Software Requirements Specification for Solar Water Heating System With No Phase Change Material

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Contents

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

The unit system used throughout is SI (Système International d'Unités). In addition to the basic units, several derived units are also used. For each unit, the Table of Units lists the symbol, a description, and the SI name.

Table 1: Table of Units

Symbol	Description	SI Name
°C	temperature	centigrade
J	energy	joule
kg	mass	kilogram
m	length	metre
s	time	second
W	power	watt

1.2 Table of Symbols

The symbols used in this document are summarized in the Table of Symbols along with their units. The choice of symbols was made to be consistent with the heat transfer literature and with existing documentation for solar water heating systems with no phase change material. The symbols are listed in alphabetical order. For vector quantities, the units shown are for each component of the vector.

Table 2: Table of Symbols

Symbol	Description	Units
A_{C}	Heating coil surface area	m^2
$A_{\mathrm{C}}{}^{\max}$	Maximum surface area of coil	m^2
A_{in}	Surface area over which heat is transferred in	m^2
A_{out}	Surface area over which heat is transferred out	m^2
A_{tol}	Absolute tolerance	–
$AR_{\max}$	Maximum aspect ratio	–
$AR_{\min}$	Minimum aspect ratio	–

Table 2: Table of Symbols (Continued)

Symbol	Description	Units
C	Specific heat capacity	$\frac{\text{J}}{\text{kg°C}}$
C^{L}	Specific heat capacity of a liquid	$\frac{\text{J}}{\text{kg°C}}$
C_{W}	Specific heat capacity of water	$\frac{\text{J}}{\text{kg°C}}$
$C_{\text{W}}{}^{\text{max}}$	Maximum specific heat capacity of water	$\frac{\text{J}}{\text{kg°C}}$
$C_{\text{W}}{}^{\text{min}}$	Minimum specific heat capacity of water	$\frac{\text{J}}{\text{kg°C}}$
D	Diameter of tank	m
E	Sensible heat	J
E_{W}	Change in heat energy in the water	J
g	Volumetric heat generation per unit volume	$\frac{\text{W}}{\text{m}^3}$
h	Convective heat transfer coefficient	$\frac{\text{W}}{\text{m}^2\text{°C}}$
h_{C}	Convective heat transfer coefficient between coil and water	$\frac{\text{W}}{\text{m}^2\text{°C}}$
$h_{\text{C}}{}^{\text{max}}$	Maximum convective heat transfer coefficient between coil and water	$\frac{\text{W}}{\text{m}^2\text{°C}}$
$h_{\text{C}}{}^{\text{min}}$	Minimum convective heat transfer coefficient between coil and water	$\frac{\text{W}}{\text{m}^2\text{°C}}$
L	Length of tank	m
L_{max}	Maximum length of tank	m
L_{min}	Minimum length of tank	m
m	Mass	kg
m_{W}	Mass of water	kg
$\hat{\mathbf{n}}$	Normal vector	−
q	Heat flux	$\frac{\text{W}}{\text{m}^2}$
q_{C}	Heat flux into the water from the coil	$\frac{\text{W}}{\text{m}^2}$
q_{in}	Heat flux input	$\frac{\text{W}}{\text{m}^2}$
q_{out}	Heat flux output	$\frac{\text{W}}{\text{m}^2}$
$\mathbf{q}$	Thermal flux vector	$\frac{\text{W}}{\text{m}^2}$
R_{tol}	Relative tolerance	−
S	Surface	m^2
T	Temperature	°C
ΔT	Change in temperature	°C
T_{C}	Temperature of the heating coil	°C

Table 2: Table of Symbols (Continued)

Symbol	Description	Units
T_env	Temperature of the environment	°C
T_init	Initial temperature	°C
T_W	Temperature of the water	°C
t	Time	s
t_final	Final time	s
$t_\text{final}{}^\text{max}$	Maximum final time	s
t_step	Time step for simulation	s
V	Volume	m^3
V_tank	Volume of the cylindrical tank	m^3
V_W	Volume of water	m^3
π	Ratio of circumference to diameter for any circle	–
ρ	Density	$\frac{\text{kg}}{\text{m}^3}$
ρ_W	Density of water	$\frac{\text{kg}}{\text{m}^3}$
$\rho_\text{W}{}^\text{max}$	Maximum density of water	$\frac{\text{kg}}{\text{m}^3}$
$\rho_\text{W}{}^\text{min}$	Minimum density of water	$\frac{\text{kg}}{\text{m}^3}$
τ_W	ODE parameter for water related to decay time	s
∇	Gradient	–

1.3 Abbreviations and Acronyms

Table 3: Abbreviations and Acronyms

Abbreviation	Full Form
A	Assumption
DD	Data Definition
GD	General Definition
GS	Goal Statement
IM	Instance Model
LC	Likely Change
ODE	Ordinary Differential Equation

Table 3: Abbreviations and Acronyms (Continued)

Abbreviation	Full Form
PS	Physical System Description
R	Requirement
RefBy	Referenced by
Refname	Reference Name
SRS	Software Requirements Specification
SWHSNoPCM	Solar Water Heating System With No Phase Change Material
TM	Theoretical Model
UC	Unlikely Change
Uncert.	Typical Uncertainty

2 Introduction

Due to increasing costs, diminishing availability, and negative environmental impact of fossil fuels, the demand is high for renewable energy sources and energy storage technology. Solar Water Heating System with no Phase Change Material provide a novel way of storing energy.

The following section provides an overview of the Software Requirements Specification (SRS) for solar water heating systems with no phase change material The developed program will be referred to as Solar Water Heating System With No Phase Change Material (SWHSNoPCM) based on the original, manually created version of SWHSNoPCM. This section explains the purpose of this document, the scope of the requirements, the characteristics of the intended reader, and the organization of the document.

2.1 Purpose of Document

The primary purpose of this document is to record the requirements of SWHSNoPCM. Goals, assumptions, theoretical models, definitions, and other model derivation information are specified, allowing the reader to fully understand and verify the purpose and scientific basis of SWHSNoPCM. With the exception of system constraints, this SRS will remain abstract, describing what problem is being solved, but not how to solve it.

This document will be used as a starting point for subsequent development phases, including writing the design specification and the software verification and validation plan. The design document will show how the requirements are to be realized, including decisions on the numerical algorithms and programming environment. The verification and validation plan will show the steps that will be used to increase confidence in the software documentation and the implementation. Although the SRS fits in a series of documents that follow the so-called waterfall model, the actual development process is not constrained in any way.

Even when the waterfall model is not followed, as Parnas and Clements point out [4], the most logical way to present the documentation is still to "fake" a rational design process.

2.2 Scope of Requirements

The scope of the requirements includes thermal analysis of a single solar water heating tank.

2.3 Characteristics of Intended Reader

Reviewers of this documentation should have an understanding of heat transfer theory from level 3 or 4 mechanical engineering and differential equations from level 1 and 2 calculus. The users of SWHSNoPCM can have a lower level of expertise, as explained in Sec:User Characteristics.

2.4 Organization of Document

The organization of this document follows the template for an SRS for scientific computing software proposed by [2], [6], [7], and [5]. The presentation follows the standard pattern of presenting goals, theories, definitions, and assumptions. For readers that would like a more bottom up approach, they can start reading the instance models and trace back to find any additional information they require.

The goal statements are refined to the theoretical models and the theoretical models to the instance models. The instance model to be solved is referred to as IM:eBalanceOnWtr. The instance model provides the Ordinary Differential Equation (ODE) that models the solar water heating system with no phase change material. SWHSNoPCM solves this ODE.

3 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics, and lists the system constraints.

3.1 System Context

Fig:SysCon shows the system context. A circle represents an external entity outside the software, the user in this case. A rectangle represents the software system itself (SWHSNoPCM). Arrows are used to show the data flow between the system and its environment.

Figure 1: System Context

SWHSNoPCM is mostly self-contained. The only external interaction is through the user interface. The responsibilities of the user and the system are as follows:

- User Responsibilities:
    - Provide the input data to the system, ensuring no errors in the data entry
    - Take care that consistent units are used for input variables
- SWHSNoPCM Responsibilities:
    - Detect data type mismatch, such as a string of characters instead of a floating point number
    - Determine if the inputs satisfy the required physical and software constraints
    - Calculate the required outputs

3.2 User Characteristics

The end user of SWHSNoPCM should have an understanding of undergraduate Level 1 Calculus and Physics.

3.3 System Constraints

There are no system constraints.

4 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved. This is followed by the solution characteristics specification, which presents the assumptions, theories, and definitions that are used.

4.1 Problem Description

A system is needed to investigate the heating of water in a solar water heating tank.

4.1.1 Terminology and Definitions

This subsection provides a list of terms that are used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements.

- Heat flux: The rate of thermal energy transfer through a given surface per unit time.

- Specific heat capacity: The amount of energy required to raise the temperature of the unit mass of a given substance by a given amount.

- Thermal conduction: The transfer of heat energy through a substance.

- Transient: Changing with time.

4.1.2 Physical System Description

The physical system of SWHSNoPCM, as shown in Fig:Tank, includes the following elements:

PS1: Tank containing water.

PS2: Heating coil at bottom of tank. (q_C represents the heat flux into the water from the coil.)

Figure 2: Solar water heating tank, with heat flux from heating coil of q_{C}

4.1.3 Goal Statements

Given the temperature of the heating coil, the initial temperature of the water, and the material properties, the goal statements are:

Predict-Water-Temperature: Predict the temperature of the water over time.

Predict-Water-Energy: Predict the change in heat energy in the water over time.

4.2 Solution Characteristics Specification

The instance models that govern SWHSNoPCM are presented in the Instance Model Section. The information to understand the meaning of the instance models and their derivation is also presented, so that the instance models can be verified.

4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical models by filling in the missing information for the physical system. The assumptions refine the scope by providing more detail.

Thermal-Energy-Only: The only form of energy that is relevant for this problem is thermal energy. All other forms of energy, such as mechanical energy, are assumed to be negligible. (RefBy: TM:consThermE.)

Heat-Transfer-Coeffs-Constant: All heat transfer coefficients are constant over time. (RefBy: TM:nwtnCooling.)

Constant-Water-Temp-Across-Tank: The water in the tank is fully mixed, so the temperature of the water is the same throughout the entire tank. (RefBy: GD:rocTempSimp.)

Density-Water-Constant-over-Volume: The density of water has no spatial variation; that is, it is constant over their entire volume. (RefBy: GD:rocTempSimp.)

Specific-Heat-Energy-Constant-over-Volume: The specific heat capacity of water has no spatial variation; that is, it is constant over its entire volume. (RefBy: GD:rocTempSimp.)

Newton-Law-Convective-Cooling-Coil-Water: Newton's law of convective cooling applies between the heating coil and the water. (RefBy: GD:htFluxWaterFromCoil.)

Temp-Heating-Coil-Constant-over-Time: The temperature of the heating coil is constant over time. (RefBy: GD:htFluxWaterFromCoil and LC:Temperature-Coil-Variable-Over-Day.)

Temp-Heating-Coil-Constant-over-Length: The temperature of the heating coil does not vary along its length. (RefBy: LC:Temperature-Coil-Variable-Over-Length.)

Charging-Tank-No-Temp-Discharge: The model only accounts for charging the tank, not discharging. The temperature of the water can only increase, or remain constant; it cannot decrease. This implies that the initial temperature is less than (or equal to) the temperature of the heating coil. (RefBy: LC:Discharging-Tank.)

Water-Always-Liquid: The operating temperature range of the system is such that the material (water in this case) is always in liquid state. That is, the temperature will not drop below the melting point temperature of water, or rise above its boiling point temperature. (RefBy: TM:sensHtE, IM:heatEInWtr, IM:eBalanceOnWtr, and UC:Water-Fixed-States.)

Perfect-Insulation-Tank: The tank is perfectly insulated so that there is no heat loss from the tank. (RefBy: IM:eBalanceOnWtr and LC:Tank-Lose-Heat.)

No-Internal-Heat-Generation-By-Water: No internal heat is generated by the water; therefore, the volumetric heat generation per unit volume is zero. (RefBy: IM:eBalanceOnWtr and UC:No-Internal-Heat-Generation.)

Atmospheric-Pressure-Tank: The pressure in the tank is atmospheric, so the melting point temperature and boiling point temperature of water are 0°C and 100°C, respectively. (RefBy: IM:heatEInWtr.)

Volume-Coil-Negligible: When considering the volume of water in the tank, the volume of the heating coil is assumed to be negligible. (RefBy: DD:waterVolume_nopcm.)

4.2.2 Theoretical Models

This section focuses on the general equations and laws that SWHSNoPCM is based on.

Refname	TM:consThermE
Label	Conservation of thermal energy
Equation	$$-\nabla \cdot \mathbf{q} + g = \rho\, C\, \frac{\partial T}{\partial t}$$
Description	∇ is the gradient (Unitless) $\mathbf{q}$ is the thermal flux vector ($\frac{\text{W}}{\text{m}^2}$) g is the volumetric heat generation per unit volume ($\frac{\text{W}}{\text{m}^3}$) ρ is the density ($\frac{\text{kg}}{\text{m}^3}$) C is the specific heat capacity ($\frac{\text{J}}{\text{kg}^{\circ}\text{C}}$) t is the time (s) T is the temperature (°C)
Notes	The above equation gives the law of conservation of energy for transient heat transfer in a given material. For this equation to apply, other forms of energy, such as mechanical energy, are assumed to be negligible in the system (A:Thermal-Energy-Only).
Source	Fourier Law of Heat Conduction and Heat Equation
RefBy	GD:rocTempSimp

Refname	TM:sensHtE
Label	Sensible heat energy (no state change)
Equation	$$E = C^{\mathrm{L}}\, m\, \Delta T$$
Description	E is the sensible heat (J) C^{L} is the specific heat capacity of a liquid $\left(\frac{\mathrm{J}}{\mathrm{kg}^{\circ}\mathrm{C}}\right)$ m is the mass (kg) ΔT is the change in temperature (°C)
Notes	E occurs as long as the material does not reach a temperature where a phase change occurs, as assumed in A:Water-Always-Liquid.
Source	Definition of Sensible Heat
RefBy	IM:heatEInWtr

Refname	TM:nwtnCooling
Label	Newton's law of cooling
Equation	$$q\left(t\right) = h\,\Delta T(t)$$
Description	q is the heat flux $\left(\frac{\text{W}}{\text{m}^2}\right)$ t is the time (s) h is the convective heat transfer coefficient $\left(\frac{\text{W}}{\text{m}^2{}^\circ\text{C}}\right)$ ΔT is the change in temperature ($^\circ$C)
Notes	Newton's law of cooling describes convective cooling from a surface. The law is stated as: the rate of heat loss from a body is proportional to the difference in temperatures between the body and its surroundings. h is assumed to be independent of T (from A:Heat-Transfer-Coeffs-Constant). $\Delta T(t) = T(t) - T_{\text{env}}\left(t\right)$ is the time-dependant thermal gradient between the environment and the object.
Source	[1, (pg. 8)]
RefBy	GD:htFluxWaterFromCoil

4.2.3 General Definitions

This section collects the laws and equations that will be used to build the instance models.

Refname	GD:rocTempSimp
Label	Simplified rate of change of temperature
Equation	$$m\,C\,\frac{dT}{dt} = q_{\text{in}}\,A_{\text{in}} - q_{\text{out}}\,A_{\text{out}} + g\,V$$
Description	m is the mass (kg) C is the specific heat capacity $(\frac{\text{J}}{\text{kg}^\circ\text{C}})$ t is the time (s) T is the temperature (°C) q_{in} is the heat flux input $(\frac{\text{W}}{\text{m}^2})$ A_{in} is the surface area over which heat is transferred in (m^2) q_{out} is the heat flux output $(\frac{\text{W}}{\text{m}^2})$ A_{out} is the surface area over which heat is transferred out (m^2) g is the volumetric heat generation per unit volume $(\frac{\text{W}}{\text{m}^3})$ V is the volume (m^3)
Source	–
RefBy	GD:rocTempSimp and IM:eBalanceOnWtr

Detailed derivation of simplified rate of change of temperature: Integrating TM:consThermE over a volume (V), we have:

$$-\int_V \nabla \cdot \mathbf{q}\,dV + \int_V g\,dV = \int_V \rho\,C\,\frac{\partial T}{\partial t}\,dV$$

Applying Gauss's Divergence Theorem to the first term over the surface S of the volume, with $\mathbf{q}$ as the thermal flux vector for the surface and $\hat{\mathbf{n}}$ as a unit outward normal vector for a surface:

$$-\int_S \mathbf{q} \cdot \hat{\mathbf{n}}\,dS + \int_V g\,dV = \int_V \rho\,C\,\frac{\partial T}{\partial t}\,dV$$

We consider an arbitrary volume. The volumetric heat generation per unit volume is assumed constant. Then Equation (1) can be written as:

$$q_{\text{in}}\,A_{\text{in}} - q_{\text{out}}\,A_{\text{out}} + g\,V = \int_V \rho\,C\,\frac{\partial T}{\partial t}\,dV$$

Where q_{in}, q_{out}, A_{in}, and A_{out} are explained in GD:rocTempSimp. Assuming ρ, C, and T are constant over the volume, which is true in our case by A:Constant-Water-Temp-Across-

Tank, A:Density-Water-Constant-over-Volume, and A:Specific-Heat-Energy-Constant-over-Volume, we have:

$$\rho\, C V \frac{dT}{dt} = q_{\text{in}}\, A_{\text{in}} - q_{\text{out}}\, A_{\text{out}} + g\, V$$

Using the fact that $\rho = m/V$, Equation (2) can be written as:

$$m\, C\, \frac{dT}{dt} = q_{\text{in}}\, A_{\text{in}} - q_{\text{out}}\, A_{\text{out}} + g\, V$$

Refname	GD:htFluxWaterFromCoil
Label	Heat flux into the water from the coil
Units	$\frac{\text{W}}{\text{m}^2}$
Equation	$$q_{\text{C}} = h_{\text{C}}\ (T_{\text{C}} - T_{\text{W}}\,(t))$$
Description	q_{C} is the heat flux into the water from the coil $(\frac{\text{W}}{\text{m}^2})$ h_{C} is the convective heat transfer coefficient between coil and water $(\frac{\text{W}}{\text{m}^2 \cdot \text{C}})$ T_{C} is the temperature of the heating coil (°C) T_{W} is the temperature of the water (°C) t is the time (s)
Notes	q_{C} is found by assuming that Newton's law of cooling applies (A:Newton-Law-Convective-Cooling-Coil-Water). This law (defined in TM:nwtnCooling) is used on the surface of the heating coil. A:Temp-Heating-Coil-Constant-over-Time
Source	[2]
RefBy	IM:eBalanceOnWtr

4.2.4   Data Definitions

This section collects and defines all the data needed to build the instance models.

Refname	DD:waterMass
Label	Mass of water
Symbol	m_W
Units	kg
Equation	

$$m_\text{W} = V_\text{W}\, \rho_\text{W}$$

Description	m_W is the mass of water (kg) V_W is the volume of water (m^3) ρ_W is the density of water ($\frac{\text{kg}}{\text{m}^3}$)
Source	–
RefBy	FR:Find-Mass

Refname	DD:waterVolume.nopcm
Label	Volume of water
Symbol	V_W
Units	m^3
Equation	$$V_\text{W} = V_\text{tank}$$
Description	V_W is the volume of water (m^3) V_tank is the volume of the cylindrical tank (m^3)
Notes	Based on A:Volume-Coil-Negligible. V_tank is defined in DD:tankVolume.
Source	–
RefBy	FR:Find-Mass

Refname	DD:tankVolume
Label	Volume of the cylindrical tank
Symbol	V_{tank}
Units	m^3
Equation	$$V_{\text{tank}} = \pi \left(\frac{D}{2} \right)^2 L$$
Description	V_{tank} is the volume of the cylindrical tank (m^3) π is the ratio of circumference to diameter for any circle (Unitless) D is the diameter of tank (m) L is the length of tank (m)
Source	–
RefBy	FR:Find-Mass and DD:waterVolume_nopcm

Refname	DD:balanceDecayRate
Label	ODE parameter for water related to decay time
Symbol	τ_W
Units	s
Equation	$$\tau_\text{W} = \frac{m_\text{W}\, C_\text{W}}{h_\text{C}\, A_\text{C}}$$
Description	τ_W is the ODE parameter for water related to decay time (s) m_W is the mass of water (kg) C_W is the specific heat capacity of water $\left(\frac{\text{J}}{\text{kg}^\circ\text{C}}\right)$ h_C is the convective heat transfer coefficient between coil and water $\left(\frac{\text{W}}{\text{m}^{2}{}^\circ\text{C}}\right)$ A_C is the heating coil surface area (m^2)
Source	[2]
RefBy	IM:eBalanceOnWtr and FR:Output-Input-Derived-Values

4.2.5 Instance Models

This section transforms the problem defined in the problem description into one which is expressed in mathematical terms. It uses concrete symbols defined in the data definitions to replace the abstract symbols in the models identified in theoretical models and general definitions.

The goal GS:Predict-Water-Temperature is met by IM:eBalanceOnWtr and the goal GS:Predict-Water-Energy is met by IM:heatEInWtr.

Refname	IM:eBalanceOnWtr
Label	Energy balance on water to find the temperature of the water
Input	T_C, T_{init}, t_{final}, A_C, h_C, C_W, m_W
Output	T_W
Input Constraints	$$T_C \geq T_{init}$$
Output Constraints	
Equation	$$\frac{dT_W}{dt} + \frac{1}{\tau_W} T_W = \frac{1}{\tau_W} T_C$$
Description	t is the time (s) T_W is the temperature of the water (°C) τ_W is the ODE parameter for water related to decay time (s) T_C is the temperature of the heating coil (°C)
Notes	τ_W is calculated from DD:balanceDecayRate. The above equation applies as long as the water is in liquid form, $0 < T_W < 100$ (°C) where 0 (°C) and 100 (°C) are the melting and boiling point temperatures of water, respectively (A:Water-Always-Liquid).
Source	[2, (with PCM removed)]
RefBy	UC:No-Internal-Heat-Generation, FR:Output-Values, FR:Find-Mass, and FR:Calculate-Values

Detailed derivation of the energy balance on water: To find the rate of change of T_W, we look at the energy balance on water. The volume being considered is the volume of water in the tank V_W, which has mass m_W and specific heat capacity, C_W. Heat transfer occurs in the water from the heating coil as q_C (GD:htFluxWaterFromCoil), over area A_C. No heat transfer occurs to the outside of the tank, since it has been assumed to be perfectly

insulated (A:Perfect-Insulation-Tank). Since the assumption is made that no internal heat is generated (A:No-Internal-Heat-Generation-By-Water), $g = 0$. Therefore, the equation for GD:rocTempSimp can be written as:

$$m_W\, C_W\, \tfrac{dT_W}{dt} = q_C\, A_C$$

Using GD:htFluxWaterFromCoil for q_C, this can be written as:

$$m_W\, C_W\, \tfrac{dT_W}{dt} = h_C\, A_C\, (T_C - T_W)$$

Dividing Equation (2) by $m_W\, C_W$, we obtain:

$$\tfrac{dT_W}{dt} = \tfrac{h_C\, A_C}{m_W\, C_W}\, (T_C - T_W)$$

By substituting τ_W (from DD:balanceDecayRate), this can be written as:

$$\tfrac{dT_W}{dt} = \tfrac{1}{\tau_W}\, (T_C - T_W)$$

Refname	IM:heatEInWtr
Label	Heat energy in the water
Input	T_{init}, m_{W}, C_{W}, m_{W}
Output	E_{W}
Input Constraints	
Output Constraints	
Equation	$$E_{\text{W}}(t) = C_{\text{W}}\, m_{\text{W}}\, (T_{\text{W}}(t) - T_{\text{init}})$$
Description	E_{W} is the change in heat energy in the water (J) t is the time (s) C_{W} is the specific heat capacity of water ($\frac{\text{J}}{\text{kg}^\circ\text{C}}$) m_{W} is the mass of water (kg) T_{W} is the temperature of the water (°C) T_{init} is the initial temperature (°C)
Notes	The above equation is derived using TM:sensHtE. The change in temperature is the difference between the temperature at time t (s), T_{W} and the initial temperature, T_{init} (°C). This equation applies as long as $0 < T_{\text{W}} < 100$°C (A:Water-Always-Liquid, A:Atmospheric-Pressure-Tank).
Source	[2]
RefBy	FR:Output-Values and FR:Calculate-Values

4.2.6   Data Constraints

The Data Constraints Table shows the data constraints on the input variables. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable. The uncertainty column provides an estimate of the confidence with which

the physical quantities can be measured. This information would be part of the input if one were performing an uncertainty quantification exercise. The constraints are conservative to give the user of the model the flexibility to experiment with unusual situations. The column of typical values is intended to provide a feel for a common scenario. The column for software constraints restricts the range of inputs to reasonable values.

Table 4: Input Data Constraints

Var	Physical Constraints	Software Constraints	Typical Value	Uncert.
A_C	$A_C > 0$	$A_C \leq A_C{}^{\max}$	0.12 m^2	10%
C_W	$C_W > 0$	$C_W{}^{\min} < C_W < C_W{}^{\max}$	4186 $\frac{J}{kg°C}$	10%
D	$D > 0$	$AR_{\min} \leq D \leq AR_{\max}$	0.412 m	10%
h_C	$h_C > 0$	$h_C{}^{\min} \leq h_C \leq h_C{}^{\max}$	1000 $\frac{W}{m^2°C}$	10%
L	$L > 0$	$L_{\min} \leq L \leq L_{\max}$	1.5 m	10%
T_C	$0 < T_C < 100$	–	50 °C	10%
T_{init}	$0 < T_{\text{init}} < 100$	–	40 °C	10%
t_{final}	$t_{\text{final}} > 0$	$t_{\text{final}} < t_{\text{final}}{}^{\max}$	50000 s	10%
t_{step}	$0 < t_{\text{step}} < t_{\text{final}}$	–	0.01 s	10%
ρ_W	$\rho_W > 0$	$\rho_W{}^{\min} < \rho_W \leq \rho_W{}^{\max}$	1000 $\frac{kg}{m^3}$	10%

4.2.7 Properties of a Correct Solution

The Data Constraints Table shows the data constraints on the output variables. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable.

Table 5: Output Data Constraints

Var	Physical Constraints
T_W	$T_{\text{init}} \leq T_W \leq T_C$
E_W	$E_W \geq 0$

5 Requirements

This section provides the functional requirements, the tasks and behaviours that the software is expected to complete, and the non-functional requirements, the qualities that the software is expected to exhibit.

5.1 Functional Requirements

This section provides the functional requirements, the tasks and behaviours that the software is expected to complete.

Input-Values: Input the values from Tab:ReqInputs, which define the tank parameters, material properties, and initial conditions.

Find-Mass: Use the inputs in FR:Input-Values to find the mass needed for IM:eBalanceOnWtr, using DD:waterMass, DD:waterVolume_nopcm, and DD:tankVolume.

Check-Input-with-Physical_Constraints: Verify that the inputs satisfy the required physical constraints.

Output-Input-Derived-Values: Output the input values and derived values in the following list: the values (from FR:Input-Values), the mass (from FR:Find-Mass), and τ_W (from DD:balanceDecayRate).

Calculate-Values: Calculate the following values: $T_W(t)$ (from IM:eBalanceOnWtr) and $E_W(t)$ (from IM:heatEInWtr).

Output-Values: Output $T_W(t)$ (from IM:eBalanceOnWtr) and $E_W(t)$ (from IM:heatEInWtr).

Table 6: Required Inputs

Symbol	Description	Units
A_C	Heating coil surface area	m^2
A_{tol}	Absolute tolerance	–
C_W	Specific heat capacity of water	$\frac{J}{kg°C}$
D	Diameter of tank	m
E_W	Change in heat energy in the water	J
h_C	Convective heat transfer coefficient between coil and water	$\frac{W}{m^2°C}$
L	Length of tank	m
R_{tol}	Relative tolerance	–
T_C	Temperature of the heating coil	°C
T_{init}	Initial temperature	°C
t_{final}	Final time	s
t_{step}	Time step for simulation	s
ρ_W	Density of water	$\frac{kg}{m^3}$

5.2 Non-Functional Requirements

This section provides the non-functional requirements, the qualities that the software is expected to exhibit.

Correctness: The outputs of the code have the properties of a correct solution.

Verifiability: The code is tested with complete verification and validation plan.

Understandability: The code is modularized with complete module guide and module interface specification.

Reusability: The code is modularized.

Maintainability: If a likely change is made to the finished software, it will take at most 10% of the original development time, assuming the same development resources are available.

6 Likely Changes

This section lists the likely changes to be made to the software.

Temperature-Coil-Variable-Over-Day: A:Temp-Heating-Coil-Constant-over-Time - The temperature of the heating coil will change over the course of the day, depending on the energy received from the sun.

Temperature-Coil-Variable-Over-Length: A:Temp-Heating-Coil-Constant-over-Length - The temperature of the heating coil will actually change along its length as the water within it cools.

Discharging-Tank: A:Charging-Tank-No-Temp-Discharge - The model currently only accounts for charging of the tank. That is, increasing the temperature of the water to match the temperature of the coil. A more complete model would also account for discharging of the tank.

Tank-Lose-Heat: A:Perfect-Insulation-Tank - Any real tank cannot be perfectly insulated and will lose heat.

7 Unlikely Changes

This section lists the unlikely changes to be made to the software.

Water-Fixed-States: A:Water-Always-Liquid - It is unlikely for the change of water from liquid to a solid, or from liquid to gas to be considered.

No-Internal-Heat-Generation: A:No-Internal-Heat-Generation-By-Water - Is used for the derivations of IM:eBalanceOnWtr.

8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an "X" should be modified as well. Tab:TraceMatAvsA shows the dependencies of the assumptions on each other. Tab:TraceMatAvsAll shows the dependencies of the data definitions, theoretical models, general definitions, instance models, requirements, likely changes, and unlikely changes on the assumptions. Tab:TraceMatRefvsRef shows the dependencies of the data definitions, theoretical models, general definitions, and instance models on each other. Tab:TraceMatAllvsR shows the dependencies of the requirements and goal statements on the data definitions, theoretical models, general definitions, and instance models.

	A:Thermal-Energy-Only	A:Heat-Transfer-Coef
A:Thermal-Energy-Only		
A:Heat-Transfer-Coeffs-Constant		
A:Constant-Water-Temp-Across-Tank		
A:Density-Water-Constant-over-Volume		
A:Specific-Heat-Energy-Constant-over-Volume		
A:Newton-Law-Convective-Cooling-Coil-Water		
A:Temp-Heating-Coil-Constant-over-Time		
A:Temp-Heating-Coil-Constant-over-Length		
A:Charging-Tank-No-Temp-Discharge		
A:Water-Always-Liquid		
A:Perfect-Insulation-Tank		
A:No-Internal-Heat-Generation-By-Water		
A:Atmospheric-Pressure-Tank		
A:Volume-Coil-Negligible		

	A:Thermal-Energy-Only	A:Heat-Transfer-Coeffs-C
DD:waterMass		
DD:waterVolume_nopcm		

	A:Thermal-Energy-Only	A:Heat-Transfer-Coeffs-(
DD:tankVolume		
DD:balanceDecayRate		
TM:consThermE	X	
TM:sensHtE		
TM:nwtnCooling		X
GD:rocTempSimp		
GD:htFluxWaterFromCoil		
IM:eBalanceOnWtr		
IM:heatEInWtr		
FR:Input-Values		
FR:Find-Mass		
FR:Check-Input-with-Physical_Constraints		
FR:Output-Input-Derived-Values		
FR:Calculate-Values		
FR:Output-Values		
NFR:Correctness		
NFR:Verifiability		
NFR:Understandability		
NFR:Reusability		
NFR:Maintainability		
LC:Temperature-Coil-Variable-Over-Day		
LC:Temperature-Coil-Variable-Over-Length		
LC:Discharging-Tank		
LC:Tank-Lose-Heat		
UC:Water-Fixed-States		
UC:No-Internal-Heat-Generation		

	DD:waterMass	DD:waterVolume_nopcm	DD:tankVolume	DD
DD:waterMass				
DD:waterVolume_nopcm			X	
DD:tankVolume				
DD:balanceDecayRate				
TM:consThermE				
TM:sensHtE				
TM:nwtnCooling				
GD:rocTempSimp				
GD:htFluxWaterFromCoil				
IM:eBalanceOnWtr				X
IM:heatEInWtr				

	DD:waterMass	DD:waterVolume_nopcm	DD:ta
GS:Predict-Water-Temperature			
GS:Predict-Water-Energy			
FR:Input-Values			
FR:Find-Mass	X	X	X
FR:Check-Input-with-Physical_Constraints			
FR:Output-Input-Derived-Values			
FR:Calculate-Values			
FR:Output-Values			
NFR:Correctness			
NFR:Verifiability			
NFR:Understandability			
NFR:Reusability			
NFR:Maintainability			

The purpose of the traceability graphs is also to provide easy references on what has to be additionally modified if a certain component is changed. The arrows in the graphs

represent dependencies. The component at the tail of an arrow is depended on by the component at the head of that arrow. Therefore, if a component is changed, the components that it points to should also be changed. Fig:TraceGraphAvsA shows the dependencies of assumptions on each other. Fig:TraceGraphAvsAll shows the dependencies of data definitions, theoretical models, general definitions, instance models, requirements, likely changes, and unlikely changes on the assumptions. Fig:TraceGraphRefvsRef shows the dependencies of data definitions, theoretical models, general definitions, and instance models on each other. Fig:TraceGraphAllvsR shows the dependencies of requirements and goal statements on the data definitions, theoretical models, general definitions, and instance models. Fig:TraceGraphAllvsAll shows the dependencies of dependencies of assumptions, models, definitions, requirements, goals, and changes with each other.
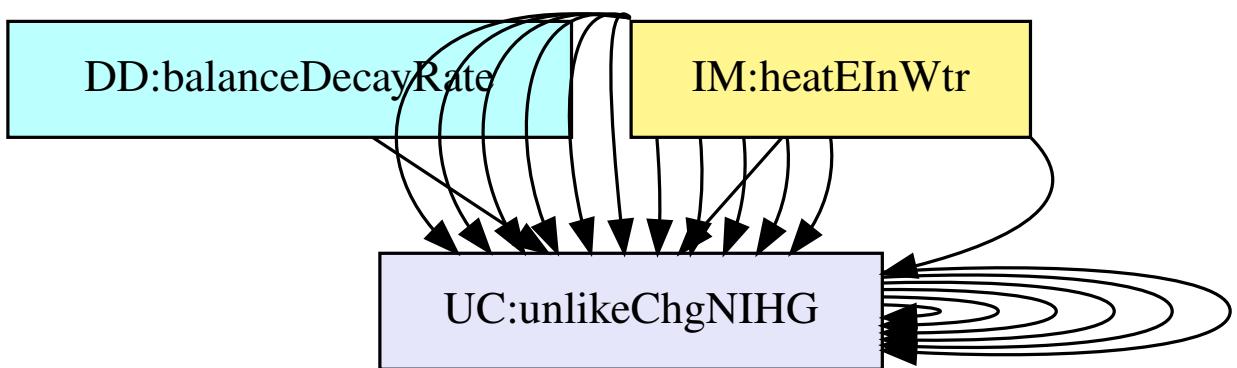

Figure 3: TraceGraphAvsA

Figure 4: TraceGraphAvsAll
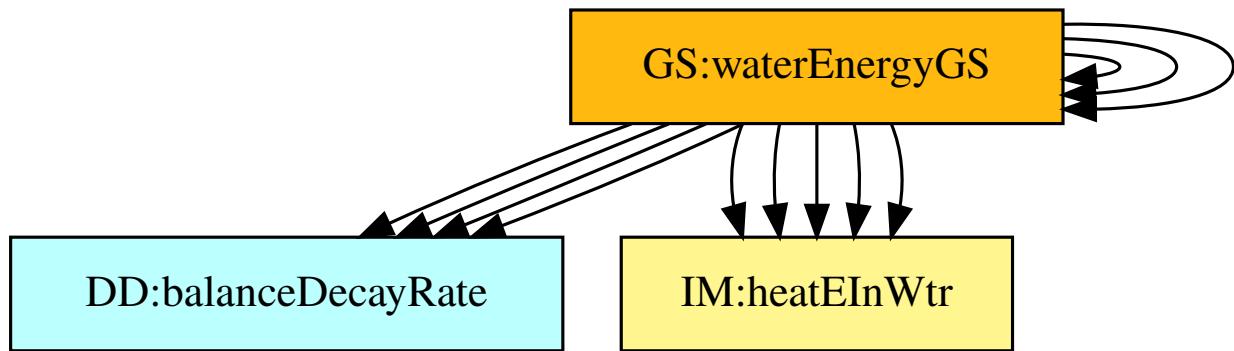
Figure 5: TraceGraphRefvsRef

Figure 6: TraceGraphAllvsR

Figure 7: TraceGraphAllvsAll

For convenience, the following graphs can be found at the links below:

- TraceGraphAvsA

- TraceGraphAvsAll

- TraceGraphRefvsRef

- TraceGraphAllvsR

- TraceGraphAllvsAll

9 Values of Auxiliary Constants

This section contains the standard values that are used for calculations in SWHSNoPCM.

Table 11: Auxiliary Constants

Symbol	Description	Value	Unit
$A_\text{C}{}^\text{max}$	maximum surface area of coil	100000	m^2

Continued on next page

Table 11: Auxiliary Constants (Continued)

Symbol	Description	Value	Unit
AR_{max}	maximum aspect ratio	100	–
AR_{min}	minimum aspect ratio	0.01	–
$C_{\mathrm{W}}{}^{\mathrm{max}}$	maximum specific heat capacity of water	4210	$\frac{\mathrm{J}}{\mathrm{kg°C}}$
$C_{\mathrm{W}}{}^{\mathrm{min}}$	minimum specific heat capacity of water	4170	$\frac{\mathrm{J}}{\mathrm{kg°C}}$
$h_{\mathrm{C}}{}^{\mathrm{max}}$	maximum convective heat transfer coefficient between coil and water	10000	$\frac{\mathrm{W}}{\mathrm{m^2°C}}$
$h_{\mathrm{C}}{}^{\mathrm{min}}$	minimum convective heat transfer coefficient between coil and water	10	$\frac{\mathrm{W}}{\mathrm{m^2°C}}$
L_{max}	maximum length of tank	50	m
L_{min}	minimum length of tank	0.1	m
$t_{\mathrm{final}}{}^{\mathrm{max}}$	maximum final time	86400	s
$\rho_{\mathrm{W}}{}^{\mathrm{max}}$	maximum density of water	1000	$\frac{\mathrm{kg}}{\mathrm{m^3}}$
$\rho_{\mathrm{W}}{}^{\mathrm{min}}$	minimum density of water	950	$\frac{\mathrm{kg}}{\mathrm{m^3}}$

10   References

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