Software Requirements Specification for Solar Water Heating Systems

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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, Tab:ToU lists the symbol, a description and the SI name.

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

Table 1: Table of Units

1.2 Table of Symbols

The symbols used in this document are summarized in Tab:ToS 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. The symbols are listed in alphabetical order. For vector quantities, the units shown are for each component of the vector.

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	–
C	Specific heat capacity	$\frac{\mathrm{J}}{\mathrm{kg°C}}$
C^{L}	Specific heat capacity of a liquid	$\frac{\mathrm{J}}{\mathrm{kg°C}}$
C_{W}	Specific heat capacity of water	$\frac{\mathrm{J}}{\mathrm{kg°C}}$

Symbol	Description	Units
${C_{\mathrm{W}}}^{\max}$	Maximum specific heat capacity of water	$\frac{\mathrm{J}}{\mathrm{kg}^{\circ}\mathrm{C}}$
${C_{\mathrm{W}}}^{\min}$	Minimum specific heat capacity of water	$\frac{\mathrm{J}}{\mathrm{kg}^{\circ}\mathrm{C}}$
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	$\frac{\mathrm{W}}{\mathrm{m}^3}$
h	Convective heat transfer coefficient	$\frac{\mathrm{W}}{\mathrm{m}^2{}^{\circ}\mathrm{C}}$
h_{C}	Convective heat transfer coefficient between coil and water	$\frac{\mathrm{W}}{\mathrm{m}^2{}^{\circ}\mathrm{C}}$
${h_{\mathrm{C}}}^{\max}$	Maximum convective heat transfer coefficient between coil and water	$\frac{\mathrm{W}}{\mathrm{m}^2{}^{\circ}\mathrm{C}}$
${h_{\mathrm{C}}}^{\min}$	Minimum convective heat transfer coefficient between coil and water	$\frac{\mathrm{W}}{\mathrm{m}^2{}^{\circ}\mathrm{C}}$
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	$\frac{\mathrm{W}}{\mathrm{m}^2}$
q_{C}	Heat flux into the water from the coil	$\frac{\mathrm{W}}{\mathrm{m}^2}$
q_{in}	Heat flux input	$\frac{\mathrm{W}}{\mathrm{m}^2}$
q_{out}	Heat flux output	$\frac{\mathrm{W}}{\mathrm{m}^2}$
$\mathbf{q}$	Thermal flux vector	$\frac{\mathrm{W}}{\mathrm{m}^2}$
R_{tol}	Relative tolerance	–
S	Surface	m^2
T	Temperature	$^{\circ}\mathrm{C}$
ΔT	Change in temperature	$^{\circ}\mathrm{C}$
T_{C}	Temperature of the heating coil	$^{\circ}\mathrm{C}$
T_{env}	Temperature of the environment	$^{\circ}\mathrm{C}$
T_{init}	Initial temperature	$^{\circ}\mathrm{C}$
T_{W}	Temperature of the water	$^{\circ}\mathrm{C}$
t	Time	s
t_{final}	Final time	s
${t_{\mathrm{final}}}^{\max}$	Maximum final time	s

Symbol	Description	Units
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	–

Table 2: Table of Symbols

1.3 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
PS	Physical System Description
R	Requirement
SRS	Software Requirements Specification
SWHS	Solar Water Heating System
TM	Theoretical Model
UC	Unlikely Change
Uncert.	Typical Uncertainty

Table 3: Abbreviations and Acronyms

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 systems provide a novel way of storing energy.

The following section provides an overview of the Software Requirements Specification (SRS) for solar water heating systems. The developed program will be referred to as Solar Water Heating System (SWHS). 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 the Solar Water Heating System. 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 SWHS. 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 SWHS 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] and [5]. The presentation follows the standard pattern of presenting goals, theories, definitions, and assumptions. For readers that would like a more bottom up

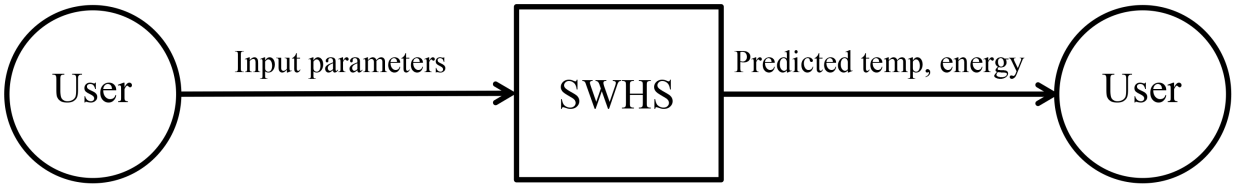

Figure 1: Fig:SysCon: System Context

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. SWHS 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 (SWHS). Arrows are used to show the data flow between the system and its environment.

SWHS 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
- SWHS 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 SWHS 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 SWHS, 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.)

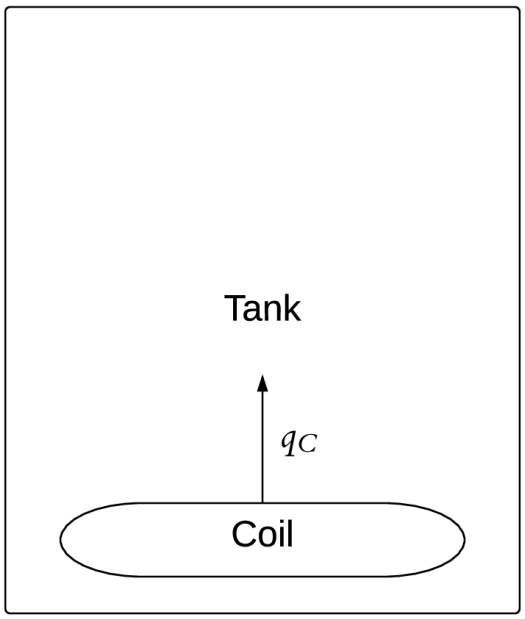

Figure 2: Solar water heating tank, with heat flux from heating coil of q_C

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:

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

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

4.2 Solution Characteristics Specification

The instance models that govern SWHS are presented in Sec:Instance Models. 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.

rmal-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.)

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

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.)

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

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

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

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

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

o-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.)

ter-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: UC:Water-Fixed-States, TM:sensHtE, IM:heatEInWtr, and IM:eBalanceOnWtr.)

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

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

eric-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.)

me-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 SWHS 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 ($^\circ$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 ($\frac{\mathrm{J}}{\mathrm{kg}^{\circ}\mathrm{C}}$) m is the mass (kg) ΔT is the change in temperature ($^{\circ}$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	$$q(t) = h\Delta T(t)$$
Description	q is the heat flux ($\frac{\text{W}}{\text{m}^2}$) t is the time (s) h is the convective heat transfer coefficient ($\frac{\text{W}}{\text{m}^2{}^\circ\text{C}}$) 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). $\Delta T(t) = T(t) - T_{\text{env}}(t)$ 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	$$mC\frac{dT}{dt} = q_{\text{in}}A_{\text{in}} - q_{\text{out}}A_{\text{out}} + gV$$
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 ($^\circ$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:

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

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:

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

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

$$mC\frac{dT}{dt} = q_{\text{in}}A_{\text{in}} - q_{\text{out}}A_{\text{out}} + gV$$

Refname	**GD:htFluxWaterFromCoil**
Label	Heat flux into the water from the coil
Units	$\frac{\text{W}}{\text{m}^2}$
Equation	$$q_{\text{C}} = h_{\text{C}} \left(T_{\text{C}} - T_{\text{W}} \left(t \right) \right)$$
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 ($\frac{\text{W}}{\text{m}^2 {}^\circ\text{C}}$) T_{C} is the temperature of the heating coil ($^\circ$C) T_{W} is the temperature of the water ($^\circ$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	$$m_{\mathrm{W}} = V_{\mathrm{W}} \rho_{\mathrm{W}}$$
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 ($\frac{\mathrm{kg}}{\mathrm{m}^3}$)
Source	–
RefBy	FR:Find-Mass

Refname	**DD:waterVolume.nopcm**
Label	Volume of water
Symbol	V_{W}
Units	m^3
Equation	$$V_{\mathrm{W}} = V_{\mathrm{tank}}$$
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	DD:waterVolume_nopcm and FR:Find-Mass

Refname	**DD:balanceDecayRate**
Label	ODE parameter for water related to decay time
Symbol	τ_{W}
Units	s
Equation	$\tau_{\mathrm{W}} = \frac{m_{\mathrm{W}} C_{\mathrm{W}}}{h_{\mathrm{C}} A_{\mathrm{C}}}$
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 ($\frac{\mathrm{J}}{\mathrm{kg}^{\circ}\mathrm{C}}$) h_{C} is the convective heat transfer coefficient between coil and water ($\frac{\mathrm{W}}{\mathrm{m}^2{}^{\circ}\mathrm{C}}$) A_{C} is the heating coil surface area (m^2)
Source	[2]
RefBy	FR:Output-Input-Derived-Values and IM:eBalanceOnWtr

4.2.5 Instance Models

This section transforms the problem defined in Sec:Problem Description into one which is expressed in mathematical terms. It uses concrete symbols defined in Sec:Data Definitions to replace the abstract symbols in the models identified in Sec:Theoretical Models and Sec: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	$$\frac{dT_W}{dt} = \frac{1}{\tau_W}(T_C - T_W(t))$$
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:Find-Mass, and FR:Calculate-Temperature-Water-Over-Time

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:

$$m_{\mathrm{W}} C_{\mathrm{W}} \frac{dT_{\mathrm{W}}}{dt} = q_{\mathrm{C}} A_{\mathrm{C}}$$

Using GD:htFluxWaterFromCoil for q_{C}, this can be written as:

$$m_{\mathrm{W}} C_{\mathrm{W}} \frac{dT_{\mathrm{W}}}{dt} = h_{\mathrm{C}} A_{\mathrm{C}} \left(T_{\mathrm{C}} - T_{\mathrm{W}}\right)$$

Dividing Equation (2) by $m_{\mathrm{W}} C_{\mathrm{W}}$, we obtain:

$$\frac{dT_{\mathrm{W}}}{dt} = \frac{h_{\mathrm{C}} A_{\mathrm{C}}}{m_{\mathrm{W}} C_{\mathrm{W}}} \left(T_{\mathrm{C}} - T_{\mathrm{W}}\right)$$

By substituting τ_{W} (from DD:balanceDecayRate), this can be written as:

$$\frac{dT_{\mathrm{W}}}{dt} = \frac{1}{\tau_{\mathrm{W}}} \left(T_{\mathrm{C}} - T_{\mathrm{W}}\right)$$

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 ($\frac{\text{J}}{\text{kg°C}}$) 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:Calculate-Change-Heat_Energy-Water-Over-Time

4.2.6 Data Constraints

Tab:InDataConstraints 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.

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}	$0 < T_{init} < 100$	–	40 °C	10%
t_{final}	$t_{final} > 0$	$t_{final} < {t_{final}}^{max}$	50000 s	10%
t_{step}	$0 < t_{step} < t_{final}$	–	0.01 s	10%
ρ_W	$\rho_W > 0$	${\rho_W}^{min} < \rho_W \leq {\rho_W}^{max}$	1000 $\frac{kg}{m^3}$	10%

Table 4: Input Data Constraints

4.2.7 Properties of a Correct Solution

Tab:OutDataConstraints 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.

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

Table 5: Output Data Constraints

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.

nput-Initial-Values: Input the following values described in Tab:ReqInputs, which define the tank parameters, material properties, and initial conditions.

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

ysical_Constraints: Verify that the inputs satisfy the required physical constraints shown in Sec:Data Constraints.

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

-Water-Over-Time: Calculate and output the temperature of the water ($T_W(t)$) over the simulation time (from IM:eBalanceOnWtr).

-Water-Over-Time: Calculate and output the change in heat energy in the water ($E_W(t)$) over the simulation time (from IM:heatEInWtr).

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
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	$\frac{kg}{m^3}$

Table 6: Required Inputs following FR:Input-Initial-Values

5.2 Non-Functional Requirements

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

Correct: The outputs of the code have the properties described in Sec:Properties of a Correct Solution.

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

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

Reusable: The code is modularized.

Maintainable: The traceability between requirements, assumptions, theoretical models, general definitions, data definitions, instance models, likely changes, unlikely changes, and modules is completely recorded in traceability matrices in the SRS and module guide.

6 Likely Changes

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

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.

iable-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.

l-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 assumptions on the assumptions. Tab:TraceMatAvsAll shows the dependencies of data definitions, theoretical models, general definitions, instance models, requirements, likely changes, and unlikely changes on the assumptions. Tab:TraceMatRefvsRef shows the dependencies of data definitions, theoretical models, general definitions, and instance models with each other. Tab:TraceMatAllvsR shows the dependencies of requirements, 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-Transfe**
DD:waterMass		
DD:waterVolume_nopcm		
DD:tankVolume		
DD:balanceDecayRate		
TM:consThermE	X	
TM:sensHtE		
TM:nwtnCooling		X
GD:rocTempSimp		

	A:Thermal-Energy-Only	A:Heat-Transfe
GD:htFluxWaterFromCoil		
IM:eBalanceOnWtr		
IM:heatEInWtr		
FR:Input-Initial-Values		
FR:Find-Mass		
FR:Check-Input-with-Physical_Constraints		
FR:Output-Input-Derived-Values		
FR:Calculate-Temperature-Water-Over-Time		
FR:Calculate-Change-Heat_Energy-Water-Over-Time		
NFR:Correct		
NFR:Verifiable		
NFR:Understandable		
NFR:Reusable		
NFR:Maintainable		
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				

Table

	DD:waterMass	DD:waterVolume_nopcm
GS:Predict-Water-Temperature		
GS:Predict-Water-Energy		
FR:Input-Initial-Values		
FR:Find-Mass	X	X
FR:Check-Input-with-Physical_Constraints		
FR:Output-Input-Derived-Values		
FR:Calculate-Temperature-Water-Over-Time		
FR:Calculate-Change-Heat_Energy-Water-Over-Time		
NFR:Correct		
NFR:Verifiable		
NFR:Understandable		
NFR:Reusable		
NFR:Maintainable		

9 Values of Auxiliary Constants

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

Symbol	Description	Value	Unit
${A_C}^{max}$	maximum surface area of coil	100000	m^2
AR_{max}	maximum aspect ratio	100	–
AR_{min}	minimum aspect ratio	0.01	–
${C_W}^{max}$	maximum specific heat capacity of water	4210	$\frac{J}{kg^\circ C}$
${C_W}^{min}$	minimum specific heat capacity of water	4170	$\frac{J}{kg^\circ C}$
${h_C}^{max}$	maximum convective heat transfer coefficient between coil and water	10000	$\frac{W}{m^{2\circ}C}$
${h_C}^{min}$	minimum convective heat transfer coefficient between coil and water	10	$\frac{W}{m^{2\circ}C}$
L_{max}	maximum length of tank	50	m
L_{min}	minimum length of tank	0.1	m
${t_{final}}^{max}$	maximum final time	86400	s
${\rho_W}^{max}$	maximum density of water	1000	$\frac{kg}{m^3}$
${\rho_W}^{min}$	minimum density of water	950	$\frac{kg}{m^3}$

Symbol	Description	Value	Unit

Table 11: Auxiliary Constants

10 References

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