
   ACONGP = 0.26052;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL AHX1
#
   $MODEL AHX2, FLUID = WATER
#
   $ELEMENT STNAHX
#
   $SUBSTITUTIONS
#
   AHTXA = 0.09091;   # Heat transfer area per fluid node (sq m)
   AHTXD = 0.011;     # Pipe diameter (m)
   AHTXL = 2.631;     # Length of node (m)
   AHTXC = 1250.0;    # Wall capacitance (J/K)
   AHTXQ = 150.0;     # Heat source per node (W)
   AHTXCD = 125.0;    # Coductivity from fluid to wall (W/K)
   ACONGP = 0.26052;  # Constant GP value with rho=1000 Kg/m**3
#
   $ENDMODEL AHX2
#
   $MODEL VPUMP, FLUID = WATER
#
# Variable speed pump modelled as a mass source and sink
# Used to regulate pressure drop over payloads to 0.39 - 0.41 bar
#
   $NODES
```

Listing 10-1 Model file for single-phase transient fluid loop

```
#
   F1 = 'MASS SINK', A = 0.1, FD = 0.02, FL = 1.592,
   P = 10.0E5, T = 20.0, FF = 0.0, FM = -0.1, FR = T1 ;
#
   F2 = 'MASS SOURCE', A = 0.1, FD = 0.02, FL = 1.592,
   P = 10.0E5, T = 20.0, FF = 0.0, FM = 0.1, FR = T1 ;
#
   D3 = 'PUMP WALL', T =20.0, C = 750.0 ;
   D4 = 'PUMP WALL', T =20.0, C = 750.0 ;
#
   $CONDUCTORS
#
# Conduction links to pipe wall
#
   GL(1, 3) = * ;
   GL(2, 4) = * ;
#
   $ENDMODEL VPUMP
#
   $MODEL TEE1, FLUID = WATER
#
# Use library tee piece element to model momentum
# losses due to a 90 degree bend
#
   $ELEMENT TEE
#
   $SUBSTITUTIONS
#
   TA1 = 0.03456 ; TFD1 = 0.011 ; TFL1 = 1.0 ; TP1 = 10.0E5 ;
   TFE1 = 83.6E3 ; TT1 = 20.0 ; TFF1 = 0.1E-3 ;
#
   TA2 = 0.03456 ; TFD2 = 0.011 ; TFL2 = 1.0 ; TP2 = 10.0E5 ;
   TFE2 = 83.6E3 ; TT2 = 20.0 ; TFF2 = 0.1E-3 ;
#
   MFLOW = 0.01 ;
#
   TGP = 1.0E10 ;
#
   $ENDMODEL TEE1
#
   $MODEL TEE2, FLUID = WATER
#
      $REPEAT TEE1
#
   $ENDMODEL TEE2
#
   $MODEL TEE3, FLUID = WATER
#
      $REPEAT TEE1
#
   $ENDMODEL TEE3
#
   $MODEL TEE4, FLUID = WATER
#
      $REPEAT TEE1
#
   $ENDMODEL TEE4
#
# Main model
#
$LOCALS
#
# Initialisation values for GP's of orifice payloads
#
$REAL
#
# GP = 0.5 * RO * (MAXFR/A) ** 2 /DELTAP
#
```

Listing 10-1 Model file for single-phase transient fluid loop

```
# These used if density assumed constant = 1000 Kg/m**3
#
RL1 = 3.86E-4;   # GP for orifice for payload 1 MAXFR = 1.67 E-5
RL2 = 3.86E-4;   # GP for orifice for payload 2 MAXFR = 1.67 E-5
RL3 = 3.86E-4;   # GP for orifice for payload 3 MAXFR = 1.67 E-5
RL4 = 9.6E-5;    # GP for orifice for payload 4 MAXFR = 8.33 E -6
RL7 = 1.54E-3;   # GP for orifice for payload 7 MAXFR = 3.34 E-5
RL9 = 1.54E-3;   # GP for orifice for payload 9 MAXFR = 3.34 E-5
RL10 = 3.86E-4;  # GP for orifice for payload 10 MAXFR = 1.67 E-5
#
# Heat transfer area for nodes
#
RL20 = 0.03456;      # HTA for pipe nodes 1m long
#
# Thermal node pipe capacitance
#
RL30 = 107.973;      #Capacitance of pipe wall V*RHO*Cp - 1m pipes
#
$NODES
#
##########################################
# Generate fluid nodes along the pipe work
##########################################
#
F1 = 'AFTER IHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F2 = 'BEFORE CHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F3 = 'AFTER CHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F4 = 'BEFORE COLDPL',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F5 = 'AFTER COLDPL',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F6 = 'BEFORE BY-PASS',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F7 = 'TOP HEADER',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F8 = 'BEFORE AHX1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F9 = 'AFTER AHX1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F10 = 'BEFORE AHX2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F11 = 'AFTER AHX2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F12 = 'BEFORE PL1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F13 = 'AFTER PL1',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F14 = 'BEFORE PL2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F15 = 'AFTER PL2',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F16 = 'BEFORE PL3',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F17 = 'AFTER PL3',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F18 = 'BEFORE PL4',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F19 = 'AFTER PL4',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F20 = 'BEFORE PL7',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F21 = 'AFTER PL7',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F22 = 'BEFORE PL9',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
```

Listing 10-1 Model file for single-phase transient fluid loop

```
F23 = 'AFTER PL9',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F24 = 'BEFORE PL10',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F25 = 'AFTER PL10',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F26 = 'BOTTOM HEADER',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
J27 = 'BEFORE PUMP',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F28 = 'AFTER PUMP',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F29 = 'BEFORE IHX',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
F30 = 'BY-PASS',A=RL20,FD=0.011,FL=1.0,P=10.0E5,FF=0.1E-3,T=20.0;
#
####################################
# Generate nodes along the pipe wall
####################################
#
#  Node length 1.0 m
#
FOR KL1 = 1001 TO 1030 DO
   DKL1 = 'PIPE WALL',T=20.0,C= RL30;
END DO
#
# Thermal boundary node for the IHX heat exchanger
#
B9999 = 'IHX B/NODE',T=2.0;
#
$CONDUCTORS
#
#########################################
# Generate mass flow links along the pipe
#########################################
#
M(1, TEE1:1) = 0.1;
M(TEE1:1, 2) = 0.1;
M(2, CHX:1) = 0.1;
M(CHX:2, 3) = 0.1;
M(3, TEE2:1) = 0.1;
M(TEE2:1, 6) = 0.1;
M(TEE1:2, 4) = 0.1;
M(4, COLDPL:1) = 0.1;
M(COLDPL:2, 5) = 0.1;
M(5, TEE2:2) = 0.1;
M(6, TEE3:1) = 0.1;
M(TEE3:1, 7) = 0.1;
#
# Top header links
#
M(7, 8) = 0.01;
M(7, 10) = 0.01;
M(7, 12) = 0.01;
M(7, 14) = 0.01;
M(7, 16) = 0.01;
M(7, 18) = 0.01;
M(7, 20) = 0.01;
M(7, 22) = 0.01;
M(7, 24) = 0.01;
#
M(8, AHX1:1) = 0.01;
M(AHX1:4, 9) = 0.01;
M(10, AHX2:1) = 0.01;
M(AHX2:4, 11) = 0.01;
M(12, PL1:1) = 0.01;
M(PL1:2, 13) = 0.01;
M(14, PL2:1) = 0.01;
```

Listing 10-1 Model file for single-phase transient fluid loop

```
M(PL2:2, 15) = 0.01;
M(16, PL3:1) = 0.01;
M(PL3:2, 17) = 0.01;
M(18, PL4:1) = 0.01;
M(PL4:2, 19) = 0.01;
M(20, PL7:1) = 0.01;
M(PL7:2, 21) = 0.01;
M(22, PL9:1) = 0.01;
M(PL9:2, 23) = 0.01;
M(24, PL10:1) = 0.01;
M(PL10:2, 25) = 0.01;
#
# Bottom header links
#
M(9, 26) = 0.01;
M(11, 26) = 0.01;
M(13, 26) = 0.01;
M(15, 26) = 0.01;
M(17, 26) = 0.01;
M(19, 26) = 0.01;
M(21, 26) = 0.01;
M(23, 26) = 0.01;
M(25, 26) = 0.01;
#
M(26, SCPL:1) = 0.1;
M(SCPL:2, 27) = 0.1;
M(27, VPUMP:1) = 0.1;
M(VPUMP:2, 28) = 0.1;
M(28, TEE4:1) = 0.1;
M(TEE4:1, 29) = 0.1;
M(29, IHX:1) = 0.1;
M(IHX:2, 1) = 0.1;
#
M(TEE4:2, 30) = 0.1;
M(30, TEE3:2) = 0.1;
#
#################################################################
# Generate conduction links from the fluid nodes to the pipe wall
# Use function NUVRE (Nusselt No versus Reynolds number)
#################################################################
#
FOR KL1 = 1 TO 30 DO
   KL2 = KL1 + 1000;
   GL(KL1, KL2) = NUVRE(FKL1, NRHT);
END DO
#
###################################################
# IHX intermodel links to the thermal boundary node
###################################################
#
GL(IHX:3, 9999) = 4550.0;
GL(IHX:4, 9999) = 4550.0;
#
GP(TEE1:2, 4) = 0.01140 ; # Orifice within by-pass for CHX
#
########################
# Set up payload orifices
########################
#
# pipe length before (PL1)
#
GP(7, 12) = RL1;
#
# pipe length before (PL2)
#
GP(7, 14) = RL2;
#
# Pipe length before (PL3)
```

Listing 10-1 Model file for single-phase transient fluid loop

```
#
GP(7, 16) = RL3;
#
# Pipe length before (PL4)
#
GP(7, 18) = RL4;
#
# Pipe length before (PL7)
#
GP(7, 20) = RL7;
#
# Pipe length before (PL9)
#
GP(7, 22) = RL9;
#
# Pipe length before (PL10)
#
GP(7, 24) = RL10;
#
########################
# AHX1 and AHX2 orifices
########################
#
GP(7, 8) = 3.38E-3;
GP(7, 10) = 5.393E-4;
#
############################
# BY-PASS V2WM control valve
############################
#
GP(TEE4:2, 30) = 4.429E-4; # Set at valve opening of 0.2
#
########################################################
# Expansion and contraction losses to VPUMP using ACLOSS
########################################################
#
GP(27, VPUMP:1) = ACLOSS(F27, F:VPUMP:1);
GP(VPUMP:2, 28) = ACLOSS(F:VPUMP:2, F28);
#
$CONSTANTS
#
$INTEGER
#
COUNT = 0;      # Counter for solution number
#
$REAL
#
XNEW = 0.2;     # New valve opening fraction before damping
XBYP = 0.2;     # Opening fraction of bypass valve used
LBPD = 0.399E5; # Lower pressure where no pump action taken
UBPD = 0.401E5; # Upper pressure where no pump action taken
#
$CONTROL
#
DAMPT = 0.5;
RELXCA = 0.01;
RELXMA = 0.005;
FRLXCA = 0.01;
NLOOP = 50;
TIMEO = 0.0;
TIMEND = 60.0;
OUTINT = 60.0;
DTIMEI = 1.0;
#
PABS = 1.01E5;
GRAVZ = 9.81;
#
$ARRAYS
```

Listing 10-1 Model file for single-phase transient fluid loop

```
#
# Array defining Reynolds number against Nusselt number
#
$REAL
#
NRHT(2,8) = 4000.0, 214.0, 8000.0, 296.0, 12000.0,
            373.0, 16000.0, 446.0, 20000.0, 776.0, 40000.0,
            1351.0, 80000.0, 1992.0, 130000.0, 2000.0 ;
#
$SUBROUTINES
#
      SUBROUTINE SETINL
C
      IF(QI:COLDPL:3 .LT. 1.0E-3)THEN
         M:TEE1:(1, 2) = MINFLO
C
         CALL STATST('M:TEE1:(1, 2)', 'OFF')
C
         M(TEE1:2, 4) = MINFLO
C
         CALL STATST('M(TEE1:2, 4)', 'OFF')
C
         M(4, COLDPL:1) = MINFLO
C
         CALL STATST('M(4, COLDPL:1)','OFF')
C
         M:COLDPL:(1, 2) = MINFLO
C
         CALL STATST('M:COLDPL:(1, 2)','OFF')
C
         M(COLDPL:2, 5) = MINFLO
C
         CALL STATST('M(COLDPL:2, 5)','OFF')
C
         M(5, TEE2:2) = MINFLO
C
         CALL STATST('M(5, TEE2:2)','OFF')
C
         M:TEE2:(1, 2) = MINFLO
C
         CALL STATST('M:TEE2:(1, 2)','OFF')
C
      ELSE
C
         CALL STATST('M:TEE1:(1, 2)', 'ON')
C
         CALL STATST('M(TEE1:2, 4)', 'ON')
C
         CALL STATST('M(4, COLDPL:1)','ON')
C
         CALL STATST('M:COLDPL:(1, 2)','ON')
C
         CALL STATST('M(COLDPL:2, 5)','ON')
C
         CALL STATST('M(5, TEE2:2)','ON')
C
         CALL STATST('M:TEE2:(1, 2)','ON')
C
      END IF
C
      IF(QI:PL1:3 .LT. 1.0E-3)THEN
         M(7, 12) = MINFLO
C
         CALL STATST('M(7, 12)','OFF')
C
         M(12, PL1:1) = MINFLO
C
         CALL STATST('M(12, PL1:1)','OFF')
```

Listing 10-1 Model file for single-phase transient fluid loop

```
C
         M:PL1:(1, 2) = MINFLO
C
         CALL STATST('M:PL1:(1, 2)','OFF')
C
         M(PL1:2, 13) = MINFLO
C
         CALL STATST('M(PL1:2, 13)','OFF')
C
         M(13, 26) = MINFLO
C
         CALL STATST('M(13, 26)','OFF')
C
      ELSE
C
         CALL STATST('M(7, 12)','ON')
C
         CALL STATST('M(12, PL1:1)','ON')
C
         CALL STATST('M:PL1:(1, 2)','ON')
C
         CALL STATST('M(PL1:2, 13)','ON')
C
         CALL STATST('M(13, 26)','ON')
C
      END IF
C
      IF(QI:PL2:3 .LT. 1.0E-3)THEN
         M(7, 14) = MINFLO
C
         CALL STATST('M(7, 14)', 'OFF')
C
         M(14, PL2:1) = MINFLO
C
         CALL STATST('M(14, PL2:1)', 'OFF')
C
         M:PL2:(1, 2) = MINFLO
C
         CALL STATST('M:PL2:(1, 2)', 'OFF')
C
         M(PL2:2, 15) = MINFLO
C
         CALL STATST('M(PL2:2, 15)', 'OFF')
C
         M(15, 26) = MINFLO
C
         CALL STATST('M(15, 26)', 'OFF')
C
      ELSE
C
         CALL STATST('M(7, 14)', 'ON')
C
         CALL STATST('M(14, PL2:1)', 'ON')
C
         CALL STATST('M:PL2:(1, 2)', 'ON')
C
         CALL STATST('M(PL2:2, 15)', 'ON')
C
         CALL STATST('M(15, 26)', 'ON')
C
      END IF
C
      IF(QI:PL3:3 .LT. 1.0E-3)THEN
         M(7, 16) = MINFLO
C
         CALL STATST('M(7, 16)','OFF')
C
         M(16, PL3:1) = MINFLO
```

Listing 10-1 Model file for single-phase transient fluid loop

```
C
         CALL STATST('M(16, PL3:1)','OFF')
C
         M:PL3:(1, 2) = MINFLO
C
         CALL STATST('M:PL3:(1, 2)','OFF')
C
         M(PL3:2, 17) = MINFLO
C
         CALL STATST('M(PL3:2, 17)','OFF')
C
         M(17, 26) = MINFLO
C
         CALL STATST('M(17, 26)','OFF')
C
      ELSE
C
         CALL STATST('M(7, 16)','ON')
C
         CALL STATST('M(16, PL3:1)','ON')
C
         CALL STATST('M:PL3:(1, 2)','ON')
C
         CALL STATST('M(PL3:2, 17)','ON')
C
         CALL STATST('M(17, 26)','ON')
C
      END IF
C
      IF(QI:PL4:3 .LT. 1.0E-3)THEN
         M(7, 18) = MINFLO
C
         CALL STATST('M(7, 18)','OFF')
C
         M(18, PL4:1) = MINFLO
C
         CALL STATST('M(18, PL4:1)','OFF')
C
         M:PL4:(1, 2) = MINFLO
C
         CALL STATST('M:PL4:(1, 2)','OFF')
C
         M(PL4:2, 19) = MINFLO
C
         CALL STATST('M(PL4:2, 19)','OFF')
C
         M(19, 26) = MINFLO
C
         CALL STATST('M(19, 26)','OFF')
C
      ELSE
C
         CALL STATST('M(7, 18)','ON')
C
         CALL STATST('M(18, PL4:1)','ON')
C
         CALL STATST('M:PL4:(1, 2)','ON')
C
         CALL STATST('M(PL4:2, 19)','ON')
C
         CALL STATST('M(19, 26)','ON')
C
      END IF
C
      IF(QI:PL7:3 .LT. 1.0E-3)THEN
         M(7, 20) = MINFLO
C
         CALL STATST('M(7, 20)','OFF')
```

Listing 10-1 Model file for single-phase transient fluid loop

```
C
          M(20, PL7:1) = MINFLO
C
          CALL STATST('M(20, PL7:1)','OFF')
C
          M:PL7:(1, 2) = MINFLO
C
          CALL STATST('M:PL7:(1, 2)','OFF')
C
          M(PL7:2, 21) = MINFLO
C
          CALL STATST('M(PL7:2, 21)','OFF')
C
          M(21, 26) = MINFLO
C
          CALL STATST('M(21, 26)','OFF')
C
       ELSE
C
          CALL STATST('M(7, 20)','ON')
C
          CALL STATST('M(20, PL7:1)','ON')
C
          CALL STATST('M:PL7:(1, 2)','ON')
C
          CALL STATST('M(PL7:2, 21)','ON')
C
          CALL STATST('M(21, 26)','ON')
C
       END IF
C
       IF(QI:PL9:3 .LT. 1.0E-3)THEN
          M(7, 22) = MINFLO
C
          CALL STATST('M(7, 22)','OFF')
C
          M(22, PL9:1) = MINFLO
C
          CALL STATST('M(22, PL9:1)','OFF')
C
          M:PL9:(1, 2) = MINFLO
C
          CALL STATST('M:PL9:(1, 2)','OFF')
C
          M(PL9:2, 23) = MINFLO
C
          CALL STATST('M(PL9:2, 23)','OFF')
C
          M(23, 26) = MINFLO
C
          CALL STATST('M(23, 26)','OFF')
C
       ELSE
C
          CALL STATST('M(7, 22)','ON')
C
          CALL STATST('M(22, PL9:1)','ON')
C
          CALL STATST('M:PL9:(1, 2)','ON')
C
          CALL STATST('M(PL9:2, 23)','ON')
C
          CALL STATST('M(23, 26)','ON')
C
       END IF
C
       IF(QI:PL10:3 .LT. 1.0E-3)THEN
          M(7, 24) = MINFLO
```

Listing 10-1 Model file for single-phase transient fluid loop

```
C
         CALL STATST('M(7, 24)','OFF')
C
         M(24, PL10:1) = MINFLO
C
         CALL STATST('M(24, PL10:1)','OFF')
C
         M:PL10:(1, 2) = MINFLO
C
         CALL STATST('M:PL10:(1, 2)','OFF')
C
         M(PL10:2, 25) = MINFLO
C
         CALL STATST('M(PL10:2, 25)','OFF')
C
         M(25, 26) = MINFLO
C
         CALL STATST('M(25, 26)','OFF')
C
       ELSE
C
         CALL STATST('M(7, 24)','ON')
C
         CALL STATST('M(24, PL10:1)','ON')
C
         CALL STATST('M:PL10:(1, 2)','ON')
C
         CALL STATST('M(PL10:2, 25)','ON')
C
         CALL STATST('M(25, 26)','ON')
C
       END IF
C
C=======================================================================
C
       RETURN
C
C=======================================================================
C
       END
C
C=======================================================================
C
       DOUBLE PRECISION FUNCTION PUMPM()
C
C=======================================================================
C
C LOCALS
C   PDIFF  DOUBLE PRECISION Pressure difference accross Payloads
C   DAMP   DOUBLE PRECISION Damping factor to be used
C   MNEW   DOUBLE PRECISION New mass source
C
C=======================================================================
C
       DOUBLE PRECISION PDIFF, DAMP, MNEW
C
C=======================================================================
C
       IF(MODULE .EQ. 'FLTNSS')THEN
          DAMP = 1.0
       ELSE
C
          IF(DTIMEU .GE. 15.0)THEN
             DAMP = 1.0
          ELSE
             DAMP = 15.0 / DTIMEU
          END IF
C
```

Listing 10-1 Model file for single-phase transient fluid loop

```
       END IF
C
C Calculate pressure differnce accross payloads
C
       PDIFF = P7 - P26
C
       IF(PDIFF .LT. 1.0E-10) THEN
C
C No pressure difference
C
          PUMPM = FM:VPUMP:2
       ELSE
C
          IF(PDIFF .GT. LBPD .AND. PDIFF .LT. UBPD)THEN
C
C Do not adjust pump speed
C
             PUMPM = FM:VPUMP:2
          ELSE
             MNEW = SQRT(M(TEE3:1, 7) ** 2 * 0.4E5 / PDIFF)
             PUMPM = FM:VPUMP:2 + (MNEW - FM:VPUMP:2) / DAMP
C
          END IF
C
       END IF
C
C=====================================================================
C
       RETURN
C
C=====================================================================
C
       END
C
$VARIABLES1
C
C Calculate mass flow of pump
C
      IF(SOLTYP .EQ. 'FLUID')THEN
         FM:VPUMP:2 = PUMPM()
         FM:VPUMP:1 = -1.0 * FM:VPUMP:2
      END IF
C
$VARIABLES2
C
      DOUBLE PRECISION DAMP
C
C LOCALS:
C DAMP   DOUBLE PRECISION Damping factor used
C
C Damping factor = 0.25 for steady state analysis
C Damping factor = 1.0 for transient analysis
C
      IF(MODULE .EQ. 'FLTNSS')THEN
         DAMP = 0.25
      ELSE
         DAMP = 1.0
      END IF
C
C Calculate valve char of by-pass valve
C
      IF(T7 .LT. 17.0) THEN
         XNEW = 1.0
C
      ELSE IF(T7 .GT. 22.0) THEN
         XNEW = 0.001
      ELSE
         XNEW = -1 * 0.1998 * T7 + 4.3966
```

Listing 10-1 Model file for single-phase transient fluid loop

```
      END IF
C
C Use GP=RHO*XOPEN**2/(2*E*A**2)  E=5.0E12 RHO=1000
C note RHO /(2*E*A**2) = constant = 0.011073
C
      XBYP = XBYP + DAMP * (XNEW - XBYP)
C
      GP(TEE4:2, 30) = 0.011073 * XBYP ** 2
C
      IF(MODULE .EQ. 'FLTNTS')THEN
C
C Set the time step equal to the Courant limiting time step
C
         DTIMEI = DTCOUR
      END IF
C
$EXECUTION DYSTOR=100000
C
      FORMAT = 'F10.4'
      HEADER = 'Single phase columbus model - transient analysis'
C
C Call subroutine SETINL to set mass flow links inactive to represent
C closed valves (Test for no heat input)
C
      CALL SETINL
C
C Set up conditions for transient
C Switch power on too payloads PL2, PL3, PL4, PL9
C
      QI:CHX:3 = 1400.0
      QI:CHX:4 = 1400.0
      QI:COLDPL:3 = 0.0
      QI:COLDPL:4 = 0.0
      QI:AHX1:5 = 350.0
      QI:AHX1:6 = 350.0
      QI:AHX1:7 = 350.0
      QI:AHX1:8 = 350.0
      QI:AHX2:5 = 150.0
      QI:AHX2:6 = 150.0
      QI:AHX2:7 = 150.0
      QI:AHX2:8 = 150.0
      QI:PL1:3 = 315.0
      QI:PL1:4 = 315.0
      QI:PL2:3 = 125.0
      QI:PL2:4 = 125.0
      QI:PL3:3 = 200.0
      QI:PL3:4 = 200.0
      QI:PL4:3 = 185.0
      QI:PL4:4 = 185.0
      QI:PL7:3 = 1000.0
      QI:PL7:4 = 1000.0
      QI:PL9:3 = 375.0
      QI:PL9:4 = 375.0
      QI:PL10:3 = 190.0
      QI:PL10:4 = 190.0
C
      CALL SETINL
C
      CALL FLTNTS
C
$OUTPUTS
C
      CALL PRNDTB(' ','L, T, P, QI', CURRENT)
      CALL PRNDBL(' ', 'M ',CURRENT)
      CALL PRNDPT(' ', 'VFLO, U, RE, RHO', CURRENT)
C
$ENDMODEL COLTR
```

Listing 10-2 Global file for single-phase transient fluid loop

```
$USER_ELEMENTS
$MODEL STNHTX


$NODES
F1 = 'INLET',A = %HTXA%,FD=%HTXD%,FL=%HTXL%,P=10.0E5,T=20.0,FF=0.0;
F2 = 'OUTLET',A = %HTXA%,FD=%HTXD%,FL=%HTXL%,P=10.0E5,T=20.0,FF=0.0;
D3 = 'WALL',T=20.0,C=%HTXC%,QI=%HTXQ%;
D4 = 'WALL',T=20.0,C=%HTXC%,QI=%HTXQ%;
$CONDUCTORS
#
# Mass flow links
#
M(1,2)=0.1;
#
# Conduction links to the wall
#
GL(1,3) = %HTXCD% ;
GL(2,4) = %HTXCD% ;
#
# Fluid conductance
#
# Constant value taking RHO = 1000 KG/M**3
#
GP(1,2) = %CONGP% ;
#
$ENDMODEL STNHTX
#
$MODEL STNAHX
$NODES
F1='AHX INLET',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0,FF=0.0;
F2='AHX NODE',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0,FF=0.0;
F3='AHX NODE',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0,FF=0.0;
F4='AHX OUTLET',A=%AHTXA%,FD=%AHTXD%,FL=%AHTXL%,P=10.0E5,T=20.0, FF=0.0;
#
D5='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
D6='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
D7='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
D8='AHX WALL',T=20.0,C=%AHTXC%,QI=%AHTXQ%;
#
$CONDUCTORS
#
# Mass flow links
#
M(1,2) = 0.1 ;
M(2,3) = 0.1 ;
M(3,4) = 0.1 ;
#
# Conduction links to the wall
#
GL(1,5) = %AHTXCD% ;
GL(2,6) = %AHTXCD% ;
GL(3,7) = %AHTXCD% ;
GL(4,8) = %AHTXCD% ;
#
# Fluid conductance - Assuming density = 1000Kg/m**3
#
GP(1,2) = %ACONGP% ;
GP(2,3) = %ACONGP% ;
GP(3,4) = %ACONGP% ;
#
$ENDMODEL STNAHX
```

Listing 10-3 Output for single-phase transient fluid loop model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     1
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis





 TIMEN =      0.00      MODULE FLTNTS      RELXMC = 4.915E-03
DTIMEU =    1.0000      DTCOUR =    0.4722
CSGMIN =    0.1573  AT NODE 1001 IN SUB-MODEL  COLTR


TABLE OUTPUT WITH ZENTS = 'L,T,P,QI'
FOR NODES OF ZLABEL = ' '

================================================================================

COLTR


         NODE   LABEL                              T             P

        1001    PIPE WALL                        20.00
        1002    PIPE WALL                        20.00
        1003    PIPE WALL                        20.00
        1004    PIPE WALL                        20.00
        1005    PIPE WALL                        20.00
        1006    PIPE WALL                        20.00
        1007    PIPE WALL                        20.00
        1008    PIPE WALL                        20.00
        1009    PIPE WALL                        20.00
        1010    PIPE WALL                        20.00
        1011    PIPE WALL                        20.00
        1012    PIPE WALL                        20.00
        1013    PIPE WALL                        20.00
        1014    PIPE WALL                        20.00
        1015    PIPE WALL                        20.00
        1016    PIPE WALL                        20.00
        1017    PIPE WALL                        20.00
        1018    PIPE WALL                        20.00
        1019    PIPE WALL                        20.00
        1020    PIPE WALL                        20.00
        1021    PIPE WALL                        20.00
        1022    PIPE WALL                        20.00
        1023    PIPE WALL                        20.00
        1024    PIPE WALL                        20.00
        1025    PIPE WALL                        20.00
        1026    PIPE WALL                        20.00
        1027    PIPE WALL                        20.00
        1028    PIPE WALL                        20.00
        1029    PIPE WALL                        20.00
        1030    PIPE WALL                        20.00
        9999    IHX B/NODE                        2.00

           1    AFTER IHX                        20.00    1119484.69
           2    BEFORE CHX                       20.00    1107194.88
           3    AFTER CHX                        20.00    1081576.85

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     2
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        NODE   LABEL                              T            P

          4    BEFORE COLDPL                    20.00    1000000.00
          5    AFTER COLDPL                     20.00    1000000.00
          6    BEFORE BY-PASS                   20.00    1069286.83
          7    TOP HEADER                       20.00    1054005.05
          8    BEFORE AHX1                      20.00    1018938.02
          9    AFTER AHX1                       20.00    1017097.85
         10    BEFORE AHX2                      20.00    1016954.81
         11    AFTER AHX2                       20.00    1016664.22
         12    BEFORE PL1                       20.00    1016748.49
         13    AFTER PL1                        20.00    1016648.43
         14    BEFORE PL2                       20.00    1016748.49
         15    AFTER PL2                        20.00    1016648.43
         16    BEFORE PL3                       20.00    1016748.49
         17    AFTER PL3                        20.00    1016648.43
         18    BEFORE PL4                       20.00    1016662.09
         19    AFTER PL4                        20.00    1016625.86
         20    BEFORE PL7                       20.00    1017289.82
         21    AFTER PL7                        20.00    1016839.08
         22    BEFORE PL9                       20.00    1017289.82
         23    AFTER PL9                        20.00    1016839.08
         24    BEFORE PL10                      20.00    1016748.49
         25    AFTER PL10                       20.00    1016648.43
         26    BOTTOM HEADER                    20.00    1016603.34
         27    BEFORE PUMP                      20.00    1000000.00
         28    AFTER PUMP                       20.00    1158199.48
         29    BEFORE IHX                       20.00    1145102.28
         30    BY-PASS                          20.00    1063357.01


        NODE          QI

       1001          0.00
       1002          0.00
       1003          0.00
       1004          0.00
       1005          0.00
       1006          0.00
       1007          0.00
       1008          0.00
       1009          0.00
       1010          0.00
       1011          0.00
       1012          0.00
       1013          0.00
       1014          0.00
       1015          0.00
       1016          0.00
       1017          0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     3
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis




        NODE          QI

       1018          0.00
       1019          0.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        1020          0.00
        1021          0.00
        1022          0.00
        1023          0.00
        1024          0.00
        1025          0.00
        1026          0.00
        1027          0.00
        1028          0.00
        1029          0.00
        1030          0.00
        9999          0.00

           1
           2
           3
           4
           5
           6
           7
           8
           9
          10
          11
          12
          13
          14
          15
          16
          17
          18
          19
          20
          21
          22
          23
          24
          25
          26
          27
          28
          29
          30

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     4
21 AUGUST 2006                  13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:CHX


         NODE   LABEL                             T             P

           3    WALL                            20.00
           4    WALL                            20.00

           1    INLET                           20.00    1104126.56
           2    OUTLET                          20.00    1084645.21


         NODE          QI

           3       1400.00
           4       1400.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
           1
           2

================================================================================

COLTR:COLDPL


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1000000.00
           2    OUTLET                           20.00    1000000.00


         NODE          QI

           3          0.00
           4          0.00

           1
           2

================================================================================

COLTR:PL1


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1016725.95
           2    OUTLET                           20.00    1016670.98


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     5
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis




         NODE          QI

           3        315.00
           4        315.00

           1
           2

================================================================================

COLTR:PL2


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1016725.95
           2    OUTLET                           20.00    1016670.98
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        NODE          QI

          3       125.00
          4       125.00

          1
          2

================================================================================

COLTR:PL3


        NODE   LABEL                              T             P

          3    WALL                             20.00
          4    WALL                             20.00

          1    INLET                            20.00    1016725.95
          2    OUTLET                           20.00    1016670.98


        NODE          QI

          3       200.00
          4       200.00

          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     6
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:PL4


        NODE   LABEL                              T             P

          3    WALL                             20.00
          4    WALL                             20.00

          1    INLET                            20.00    1016650.83
          2    OUTLET                           20.00    1016637.12


        NODE          QI

          3       185.00
          4       185.00

          1
          2

================================================================================

COLTR:PL7


        NODE   LABEL                              T             P

          3    WALL                             20.00
          4    WALL                             20.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
          1    INLET                            20.00    1017171.95
          2    OUTLET                           20.00    1016956.95


        NODE          QI

          3       1000.00
          4       1000.00

          1
          2

================================================================================

COLTR:PL9


        NODE   LABEL                              T             P

          3    WALL                             20.00
          4    WALL                             20.00

          1    INLET                            20.00    1017171.95
          2    OUTLET                           20.00    1016956.95


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     7
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




        NODE          QI

          3        375.00
          4        375.00

          1
          2

================================================================================

COLTR:PL10


        NODE   LABEL                              T             P

          3    WALL                             20.00
          4    WALL                             20.00

          1    INLET                            20.00    1016725.95
          2    OUTLET                           20.00    1016670.98


        NODE          QI

          3        190.00
          4        190.00

          1
          2

================================================================================
```

Listing 10-3 Output for single-phase transient fluid loop model

```
COLTR:SCPL


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1012586.35
           2    OUTLET                           20.00    1004017.02


         NODE          QI

           3         75.00
           4         75.00

           1
           2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     8
21 AUGUST 2006                  13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:IHX


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1142034.00
           2    OUTLET                           20.00    1122553.00


         NODE          QI

           3          0.00
           4          0.00

           1
           2

================================================================================

COLTR:AHX1


         NODE   LABEL                              T             P

           5    AHX WALL                         20.00
           6    AHX WALL                         20.00
           7    AHX WALL                         20.00
           8    AHX WALL                         20.00

           1    AHX INLET                        20.00    1018690.77
           2    AHX NODE                         20.00    1018242.21
           3    AHX NODE                         20.00    1017793.66
           4    AHX OUTLET                       20.00    1017345.11


         NODE          QI

           5        350.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
           6        350.00
           7        350.00
           8        350.00

           1
           2
           3
           4

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     9
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:AHX2


         NODE   LABEL                              T             P

           5    AHX WALL                         20.00
           6    AHX WALL                         20.00
           7    AHX WALL                         20.00
           8    AHX WALL                         20.00

           1    AHX INLET                        20.00    1016924.37
           2    AHX NODE                         20.00    1016847.80
           3    AHX NODE                         20.00    1016771.23
           4    AHX OUTLET                       20.00    1016694.65


         NODE          QI

           5        150.00
           6        150.00
           7        150.00
           8        150.00

           1
           2
           3
           4

================================================================================

COLTR:VPUMP


         NODE   LABEL                              T             P

           3    PUMP WALL                        20.00
           4    PUMP WALL                        20.00

           1    MASS SINK                        20.00     996927.89
           2    MASS SOURCE                      20.00    1164933.24


         NODE          QI

           3          0.00
           4          0.00

           1
           2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    10
21 AUGUST 2006                   13:44:21                                  COLTR
```

Listing 10-3 Output for single-phase transient fluid loop model

```
Single phase columbus model - transient analysis



COLTR:TEE1


         NODE   LABEL                            T             P


           1                                   20.00    1113348.07
           2                                   20.00    1000000.00


         NODE          QI


           1
           2
================================================================================

COLTR:TEE2


         NODE   LABEL                            T             P


           1                                   20.00    1075440.12
           2                                   20.00    1000000.00


         NODE          QI


           1
           2
================================================================================

COLTR:TEE3


         NODE   LABEL                            T             P


           1                                   20.00    1063150.07
           2                                   20.00    1063215.25


         NODE          QI


           1
           2
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    11
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis



COLTR:TEE4


         NODE   LABEL                            T             P
```

Listing 10-3 Output for single-phase transient fluid loop model

```
          1                                    20.00    1150166.01
          2                                    20.00    1149947.68


        NODE          QI


          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    12
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




 TIMEN =      0.00      MODULE FLTNTS      RELXMC = 4.915E-03
DTIMEU =    1.0000      DTCOUR =    0.4722
CSGMIN =    0.1573  AT NODE 1001 IN SUB-MODEL  COLTR


BLOCK OUTPUT WITH ZENTS = 'M'
FOR NODES OF ZLABEL = ' '


COLTR

VALUES FOR CONDUCTORS M  :
M (1,Z12:2)  =    -0.1747      M (1,Z16:1)  =     0.1747
M (2,Z2:1)   =     0.1747      M (2,Z16:1)  =    -0.1747
M (3,Z2:2)   =    -0.1747      M (3,Z17:1)  =     0.1747
M (4,Z3:1)   =     0.0000 X    M (4,Z16:2)  =     0.0000 X
M (5,Z3:2)   =     0.0000 X    M (5,Z17:2)  =     0.0000 X
M (6,Z17:1)  =    -0.1747      M (6,Z18:1)  =     0.1747
M (7,8)      =     0.0459      M (7,10)     =     0.0190
M (7,12)     =     0.0161      M (7,14)     =     0.0161
M (7,16)     =     0.0161      M (7,18)     =     0.0080
M (7,20)     =     0.0318      M (7,22)     =     0.0318
M (7,24)     =     0.0161      M (7,Z18:1)  =    -0.2009
M (8,7)      =    -0.0459      M (8,Z13:1)  =     0.0459
M (9,26)     =     0.0459      M (9,Z13:4)  =    -0.0459
M (10,7)     =    -0.0190      M (10,Z14:1) =     0.0190
M (11,26)    =     0.0190      M (11,Z14:4) =    -0.0190
M (12,7)     =    -0.0161      M (12,Z4:1)  =     0.0161
M (13,26)    =     0.0161      M (13,Z4:2)  =    -0.0161
M (14,7)     =    -0.0161      M (14,Z5:1)  =     0.0161
M (15,26)    =     0.0161      M (15,Z5:2)  =    -0.0161
M (16,7)     =    -0.0161      M (16,Z6:1)  =     0.0161
M (17,26)    =     0.0161      M (17,Z6:2)  =    -0.0161
M (18,7)     =    -0.0080      M (18,Z7:1)  =     0.0080
M (19,26)    =     0.0080      M (19,Z7:2)  =    -0.0080
M (20,7)     =    -0.0318      M (20,Z8:1)  =     0.0318
M (21,26)    =     0.0318      M (21,Z8:2)  =    -0.0318
M (22,7)     =    -0.0318      M (22,Z9:1)  =     0.0318
M (23,26)    =     0.0318      M (23,Z9:2)  =    -0.0318
M (24,7)     =    -0.0161      M (24,Z10:1) =     0.0161
M (25,26)    =     0.0161      M (25,Z10:2) =    -0.0161
M (26,9)     =    -0.0459      M (26,11)    =    -0.0190
M (26,13)    =    -0.0161      M (26,15)    =    -0.0161
M (26,17)    =    -0.0161      M (26,19)    =    -0.0080
M (26,21)    =    -0.0318      M (26,23)    =    -0.0318
M (26,25)    =    -0.0161      M (26,Z11:1) =     0.2009
M (27,Z11:2) =    -0.2009      M (27,Z15:1) =     0.2009
```

Listing 10-3 Output for single-phase transient fluid loop model

```
M (28,Z15:2) =    -0.2009      M (28,Z19:1) =     0.2009

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    13
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




M (29,Z12:1) =     0.1747      M (29,Z19:1) =    -0.1747
M (30,Z18:2) =     0.0263      M (30,Z19:2) =    -0.0263


COLTR:CHX

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.1747      M (1,Z1:2) =    -0.1747
M (2,1)    =    -0.1747      M (2,Z1:3) =     0.1747


COLTR:COLDPL

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:4) =     0.0000 X
M (2,1)    =     0.0000 X    M (2,Z1:5) =     0.0000 X


COLTR:PL1

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0161      M (1,Z1:12) =    -0.0161
M (2,1)     =    -0.0161      M (2,Z1:13) =     0.0161


COLTR:PL2

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0161      M (1,Z1:14) =    -0.0161
M (2,1)     =    -0.0161      M (2,Z1:15) =     0.0161


COLTR:PL3

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0161      M (1,Z1:16) =    -0.0161
M (2,1)     =    -0.0161      M (2,Z1:17) =     0.0161


COLTR:PL4

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0080      M (1,Z1:18) =    -0.0080
M (2,1)     =    -0.0080      M (2,Z1:19) =     0.0080


COLTR:PL7

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0318      M (1,Z1:20) =    -0.0318
M (2,1)     =    -0.0318      M (2,Z1:21) =     0.0318

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    14
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis
```

Listing 10-3 Output for single-phase transient fluid loop model

```
COLTR:PL9

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0318      M (1,Z1:22) =    -0.0318
M (2,1)     =    -0.0318      M (2,Z1:23) =     0.0318


COLTR:PL10

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0161      M (1,Z1:24) =    -0.0161
M (2,1)     =    -0.0161      M (2,Z1:25) =     0.0161


COLTR:SCPL

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.2009      M (1,Z1:26) =    -0.2009
M (2,1)     =    -0.2009      M (2,Z1:27) =     0.2009


COLTR:IHX

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.1747      M (1,Z1:29) =    -0.1747
M (2,1)     =    -0.1747      M (2,Z1:1)  =     0.1747


COLTR:AHX1

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0459      M (1,Z1:8) =    -0.0459
M (2,1)    =    -0.0459      M (2,3)    =     0.0459
M (3,2)    =    -0.0459      M (3,4)    =     0.0459
M (4,3)    =    -0.0459      M (4,Z1:9) =     0.0459


COLTR:AHX2

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0190      M (1,Z1:10) =    -0.0190
M (2,1)     =    -0.0190      M (2,3)     =     0.0190
M (3,2)     =    -0.0190      M (3,4)     =     0.0190
M (4,3)     =    -0.0190      M (4,Z1:11) =     0.0190


COLTR:VPUMP

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    15
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis




VALUES FOR CONDUCTORS M  :
M (1,Z1:27) =    -0.2009      M (2,Z1:28) =     0.2009


COLTR:TEE1

VALUES FOR CONDUCTORS M  :
```

Listing 10-3 Output for single-phase transient fluid loop model

```
M (1,2)    =     0.0000 X    M (1,Z1:1) =    -0.1747
M (1,Z1:2) =     0.1747      M (2,1)    =     0.0000 X
M (2,Z1:4) =     0.0000 X


COLTR:TEE2

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:3) =    -0.1747
M (1,Z1:6) =     0.1747      M (2,1)    =     0.0000 X
M (2,Z1:5) =     0.0000 X


COLTR:TEE3

VALUES FOR CONDUCTORS M  :
M (1,2)     =    -0.0263      M (1,Z1:6)  =    -0.1747
M (1,Z1:7)  =     0.2009      M (2,1)     =     0.0263
M (2,Z1:30) =    -0.0263


COLTR:TEE4

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0263      M (1,Z1:28) =    -0.2009
M (1,Z1:29) =     0.1747      M (2,1)     =    -0.0263
M (2,Z1:30) =     0.0263



 KEY FOR SUB-MODEL CODE :


Z1 = COLTR


Z2 = COLTR:CHX


Z3 = COLTR:COLDPL

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    16
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis






Z4 = COLTR:PL1


Z5 = COLTR:PL2


Z6 = COLTR:PL3


Z7 = COLTR:PL4


Z8 = COLTR:PL7


Z9 = COLTR:PL9
```

Listing 10-3 Output for single-phase transient fluid loop model

```
Z10 = COLTR:PL10


Z11 = COLTR:SCPL


Z12 = COLTR:IHX


Z13 = COLTR:AHX1


Z14 = COLTR:AHX2


Z15 = COLTR:VPUMP


Z16 = COLTR:TEE1


Z17 = COLTR:TEE2


Z18 = COLTR:TEE3


Z19 = COLTR:TEE4

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    17
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




 TIMEN =      0.00      MODULE FLTNTS      RELXMC = 4.915E-03
DTIMEU =    1.0000      DTCOUR =    0.4722
CSGMIN =    0.1573  AT NODE 1001 IN SUB-MODEL  COLTR


TABLE OUTPUT WITH ZENTS = 'VFLO,U,RE,RHO'
FOR NODES OF ZLABEL = ' '

================================================================================

COLTR


      NODE        VFLO          U             RE            RHO

         1       0.00017          1.84      20164.86        998.40
         2       0.00017          1.84      20164.86        998.40
         3       0.00017          1.84      20164.86        998.39
         4       0.00000          0.00          0.00        998.35
         5       0.00000          0.00          0.00        998.35
         6       0.00017          1.84      20164.86        998.38
         7       0.00020          2.12      23198.49        998.37
         8       0.00005          0.48       5299.62        998.36
         9       0.00005          0.48       5299.62        998.36
        10       0.00002          0.20       2189.65        998.36
        11       0.00002          0.20       2189.65        998.36
        12       0.00002          0.17       1858.03        998.36
        13       0.00002          0.17       1858.03        998.36
        14       0.00002          0.17       1858.03        998.36
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        15       0.00002          0.17       1858.03        998.36
        16       0.00002          0.17       1858.03        998.36
        17       0.00002          0.17       1858.03        998.36
        18       0.00001          0.08        927.96        998.36
        19       0.00001          0.08        927.96        998.36
        20       0.00003          0.34       3674.56        998.36
        21       0.00003          0.34       3674.56        998.36
        22       0.00003          0.34       3674.56        998.36
        23       0.00003          0.34       3674.56        998.36
        24       0.00002          0.17       1858.03        998.36
        25       0.00002          0.17       1858.03        998.36
        26       0.00020          2.12      23198.49        998.36
        27       0.00020          2.12      23198.49        998.35
        28       0.00020          2.12      23198.49        998.42
        29       0.00017          1.84      20164.86        998.41
        30       0.00003          0.28       3033.63        998.38

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    18
21 AUGUST 2006                   13:44:21                                   COLTR

Single phase columbus model - transient analysis



COLTR:CHX


      NODE        VFLO          U             RE            RHO

         1       0.00017          1.84      20164.86        998.40
         2       0.00017          1.84      20164.86        998.39
================================================================================

COLTR:COLDPL


      NODE        VFLO          U             RE            RHO

         1       0.00000          0.00          0.00        998.35
         2       0.00000          0.00          0.00        998.35
================================================================================

COLTR:PL1


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.17       1858.03        998.36
         2       0.00002          0.17       1858.03        998.36
================================================================================

COLTR:PL2


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.17       1858.03        998.36
         2       0.00002          0.17       1858.03        998.36
================================================================================

COLTR:PL3


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.17       1858.03        998.36
         2       0.00002          0.17       1858.03        998.36
```

Listing 10-3 Output for single-phase transient fluid loop model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    19
21 AUGUST 2006                   13:44:21                                   COLTR

Single phase columbus model - transient analysis



COLTR:PL4


      NODE        VFLO          U             RE            RHO

         1       0.00001          0.08        927.96        998.36
         2       0.00001          0.08        927.96        998.36
================================================================================

COLTR:PL7


      NODE        VFLO          U             RE            RHO

         1       0.00003          0.34       3674.56        998.36
         2       0.00003          0.34       3674.56        998.36
================================================================================

COLTR:PL9


      NODE        VFLO          U             RE            RHO

         1       0.00003          0.34       3674.56        998.36
         2       0.00003          0.34       3674.56        998.36
================================================================================

COLTR:PL10


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.17       1858.03        998.36
         2       0.00002          0.17       1858.03        998.36
================================================================================

COLTR:SCPL


      NODE        VFLO          U             RE            RHO

         1       0.00020          2.12      23198.49        998.35
         2       0.00020          2.12      23198.49        998.35

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    20
21 AUGUST 2006                   13:44:21                                   COLTR

Single phase columbus model - transient analysis



COLTR:IHX


      NODE        VFLO          U             RE            RHO

         1       0.00017          1.84      20164.86        998.41
         2       0.00017          1.84      20164.86        998.40
================================================================================

COLTR:AHX1
```

Listing 10-3 Output for single-phase transient fluid loop model

```
     NODE       VFLO         U            RE           RHO

        1      0.00005         0.48      5299.62       998.36
        2      0.00005         0.48      5299.62       998.36
        3      0.00005         0.48      5299.62       998.36
        4      0.00005         0.48      5299.62       998.36
================================================================================

COLTR:AHX2


     NODE       VFLO         U            RE           RHO

        1      0.00002         0.20      2189.65       998.36
        2      0.00002         0.20      2189.65       998.36
        3      0.00002         0.20      2189.65       998.36
        4      0.00002         0.20      2189.65       998.36
================================================================================

COLTR:VPUMP


     NODE       VFLO         U            RE           RHO

        1      0.00020         0.64     12774.74       998.35
        2      0.00020         0.64     12774.74       998.42

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    21
21 AUGUST 2006                  13:44:21                                    COLTR

Single phase columbus model - transient analysis



COLTR:TEE1


     NODE       VFLO         U            RE           RHO

        1      0.00017         1.84     20164.86       998.40
        2      0.00000         0.00         0.00       998.35
================================================================================

COLTR:TEE2


     NODE       VFLO         U            RE           RHO

        1      0.00017         1.84     20164.86       998.38
        2      0.00000         0.00         0.00       998.35
================================================================================

COLTR:TEE3


     NODE       VFLO         U            RE           RHO

        1      0.00020         2.12     23198.50       998.38
        2      0.00003         0.28      3033.63       998.38
================================================================================

COLTR:TEE4


     NODE       VFLO         U            RE           RHO
```

Listing 10-3 Output for single-phase transient fluid loop model

```
         1       0.00020          2.12      23198.50        998.42
         2       0.00003          0.28       3033.63        998.42

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    22
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis




 TIMEN =     60.00      MODULE FLTNTS      RELXMC = 6.055E-05
DTIMEU =    0.4021      DTCOUR =    0.4566
CSGMIN = 5.830E-02  AT NODE 1026 IN SUB-MODEL  COLTR


TABLE OUTPUT WITH ZENTS = 'L,T,P,QI'
FOR NODES OF ZLABEL = ' '

================================================================================

COLTR


         NODE   LABEL                              T             P

        1001    PIPE WALL                        10.08
        1002    PIPE WALL                        10.01
        1003    PIPE WALL                        15.02
        1004    PIPE WALL                        20.00
        1005    PIPE WALL                        20.00
        1006    PIPE WALL                        15.02
        1007    PIPE WALL                        18.15
        1008    PIPE WALL                        18.12
        1009    PIPE WALL                        24.59
        1010    PIPE WALL                        18.09
        1011    PIPE WALL                        22.88
        1012    PIPE WALL                        18.09
        1013    PIPE WALL                        24.87
        1014    PIPE WALL                        18.09
        1015    PIPE WALL                        21.67
        1016    PIPE WALL                        18.09
        1017    PIPE WALL                        22.93
        1018    PIPE WALL                        18.20
        1019    PIPE WALL                        23.08
        1020    PIPE WALL                        18.11
        1021    PIPE WALL                        31.29
        1022    PIPE WALL                        18.11
        1023    PIPE WALL                        23.51
        1024    PIPE WALL                        18.09
        1025    PIPE WALL                        22.76
        1026    PIPE WALL                        24.74
        1027    PIPE WALL                        24.64
        1028    PIPE WALL                        24.25
        1029    PIPE WALL                        24.15
        1030    PIPE WALL                        24.02
        9999    IHX B/NODE                        2.00

           1    AFTER IHX                        10.08    1102932.26
           2    BEFORE CHX                       10.02    1095409.10
           3    AFTER CHX                        15.02    1080157.69

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    23
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        NODE   LABEL                              T             P

          4    BEFORE COLDPL                    20.00    1000000.00
          5    AFTER COLDPL                     20.00    1000000.00
          6    BEFORE BY-PASS                   15.02    1072649.78
          7    TOP HEADER                       18.16    1057551.96
          8    BEFORE AHX1                      18.12    1020126.34
          9    AFTER AHX1                       24.59    1018166.41
         10    BEFORE AHX2                      18.09    1018032.41
         11    AFTER AHX2                       22.90    1017720.44
         12    BEFORE PL1                       18.09    1017803.35
         13    AFTER PL1                        24.89    1017697.02
         14    BEFORE PL2                       18.09    1017801.50
         15    AFTER PL2                        21.67    1017696.13
         16    BEFORE PL3                       18.09    1017802.20
         17    AFTER PL3                        22.94    1017696.46
         18    BEFORE PL4                       18.19    1017709.33
         19    AFTER PL4                        23.09    1017671.76
         20    BEFORE PL7                       18.11    1018395.10
         21    AFTER PL7                        31.31    1017911.41
         22    BEFORE PL9                       18.11    1018402.48
         23    AFTER PL9                        23.51    1017915.50
         24    BEFORE PL10                      18.09    1017802.10
         25    AFTER PL10                       22.77    1017696.42
         26    BOTTOM HEADER                    24.75    1017650.58
         27    BEFORE PUMP                      24.65    1000000.00
         28    AFTER PUMP                       24.25    1127540.88
         29    BEFORE IHX                       24.16    1118144.73
         30    BY-PASS                          24.04    1070642.29


        NODE          QI

       1001         0.00
       1002         0.00
       1003         0.00
       1004         0.00
       1005         0.00
       1006         0.00
       1007         0.00
       1008         0.00
       1009         0.00
       1010         0.00
       1011         0.00
       1012         0.00
       1013         0.00
       1014         0.00
       1015         0.00
       1016         0.00
       1017         0.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    24
21 AUGUST 2006                  13:44:21                                 COLTR

Single phase columbus model - transient analysis




        NODE          QI

       1018         0.00
       1019         0.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        1020          0.00
        1021          0.00
        1022          0.00
        1023          0.00
        1024          0.00
        1025          0.00
        1026          0.00
        1027          0.00
        1028          0.00
        1029          0.00
        1030          0.00
        9999          0.00

           1
           2
           3
           4
           5
           6
           7
           8
           9
          10
          11
          12
          13
          14
          15
          16
          17
          18
          19
          20
          21
          22
          23
          24
          25
          26
          27
          28
          29
          30

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    25
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:CHX


         NODE   LABEL                            T             P

           3    WALL                           18.05
           4    WALL                           20.83

           1    INLET                          12.44    1093527.50
           2    OUTLET                         15.02    1082034.65


         NODE          QI

           3       1400.00
           4       1400.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
          1
          2

================================================================================

COLTR:COLDPL


         NODE   LABEL                              T             P

           3    WALL                             20.00
           4    WALL                             20.00

           1    INLET                            20.00    1000000.00
           2    OUTLET                           20.00    1000000.00


         NODE          QI

           3          0.00
           4          0.00

           1
           2

================================================================================

COLTR:PL1


         NODE   LABEL                              T             P

           3    WALL                             23.61
           4    WALL                             26.32

           1    INLET                            22.38    1017778.97
           2    OUTLET                           25.31    1017720.25


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    26
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




         NODE          QI

           3        315.00
           4        315.00

           1
           2

================================================================================

COLTR:PL2


         NODE   LABEL                              T             P

           3    WALL                             20.75
           4    WALL                             22.21

           1    INLET                            20.20    1017777.14
           2    OUTLET                           21.75    1017718.45
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        NODE          QI

          3       125.00
          4       125.00

          1
          2

================================================================================

COLTR:PL3


        NODE   LABEL                              T             P

          3    WALL                             21.88
          4    WALL                             23.83

          1    INLET                            21.06    1017777.83
          2    OUTLET                           23.16    1017719.13


        NODE          QI

          3       200.00
          4       200.00

          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    27
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:PL4


        NODE   LABEL                              T             P

          3    WALL                             23.00
          4    WALL                             24.47

          1    INLET                            22.35    1017697.19
          2    OUTLET                           24.01    1017682.54


        NODE          QI

          3       185.00
          4       185.00

          1
          2

================================================================================

COLTR:PL7


        NODE   LABEL                              T             P

          3    WALL                             29.13
          4    WALL                             35.24
```

Listing 10-3 Output for single-phase transient fluid loop model

```
          1    INLET                            25.18    1018270.22
          2    OUTLET                           31.54    1018040.33


        NODE          QI

          3       1000.00
          4       1000.00

          1
          2

================================================================================

COLTR:PL9


        NODE   LABEL                              T             P

          3    WALL                             22.41
          4    WALL                             25.00

          1    INLET                            20.88    1018277.76
          2    OUTLET                           23.53    1018048.29


EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    28
21 AUGUST 2006                   13:44:21                               COLTR

Single phase columbus model - transient analysis





        NODE          QI

          3        375.00
          4        375.00

          1
          2

================================================================================

COLTR:PL10


        NODE   LABEL                              T             P

          3    WALL                             21.73
          4    WALL                             23.61

          1    INLET                            20.95    1017777.73
          2    OUTLET                           22.97    1017719.04


        NODE          QI

          3        190.00
          4        190.00

          1
          2

================================================================================
```

Listing 10-3 Output for single-phase transient fluid loop model

```
COLTR:SCPL


         NODE   LABEL                               T             P

           3    WALL                              24.81
           4    WALL                              24.74

           1    INLET                             24.72    1013403.27
           2    OUTLET                            24.68    1004247.92


         NODE          QI

           3         75.00
           4         75.00

           1
           2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    29
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:IHX


         NODE   LABEL                               T             P

           3    WALL                               3.03
           4    WALL                               2.62

           1    INLET                             15.43    1116308.60
           2    OUTLET                            10.12    1104812.86


         NODE          QI

           3          0.00
           4          0.00

           1
           2

================================================================================

COLTR:AHX1


         NODE   LABEL                               T             P

           5    AHX WALL                          22.72
           6    AHX WALL                          24.43
           7    AHX WALL                          25.90
           8    AHX WALL                          27.09

           1    AHX INLET                         19.89    1019861.85
           2    AHX NODE                          21.64    1019382.87
           3    AHX NODE                          23.26    1018903.72
           4    AHX OUTLET                        24.67    1018424.38


         NODE          QI

           5        350.00
```

Listing 10-3 Output for single-phase transient fluid loop model

```
          6        350.00
          7        350.00
          8        350.00

          1
          2
          3
          4

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    30
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis



COLTR:AHX2


        NODE   LABEL                              T             P

          5    AHX WALL                         21.38
          6    AHX WALL                         22.77
          7    AHX WALL                         23.55
          8    AHX WALL                         23.92

          1    AHX INLET                        20.09    1018000.15
          2    AHX NODE                         21.68    1017918.42
          3    AHX NODE                         22.68    1017836.67
          4    AHX OUTLET                       23.21    1017754.91


        NODE         QI

          5        150.00
          6        150.00
          7        150.00
          8        150.00

          1
          2
          3
          4

================================================================================

COLTR:VPUMP


        NODE   LABEL                              T             P

          3    PUMP WALL                        24.36
          4    PUMP WALL                        24.15

          1    MASS SINK                        24.49     996761.57
          2    MASS SOURCE                      24.30    1134693.37


        NODE         QI

          3          0.00
          4          0.00

          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    31
21 AUGUST 2006                   13:44:21                                 COLTR
```

Listing 10-3 Output for single-phase transient fluid loop model

```
Single phase columbus model - transient analysis



COLTR:TEE1


        NODE   LABEL                              T             P


          1                                     10.06    1099170.90
          2                                     20.00    1000000.00


        NODE          QI


          1
          2
================================================================================

COLTR:TEE2


        NODE   LABEL                              T             P


          1                                     15.02    1076403.76
          2                                     20.00    1000000.00


        NODE          QI


          1
          2
================================================================================

COLTR:TEE3


        NODE   LABEL                              T             P


          1                                     18.17    1068909.01
          2                                     23.95    1069482.26


        NODE          QI


          1
          2
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    32
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis



COLTR:TEE4


        NODE   LABEL                              T             P
```

Listing 10-3 Output for single-phase transient fluid loop model

```
          1                                     24.22    1119040.80
          2                                     24.15    1117284.23


        NODE          QI


          1
          2

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    33
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




 TIMEN =     60.00      MODULE FLTNTS      RELXMC = 6.055E-05
DTIMEU =    0.4021      DTCOUR =    0.4566
CSGMIN = 5.830E-02  AT NODE 1026 IN SUB-MODEL  COLTR


BLOCK OUTPUT WITH ZENTS = 'M'
FOR NODES OF ZLABEL = ' '


COLTR

VALUES FOR CONDUCTORS M  :
M (1,Z12:2)  =    -0.1342      M (1,Z16:1)  =     0.1342
M (2,Z2:1)   =     0.1342      M (2,Z16:1)  =    -0.1342
M (3,Z2:2)   =    -0.1342      M (3,Z17:1)  =     0.1342
M (4,Z3:1)   =     0.0000 X    M (4,Z16:2)  =     0.0000 X
M (5,Z3:2)   =     0.0000 X    M (5,Z17:2)  =     0.0000 X
M (6,Z17:1)  =    -0.1342      M (6,Z18:1)  =     0.1342
M (7,8)      =     0.0474      M (7,10)     =     0.0196
M (7,12)     =     0.0166      M (7,14)     =     0.0166
M (7,16)     =     0.0166      M (7,18)     =     0.0083
M (7,20)     =     0.0329      M (7,22)     =     0.0329
M (7,24)     =     0.0166      M (7,Z18:1)  =    -0.2076
M (8,7)      =    -0.0474      M (8,Z13:1)  =     0.0474
M (9,26)     =     0.0474      M (9,Z13:4)  =    -0.0474
M (10,7)     =    -0.0196      M (10,Z14:1) =     0.0196
M (11,26)    =     0.0196      M (11,Z14:4) =    -0.0196
M (12,7)     =    -0.0166      M (12,Z4:1)  =     0.0166
M (13,26)    =     0.0166      M (13,Z4:2)  =    -0.0166
M (14,7)     =    -0.0166      M (14,Z5:1)  =     0.0166
M (15,26)    =     0.0166      M (15,Z5:2)  =    -0.0166
M (16,7)     =    -0.0166      M (16,Z6:1)  =     0.0166
M (17,26)    =     0.0166      M (17,Z6:2)  =    -0.0166
M (18,7)     =    -0.0083      M (18,Z7:1)  =     0.0083
M (19,26)    =     0.0083      M (19,Z7:2)  =    -0.0083
M (20,7)     =    -0.0329      M (20,Z8:1)  =     0.0329
M (21,26)    =     0.0329      M (21,Z8:2)  =    -0.0329
M (22,7)     =    -0.0329      M (22,Z9:1)  =     0.0329
M (23,26)    =     0.0329      M (23,Z9:2)  =    -0.0329
M (24,7)     =    -0.0166      M (24,Z10:1) =     0.0166
M (25,26)    =     0.0166      M (25,Z10:2) =    -0.0166
M (26,9)     =    -0.0474      M (26,11)    =    -0.0196
M (26,13)    =    -0.0166      M (26,15)    =    -0.0166
M (26,17)    =    -0.0166      M (26,19)    =    -0.0083
M (26,21)    =    -0.0329      M (26,23)    =    -0.0329
M (26,25)    =    -0.0166      M (26,Z11:1) =     0.2076
M (27,Z11:2) =    -0.2076      M (27,Z15:1) =     0.2076
```

Listing 10-3 Output for single-phase transient fluid loop model

```
M (28,Z15:2) =    -0.2076      M (28,Z19:1) =     0.2076

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    34
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




M (29,Z12:1) =     0.1342      M (29,Z19:1) =    -0.1342
M (30,Z18:2) =     0.0733      M (30,Z19:2) =    -0.0733


COLTR:CHX

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.1342      M (1,Z1:2) =    -0.1342
M (2,1)    =    -0.1342      M (2,Z1:3) =     0.1342


COLTR:COLDPL

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:4) =     0.0000 X
M (2,1)    =     0.0000 X    M (2,Z1:5) =     0.0000 X


COLTR:PL1

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0166      M (1,Z1:12) =    -0.0166
M (2,1)     =    -0.0166      M (2,Z1:13) =     0.0166


COLTR:PL2

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0166      M (1,Z1:14) =    -0.0166
M (2,1)     =    -0.0166      M (2,Z1:15) =     0.0166


COLTR:PL3

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0166      M (1,Z1:16) =    -0.0166
M (2,1)     =    -0.0166      M (2,Z1:17) =     0.0166


COLTR:PL4

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0083      M (1,Z1:18) =    -0.0083
M (2,1)     =    -0.0083      M (2,Z1:19) =     0.0083


COLTR:PL7

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0329      M (1,Z1:20) =    -0.0329
M (2,1)     =    -0.0329      M (2,Z1:21) =     0.0329

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    35
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis
```

Listing 10-3 Output for single-phase transient fluid loop model

```
COLTR:PL9

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0329      M (1,Z1:22) =    -0.0329
M (2,1)     =    -0.0329      M (2,Z1:23) =     0.0329


COLTR:PL10

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0166      M (1,Z1:24) =    -0.0166
M (2,1)     =    -0.0166      M (2,Z1:25) =     0.0166


COLTR:SCPL

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.2076      M (1,Z1:26) =    -0.2076
M (2,1)     =    -0.2076      M (2,Z1:27) =     0.2076


COLTR:IHX

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.1342      M (1,Z1:29) =    -0.1342
M (2,1)     =    -0.1342      M (2,Z1:1)  =     0.1342


COLTR:AHX1

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0474      M (1,Z1:8) =    -0.0474
M (2,1)    =    -0.0474      M (2,3)    =     0.0474
M (3,2)    =    -0.0474      M (3,4)    =     0.0474
M (4,3)    =    -0.0474      M (4,Z1:9) =     0.0474


COLTR:AHX2

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0196      M (1,Z1:10) =    -0.0196
M (2,1)     =    -0.0196      M (2,3)     =     0.0196
M (3,2)     =    -0.0196      M (3,4)     =     0.0196
M (4,3)     =    -0.0196      M (4,Z1:11) =     0.0196


COLTR:VPUMP

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    36
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis




VALUES FOR CONDUCTORS M  :
M (1,Z1:27) =    -0.2076      M (2,Z1:28) =     0.2076


COLTR:TEE1

VALUES FOR CONDUCTORS M  :
```

Listing 10-3 Output for single-phase transient fluid loop model

```
M (1,2)    =     0.0000 X    M (1,Z1:1) =    -0.1342
M (1,Z1:2) =     0.1342      M (2,1)    =     0.0000 X
M (2,Z1:4) =     0.0000 X


COLTR:TEE2

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0000 X    M (1,Z1:3) =    -0.1342
M (1,Z1:6) =     0.1342      M (2,1)    =     0.0000 X
M (2,Z1:5) =     0.0000 X


COLTR:TEE3

VALUES FOR CONDUCTORS M  :
M (1,2)     =    -0.0733      M (1,Z1:6)  =    -0.1342
M (1,Z1:7)  =     0.2076      M (2,1)     =     0.0733
M (2,Z1:30) =    -0.0733


COLTR:TEE4

VALUES FOR CONDUCTORS M  :
M (1,2)     =     0.0733      M (1,Z1:28) =    -0.2076
M (1,Z1:29) =     0.1342      M (2,1)     =    -0.0733
M (2,Z1:30) =     0.0733



 KEY FOR SUB-MODEL CODE :


Z1 = COLTR


Z2 = COLTR:CHX


Z3 = COLTR:COLDPL

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    37
21 AUGUST 2006                   13:44:21                                 COLTR

Single phase columbus model - transient analysis






Z4 = COLTR:PL1


Z5 = COLTR:PL2


Z6 = COLTR:PL3


Z7 = COLTR:PL4


Z8 = COLTR:PL7


Z9 = COLTR:PL9
```

Listing 10-3 Output for single-phase transient fluid loop model

```
Z10 = COLTR:PL10


Z11 = COLTR:SCPL


Z12 = COLTR:IHX


Z13 = COLTR:AHX1


Z14 = COLTR:AHX2


Z15 = COLTR:VPUMP


Z16 = COLTR:TEE1


Z17 = COLTR:TEE2


Z18 = COLTR:TEE3


Z19 = COLTR:TEE4

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    38
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis





 TIMEN =     60.00      MODULE FLTNTS      RELXMC = 6.055E-05
DTIMEU =    0.4021      DTCOUR =    0.4566
CSGMIN = 5.830E-02  AT NODE 1026 IN SUB-MODEL  COLTR


TABLE OUTPUT WITH ZENTS = 'VFLO,U,RE,RHO'
FOR NODES OF ZLABEL = ' '

================================================================================

COLTR


      NODE        VFLO          U             RE            RHO

         1       0.00013          1.41      11926.01       1000.03
         2       0.00013          1.41      11904.90       1000.04
         3       0.00013          1.41      13666.19        999.32
         4       0.00000          0.00          0.00        998.35
         5       0.00000          0.00          0.00        998.35
         6       0.00013          1.41      13667.73        999.32
         7       0.00021          2.19      22895.66        998.75
         8       0.00005          0.50       5226.88        998.74
         9       0.00005          0.50       6106.11        997.29
        10       0.00002          0.21       2157.45        998.74
        11       0.00002          0.21       2425.31        997.70
        12       0.00002          0.18       1830.88        998.74
        13       0.00002          0.18       2154.69        997.21
        14       0.00002          0.18       1830.92        998.74
```

Listing 10-3 Output for single-phase transient fluid loop model

```
        15       0.00002          0.18       1998.83        997.99
        16       0.00002          0.18       1830.90        998.74
        17       0.00002          0.18       2060.26        997.69
        18       0.00001          0.09        916.77        998.72
        19       0.00001          0.09       1032.56        997.66
        20       0.00003          0.35       3621.87        998.74
        21       0.00003          0.35       4899.69        995.41
        22       0.00003          0.35       3621.53        998.74
        23       0.00003          0.35       4126.86        997.55
        24       0.00002          0.18       1830.91        998.74
        25       0.00002          0.18       2052.26        997.73
        26       0.00021          2.19      26818.79        997.25
        27       0.00021          2.19      26755.86        997.26
        28       0.00021          2.19      26510.75        997.42
        29       0.00013          1.42      17105.59        997.44
        30       0.00007          0.77       9319.40        997.45

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    39
21 AUGUST 2006                   13:44:21                                  COLTR

Single phase columbus model - transient analysis



COLTR:CHX


      NODE        VFLO          U             RE            RHO

         1       0.00013          1.41      12743.70        999.72
         2       0.00013          1.41      13666.16        999.32
================================================================================

COLTR:COLDPL


      NODE        VFLO          U             RE            RHO

         1       0.00000          0.00          0.00        998.35
         2       0.00000          0.00          0.00        998.35
================================================================================

COLTR:PL1


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.18       2033.02        997.82
         2       0.00002          0.18       2175.11        997.10
================================================================================

COLTR:PL2


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.18       1929.04        998.31
         2       0.00002          0.18       2002.62        997.97
================================================================================

COLTR:PL3


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.18       1970.38        998.13
         2       0.00002          0.18       2070.38        997.64
```

Listing 10-3 Output for single-phase transient fluid loop model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    40
21 AUGUST 2006                   13:44:21                                   COLTR

Single phase columbus model - transient analysis



COLTR:PL4


      NODE        VFLO          U             RE            RHO

         1       0.00001          0.09       1014.61        997.83
         2       0.00001          0.09       1054.60        997.43
================================================================================

COLTR:PL7


      NODE        VFLO          U             RE            RHO

         1       0.00003          0.35       4288.67        997.14
         2       0.00003          0.35       4922.99        995.34
================================================================================

COLTR:PL9


      NODE        VFLO          U             RE            RHO

         1       0.00003          0.35       3879.55        998.16
         2       0.00003          0.35       4128.68        997.55
================================================================================

COLTR:PL10


      NODE        VFLO          U             RE            RHO

         1       0.00002          0.18       1965.11        998.15
         2       0.00002          0.18       2061.59        997.69
================================================================================

COLTR:SCPL


      NODE        VFLO          U             RE            RHO

         1       0.00021          2.19      26802.90        997.25
         2       0.00021          2.19      26779.05        997.26

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    41
21 AUGUST 2006                   13:44:21                                   COLTR

Single phase columbus model - transient analysis



COLTR:IHX


      NODE        VFLO          U             RE            RHO

         1       0.00013          1.41      13816.53        999.27
         2       0.00013          1.41      11938.40       1000.03
================================================================================

COLTR:AHX1
```

Listing 10-3 Output for single-phase transient fluid loop model

```
     NODE        VFLO         U             RE            RHO

        1       0.00005          0.50       5460.54        998.38
        2       0.00005          0.50       5697.20        998.00
        3       0.00005          0.50       5919.93        997.62
        4       0.00005          0.50       6116.26        997.27
================================================================================

COLTR:AHX2


     NODE        VFLO         U             RE            RHO

        1       0.00002          0.21       2267.14        998.34
        2       0.00002          0.21       2355.78        997.99
        3       0.00002          0.21       2412.72        997.76
        4       0.00002          0.21       2442.43        997.63
================================================================================

COLTR:VPUMP


     NODE        VFLO         U             RE            RHO

        1       0.00021          0.66      14661.51        997.30
        2       0.00021          0.66      14597.48        997.41

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    42
21 AUGUST 2006                  13:44:21                                   COLTR

Single phase columbus model - transient analysis



COLTR:TEE1


     NODE        VFLO         U             RE            RHO

        1       0.00013          1.41      11917.35       1000.03
        2       0.00000          0.00          0.00        998.35
================================================================================

COLTR:TEE2


     NODE        VFLO         U             RE            RHO

        1       0.00013          1.41      13666.51        999.32
        2       0.00000          0.00          0.00        998.35
================================================================================

COLTR:TEE3


     NODE        VFLO         U             RE            RHO

        1       0.00021          2.19      22902.29        998.75
        2       0.00007          0.77       9301.63        997.47
================================================================================

COLTR:TEE4


     NODE        VFLO         U             RE            RHO
```

Listing 10-3 Output for single-phase transient fluid loop model

```
            1        0.00021          2.19      26492.42        997.42
            2        0.00007          0.77       9343.98        997.44
```

Example 11 A Two-Phase Fluid Loop

This example illustrates the use of the general two-phase transient solution routine FGENFI. The fluid network consists of 2 heat exchangers, a pump and a side-branch accumulator.

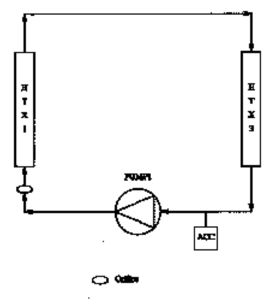

Figure 11-1 A two-phase fluid loop

Both heat exchangers are modelled using the user-defined element facility. Each heat exchanger is subdivided into 8 fluid nodes and 8 thermal nodes. The fluid nodes are linked to the thermal nodes using the GL(n1,n2) = * definition. A flow conductance value of 0.2 is defined between each node in the heat exchangers to model irreversible pressure losses. To represent heat input to the heat exchanger HTX1, internal heat sources are defined within each thermal node using the $SUBSTITUTIONS facility. The condensing heat exchanger, HTX3, is connected to a thermal boundary node using linear intermodel conductances. The conductance value is set large to force the fluid temperature to fall quickly to the boundary temperature. The temperature of the thermal boundary node is defined to be less than the saturation temperature of the fluid at the boundary pressure. Note that the fluid state descriptor FST has its default value of 'P&T'.

The solver FGENFI is a true transient and hence the solution will evolve in time from the initial fluid state defined by the user. If the loop contains no pressure boundary node then the mass of fluid in the loop is fixed by the initial conditions, and therefore the consistency and accuracy of the initial conditions are important. The steady state routine FGENSS can be called prior to the transient routine to provide consistent conditions. If no reservoir is defined then large pressure changes may occur (and possible solution failure) due to changes in density with time within the loop. This example uses an "R" type node (fixed pressure and enthalpy) to model a side branch accumulator hence avoiding large pressure fluctuations at phase change. The enthalpy of the node is specified such that the fluid is just below the point of saturation. Alternatively, instead of fixing the pressure via a boundary node, either the accumulator element ACTA or PASSA could be used. These model the actual response of an active or passive accumulator respectively.

The pump used is the centrifugal pump element PUMP_CF, with characteristic data supplied in the form of a table of values. A very small flow conductance value has been specified upstream of the heat exchanger HTX1. This results in a large pressure drop over the link and avoids the possibility of the flow reversing through the pump during the phase change from liquid to vapour.

FGENFI is a fully implicit solution routine and hence the user can define his or her own timestep via the control constant DTIMEI. In this example, DTIMEI has not been set and therefore the timestep used defaults to the value of the Courant limiting timestep DTCOUR. When choosing a timestep, it must be realised that when a phase transition occurs large changes in fluid properties and heat transfer coefficients occur; which can lead to convergence problems. FGENFI will automatically reduce the timestep used if NLOOP is reached before convergence has been achieved. Once a converged solution is obtained, the timestep is increased gradually back to the user-prescribed value.

The general solution FGENFI requires the control constants RELXCA, RELXMA, FRLXCA, OUTINT, TIMEND and NLOOP to be defined. TIMEO should be defined if the start time is different from zero and DTMIN, DTPMAX and DTMAX can be used to impose further constraints upon the time step. In this example, DTMAX is used to restrict the timestep to 1.0 seconds. QTRSOL has been set to 'NO' so that the full hydraulic transient behaviour is modelled (being a character control constant, QTRSOL cannot be set in the $CONTROL block). TABS and PABS have been set equal to zero to allow the units for temperature to be in kelvins and pressures to be absolute. NLOOP defines the maximum number of iterations within the implicit calculation at each time step. If NLOOP is reached then the time step is halved and the time step repeated. It is advisable to use a value of NLOOP no greater than about 200. If the iterations do not converge within this amount then it is likely that it is not going to converge at all and hence CPU time is wasted. The ESATAN Engineering Manual discusses further modelling guidelines such as this.

Listing 11-1 Model file for two-phase fluid loop

```
$MODEL FLOOP2, FLUID = WATER, GLOBALFILE=floop2.gbl
#
#
# Training manual floop2 - Two Phase Transient Solution
# Centrifugal pump used
#
#Copyright © 2006 ITP Engines UK Ltd.
#
   $MODEL PUMP, FLUID = WATER
#
   $ELEMENT PUMP_CF
#
   $SUBSTITUTIONS
#
   DIAM = 0.011 ;
   PRESS = 1.0E6 ;
   TEMP = 353.0 ;
   VOL = 4.999695E-4 ;
   MFLOW = 0.006;
   SPEED = 4000.0;
#
   VF_ARRAY = 0.0, 0.52E-4, 0.78E-4, 1.30E-4, 2.0E-2;
   DP_ARRAY = 1.23E5, 1.19E5, 1.14E5, 0.88E5, 0.0;
   EFF_ARRAY = 0.0, 0.482, 0.65, 0.67, 0.0;
#
   $ENDMODEL PUMP
#
   $MODEL ACCUM, FLUID = WATER
#
# Set to volume for 1.0 diameter * 1.0 length as per discussion
#
   $NODES
#
   R1 = 'ACCUMULATOR', A = 3.1426, FD = 1.0, FL = 1.0,
   P = 1.0E6, FF = 0.1E-4, T = 353.0;
#
   $ENDMODEL ACCUM
#
   $MODEL HTX1, FLUID = WATER
#
   $ELEMENT GENHTX
#
   $SUBSTITUTIONS
#
   FNUMS = 101;   # Start node numbering
   FNUMF = 108;   # End node numbering
   QINP = 1.25E3; # Heat input per node
   CAP = 107.97;  # Capacitance of pipe wall mCp [J/K]
   MSF = 0.006;   # Mass flow
#
   $ENDMODEL HTX1
#
   $MODEL HTX3, FLUID = WATER
#
   $ELEMENT GENHTX
#
   $SUBSTITUTIONS
#
   FNUMS = 301;   # Start node number
   FNUMF = 308;   # Finish node number
   QINP = 0.0;    # No heat input
   CAP = 107.97;  # Capacitance of pipe wall mCp [J/K]
   MSF = 0.006;   # Mass flow
#
   $ENDMODEL HTX3
#
# Main model
```

Listing 11-1 Model file for two-phase fluid loop

```
#
$LOCALS
#
$REAL
#
RL1 = 0.1E-4 ; # Friction factor to be defined Set to 0.01mm
#
$NODES
#
# Generate main model nodes
#
FOR KL1 = 1 TO 5 DO
   FKL1 = 'MAIN PIPE', A = 0.034557, FD = 0.011, FL = 1.0, P = 1.0E6,
   T = 353.0, FF = RL1;
END DO
#
FOR KL1 = 1 TO 5 DO
   KL2 = 1000 + KL1;
   DKL2 = 'PIPE WALL', T = 353.0, C = 107.973;
END DO
#
B300 = 'HTX3 BOUNDARY NODE', T = 356.0;
#
$CONDUCTORS
#
# Mass flow links
#
M(1, 2) = 0.006;
M(2, HTX1:101) = 0.006;
M(HTX1:108, 3) = 0.006;
M(3, 4) = 0.006;
M(4, HTX3:301) = 0.006;
M(HTX3:308, 5) = 0.006;
M(5, PUMP:1) = 0.006;
M(PUMP:2, 1) = 0.006;
M(5, ACCUM:1) = 0.0;
#
# Convective links to pipe wall
#
FOR  KL1 = 1 TO 5 DO
   KL2 = KL1 + 1000;
   GL(KL1, KL2) = *;
END DO
#
# Intermodel conductions links from HTX3 to boundary node 300
#
FOR KL1 = 1301 TO 1308 DO
   GL(300, HTX3:KL1) = 1.0E5;  # Large value to force wall temp = sink temp
END DO
#
GP(2, HTX1:101) = 1.25E-4;
#
$CONSTANTS
#
$CONTROL
#
PABS = 0.0;      # Pressures are all absolute
TABS = 0.0;      # Temperature in Kelvin
OUTINT = 60.0;   # Output interval
TIMEND = 60.0;   # End time of transient
DTMAX = 1.0;     # DTMAX used to restrict time step
NLOOP = 100;     # loop counter
RELXCA = 0.001;  # Convergence criteria
RELXMA = 0.001;  # Convergence criteria
FRLXCA = 0.001;  # Convergence criteria
#
GRAVZ = 9.81;
#
```

Listing 11-1 Model file for two-phase fluid loop

```
$EXECUTION  DYSTOR = 10000
C
      HEADER = 'Two Phase Transient Solution'
      QTRSOL = 'NO'
C
      CALL FGENFI
C
$OUTPUTS
C
      FORMAT = 'F10.4'
C
      CALL PRNDTB(' ', 'L, T, P', CURRENT)
      CALL PRNDBL(' ', 'M', CURRENT)
      CALL PRNDPT(' ', 'RHO,QUAL', CURRENT)
C
$ENDMODEL FLOOP2
```

Listing 11-2 Output for two-phase fluid loop model

```
EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     1
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution




 TIMEN =      0.00      MODULE FGENFI      DTIMEU = 1.000E+38
DTCOUR =   15.4017



TABLE OUTPUT WITH ZENTS = 'L,T,P'
FOR NODES OF ZLABEL = ' '

================================================================================

FLOOP2


         NODE   LABEL                              T             P

          300    HTX3 BOUNDARY NODE             356.00
         1001    PIPE WALL                      353.00
         1002    PIPE WALL                      353.00
         1003    PIPE WALL                      353.00
         1004    PIPE WALL                      353.00
         1005    PIPE WALL                      353.00

            1    MAIN PIPE                      353.00    1000000.00
            2    MAIN PIPE                      353.00    1000000.00
            3    MAIN PIPE                      353.00    1000000.00
            4    MAIN PIPE                      353.00    1000000.00
            5    MAIN PIPE                      353.00    1000000.00

================================================================================

FLOOP2:PUMP


         NODE   LABEL                              T             P


            1                                   353.00    1000000.00
            2                                   353.00    1000000.00

================================================================================

FLOOP2:ACCUM


         NODE   LABEL                              T             P


            1    ACCUMULATOR                    353.00    1000000.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     2
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution



FLOOP2:HTX1
```

Listing 11-2 Output for two-phase fluid loop model

```
         NODE   LABEL                              T              P

        1101    HEAT X WALL                     356.00
        1102    HEAT X WALL                     356.00
        1103    HEAT X WALL                     356.00
        1104    HEAT X WALL                     356.00
        1105    HEAT X WALL                     356.00
        1106    HEAT X WALL                     356.00
        1107    HEAT X WALL                     356.00
        1108    HEAT X WALL                     356.00

         101    HEAT X FLUID                    353.00    1000000.00
         102    HEAT X FLUID                    353.00    1000000.00
         103    HEAT X FLUID                    353.00    1000000.00
         104    HEAT X FLUID                    353.00    1000000.00
         105    HEAT X FLUID                    353.00    1000000.00
         106    HEAT X FLUID                    353.00    1000000.00
         107    HEAT X FLUID                    353.00    1000000.00
         108    HEAT X FLUID                    353.00    1000000.00

================================================================================

FLOOP2:HTX3


         NODE   LABEL                              T              P

        1301    HEAT X WALL                     356.00
        1302    HEAT X WALL                     356.00
        1303    HEAT X WALL                     356.00
        1304    HEAT X WALL                     356.00
        1305    HEAT X WALL                     356.00
        1306    HEAT X WALL                     356.00
        1307    HEAT X WALL                     356.00
        1308    HEAT X WALL                     356.00

         301    HEAT X FLUID                    353.00    1000000.00
         302    HEAT X FLUID                    353.00    1000000.00
         303    HEAT X FLUID                    353.00    1000000.00
         304    HEAT X FLUID                    353.00    1000000.00
         305    HEAT X FLUID                    353.00    1000000.00
         306    HEAT X FLUID                    353.00    1000000.00
         307    HEAT X FLUID                    353.00    1000000.00
         308    HEAT X FLUID                    353.00    1000000.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     3
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution





 TIMEN =      0.00      MODULE FGENFI      DTIMEU = 1.000E+38
DTCOUR =   15.4017




BLOCK OUTPUT WITH ZENTS = 'M'
FOR NODES OF ZLABEL = ' '


FLOOP2

VALUES FOR CONDUCTORS M  :
M (1,2)      =     0.0060      M (1,Z2:2)   =    -0.0060
```

Listing 11-2 Output for two-phase fluid loop model

```
M (2,1)      =    -0.0060      M (2,Z4:101) =     0.0060
M (3,4)      =     0.0060      M (3,Z4:108) =    -0.0060
M (4,3)      =    -0.0060      M (4,Z5:301) =     0.0060
M (5,Z2:1)   =     0.0060      M (5,Z3:1)   =     0.0000
M (5,Z5:308) =    -0.0060


FLOOP2:PUMP

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0060      M (1,Z1:5) =    -0.0060
M (2,1)    =    -0.0060      M (2,Z1:1) =     0.0060


FLOOP2:ACCUM

VALUES FOR CONDUCTORS M  :
M (1,Z1:5) =     0.0000


FLOOP2:HTX1

VALUES FOR CONDUCTORS M  :
M (101,102)  =     0.0060      M (101,Z1:2) =    -0.0060
M (102,101)  =    -0.0060      M (102,103)  =     0.0060
M (103,102)  =    -0.0060      M (103,104)  =     0.0060
M (104,103)  =    -0.0060      M (104,105)  =     0.0060
M (105,104)  =    -0.0060      M (105,106)  =     0.0060
M (106,105)  =    -0.0060      M (106,107)  =     0.0060
M (107,106)  =    -0.0060      M (107,108)  =     0.0060
M (108,107)  =    -0.0060      M (108,Z1:3) =     0.0060


FLOOP2:HTX3

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     4
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution




VALUES FOR CONDUCTORS M  :
M (301,302)  =     0.0060      M (301,Z1:4) =    -0.0060
M (302,301)  =    -0.0060      M (302,303)  =     0.0060
M (303,302)  =    -0.0060      M (303,304)  =     0.0060
M (304,303)  =    -0.0060      M (304,305)  =     0.0060
M (305,304)  =    -0.0060      M (305,306)  =     0.0060
M (306,305)  =    -0.0060      M (306,307)  =     0.0060
M (307,306)  =    -0.0060      M (307,308)  =     0.0060
M (308,307)  =    -0.0060      M (308,Z1:5) =     0.0060



 KEY FOR SUB-MODEL CODE :


Z1 = FLOOP2


Z2 = FLOOP2:PUMP


Z3 = FLOOP2:ACCUM
```

Listing 11-2 Output for two-phase fluid loop model

```
Z4 = FLOOP2:HTX1


Z5 = FLOOP2:HTX3

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     5
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution





 TIMEN =      0.00      MODULE FGENFI      DTIMEU = 1.000E+38
DTCOUR =   15.4017



TABLE OUTPUT WITH ZENTS = 'RHO,QUAL'
FOR NODES OF ZLABEL = ' '

================================================================================

FLOOP2


      NODE        RHO           QUAL

         1        972.40       0.00000
         2        972.40       0.00000
         3        972.40       0.00000
         4        972.40       0.00000
         5        972.40       0.00000
================================================================================

FLOOP2:PUMP


      NODE        RHO           QUAL

         1        972.40       0.00000
         2        972.40       0.00000
================================================================================

FLOOP2:ACCUM


      NODE        RHO           QUAL

         1        972.40       0.00000

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     6
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution



FLOOP2:HTX1


      NODE        RHO           QUAL

       101        972.40       0.00000
       102        972.40       0.00000
       103        972.40       0.00000
       104        972.40       0.00000
```

Listing 11-2 Output for two-phase fluid loop model

```
       105        972.40       0.00000
       106        972.40       0.00000
       107        972.40       0.00000
       108        972.40       0.00000
================================================================================

FLOOP2:HTX3


      NODE        RHO           QUAL

       301        972.40       0.00000
       302        972.40       0.00000
       303        972.40       0.00000
       304        972.40       0.00000
       305        972.40       0.00000
       306        972.40       0.00000
       307        972.40       0.00000
       308        972.40       0.00000

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     7
21 AUGUST 2006                  13:48:32                                  FLOOP2

Two Phase Transient Solution





 TIMEN =     60.00      MODULE FGENFI      DTIMEU =    0.1513
DTCOUR =    0.3146



TABLE OUTPUT WITH ZENTS = 'L,T,P'
FOR NODES OF ZLABEL = ' '

================================================================================

FLOOP2


         NODE   LABEL                              T             P

          300    HTX3 BOUNDARY NODE             356.00
         1001    PIPE WALL                      355.29
         1002    PIPE WALL                      354.92
         1003    PIPE WALL                      453.15
         1004    PIPE WALL                      453.11
         1005    PIPE WALL                      356.53

            1    MAIN PIPE                      355.36    1121432.27
            2    MAIN PIPE                      355.00    1121381.59
            3    MAIN PIPE                      453.15    1001896.15
            4    MAIN PIPE                      453.11    1001047.91
            5    MAIN PIPE                      356.53     999994.35

================================================================================

FLOOP2:PUMP


         NODE   LABEL                              T             P


            1                                   356.14     999969.00
            2                                   355.70    1121457.73
```

Listing 11-2 Output for two-phase fluid loop model

```
================================================================================

FLOOP2:ACCUM


         NODE   LABEL                              T              P


           1    ACCUMULATOR                     353.00    1000000.00

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     8
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution



FLOOP2:HTX1


         NODE   LABEL                              T              P

        1101    HEAT X WALL                     390.59
        1102    HEAT X WALL                     407.40
        1103    HEAT X WALL                     424.08
        1104    HEAT X WALL                     440.24
        1105    HEAT X WALL                     454.53
        1106    HEAT X WALL                     456.64
        1107    HEAT X WALL                     456.38
        1108    HEAT X WALL                     456.10

         101    HEAT X FLUID                    373.35    1005129.62
         102    HEAT X FLUID                    391.50    1005051.81
         103    HEAT X FLUID                    409.24    1004974.70
         104    HEAT X FLUID                    426.29    1004897.78
         105    HEAT X FLUID                    442.41    1004820.61
         106    HEAT X FLUID                    453.27    1004635.51
         107    HEAT X FLUID                    453.24    1003989.94
         108    HEAT X FLUID                    453.18    1002730.62

================================================================================

FLOOP2:HTX3


         NODE   LABEL                              T              P

        1301    HEAT X WALL                     356.06
        1302    HEAT X WALL                     356.02
        1303    HEAT X WALL                     356.01
        1304    HEAT X WALL                     356.01
        1305    HEAT X WALL                     356.00
        1306    HEAT X WALL                     356.00
        1307    HEAT X WALL                     356.00
        1308    HEAT X WALL                     356.00

         301    HEAT X FLUID                    413.58    1000735.89
         302    HEAT X FLUID                    383.28    1000640.55
         303    HEAT X FLUID                    369.62    1000543.80
         304    HEAT X FLUID                    362.97    1000446.03
         305    HEAT X FLUID                    359.61    1000347.66
         306    HEAT X FLUID                    357.89    1000248.94
         307    HEAT X FLUID                    356.99    1000150.04
         308    HEAT X FLUID                    356.53    1000051.04

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE     9
21 AUGUST 2006                   13:48:32                                 FLOOP2
```

Listing 11-2 Output for two-phase fluid loop model

```
Two Phase Transient Solution





 TIMEN =     60.00      MODULE FGENFI      DTIMEU =    0.1513
DTCOUR =    0.3146



BLOCK OUTPUT WITH ZENTS = 'M'
FOR NODES OF ZLABEL = ' '


FLOOP2

VALUES FOR CONDUCTORS M  :
M (1,2)      =     0.0160      M (1,Z2:2)   =    -0.0160
M (2,1)      =    -0.0160      M (2,Z4:101) =     0.0160
M (3,4)      =     0.0188      M (3,Z4:108) =    -0.0184
M (4,3)      =    -0.0188      M (4,Z5:301) =     0.0192
M (5,Z2:1)   =     0.0159      M (5,Z3:1)   =     0.0033
M (5,Z5:308) =    -0.0193


FLOOP2:PUMP

VALUES FOR CONDUCTORS M  :
M (1,2)    =     0.0160      M (1,Z1:5) =    -0.0159
M (2,1)    =    -0.0160      M (2,Z1:1) =     0.0160


FLOOP2:ACCUM

VALUES FOR CONDUCTORS M  :
M (1,Z1:5) =    -0.0033


FLOOP2:HTX1

VALUES FOR CONDUCTORS M  :
M (101,102)  =     0.0160      M (101,Z1:2) =    -0.0160
M (102,101)  =    -0.0160      M (102,103)  =     0.0160
M (103,102)  =    -0.0160      M (103,104)  =     0.0160
M (104,103)  =    -0.0160      M (104,105)  =     0.0160
M (105,104)  =    -0.0160      M (105,106)  =     0.0160
M (106,105)  =    -0.0160      M (106,107)  =     0.0176
M (107,106)  =    -0.0176      M (107,108)  =     0.0181
M (108,107)  =    -0.0181      M (108,Z1:3) =     0.0184


FLOOP2:HTX3

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    10
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution





VALUES FOR CONDUCTORS M  :
M (301,302)  =     0.0193      M (301,Z1:4) =    -0.0192
M (302,301)  =    -0.0193      M (302,303)  =     0.0193
M (303,302)  =    -0.0193      M (303,304)  =     0.0193
M (304,303)  =    -0.0193      M (304,305)  =     0.0193
```

Listing 11-2 Output for two-phase fluid loop model

```
M (305,304)  =    -0.0193      M (305,306)  =     0.0193
M (306,305)  =    -0.0193      M (306,307)  =     0.0193
M (307,306)  =    -0.0193      M (307,308)  =     0.0193
M (308,307)  =    -0.0193      M (308,Z1:5) =     0.0193



 KEY FOR SUB-MODEL CODE :


Z1 = FLOOP2


Z2 = FLOOP2:PUMP


Z3 = FLOOP2:ACCUM


Z4 = FLOOP2:HTX1


Z5 = FLOOP2:HTX3

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    11
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution





 TIMEN =     60.00      MODULE FGENFI      DTIMEU =    0.1513
DTCOUR =    0.3146



TABLE OUTPUT WITH ZENTS = 'RHO,QUAL'
FOR NODES OF ZLABEL = ' '

================================================================================

FLOOP2


      NODE        RHO           QUAL

         1        970.97       0.00000
         2        971.20       0.00000
         3         61.58       0.07841
         4         62.84       0.07666
         5        970.18       0.00000
================================================================================

FLOOP2:PUMP


      NODE        RHO           QUAL

         1        970.43       0.00000
         2        970.76       0.00000
================================================================================

FLOOP2:ACCUM


      NODE        RHO           QUAL
```

Listing 11-2 Output for two-phase fluid loop model

```
         1        972.40       0.00000

EUROPEAN  SPACE  AGENCY  THERMAL  ANALYSIS  NETWORK  (VERSION 9.6.1)  PAGE    12
21 AUGUST 2006                   13:48:32                                 FLOOP2

Two Phase Transient Solution



FLOOP2:HTX1


      NODE        RHO           QUAL

       101        958.78       0.00000
       102        944.96       0.00000
       103        930.01       0.00000
       104        914.35       0.00000
       105        898.32       0.00000
       106        272.21       0.01325
       107         98.21       0.04708
       108         60.51       0.07997
================================================================================

FLOOP2:HTX3


      NODE        RHO           QUAL

       301        926.14       0.00000
       302        951.40       0.00000
       303        961.43       0.00000
       304        965.97       0.00000
       305        968.20       0.00000
       306        969.31       0.00000
       307        969.89       0.00000
       308        970.18       0.00000
```