Software Requirements Specification for Solar Water Heating Systems

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Contents

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit with the SI name in parentheses.

symbol	unit	SI
m	length	metre
kg	mass	kilogram
s	time	second
°C	temperature	centigrade

1.2 Table of Symbols

The table that follows summarizes the symbols used in this document 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.

symbol	unit	description
A_C	m^2	coil surface area
A_{in}	m^2	surface area over which heat is transferred in
A_{out}	m^2	surface area over which heat is transferred out
C	J/(kg °C)	specific heat capacity
C^L	J/(kg °C)	specific heat capacity of a liquid
C_W	J/(kg °C)	specific heat capacity of water
D	m	diameter of tank
E_W	J	heat energy in the water

g	$\mathrm{W/m^2}$	volumetric heat generation per unit volume
h	$\mathrm{W/(m^2\,°C)}$	convective heat transfer coefficient
h_C	$\mathrm{W/(m^2\,°C)}$	convective heat transfer coefficient between coil and water
L	m	length of tank
m	kg	mass
m_W	kg	mass of water
$\hat{\mathbf{n}}$	unitless	unit outward normal vector for a surface
q	$\mathrm{W/(m^2\,°C)}$	heat flux
$\mathbf{q}$	$\mathrm{W/m^2}$	thermal flux vector
q_C	$\mathrm{W/m^2}$	heat flux from coil
q_{in}	$\mathrm{W/m^2}$	heat flux in
q_{out}	$\mathrm{W/m^2}$	heat flux out
t	s	time
T	°C	temperature
T_C	°C	temperature of coil
T_{env}	°C	temperature of environment
t_{final}	s	final time
T_{init}	°C	initial temperature
T_W	°C	temperature of water
ΔT	°C	temperature difference
V	$\mathrm{m^3}$	volume
V_W	$\mathrm{m^3}$	volume of water
ρ	$\mathrm{kg/m^3}$	density, mass per unit volume
ρ_W	$\mathrm{kg/m^3}$	density of water
τ	s	dummy variable for integration over time

1.3 Abbreviations and Acronyms

symbol	description
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
T	Theoretical Model

2 Introduction

Due to the increasing cost, diminishing availability, and negative environmental impact of fossil fuels, there is a higher demand 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 a solar water heating system. 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 system, the organization of the document and the characteristics of the intended readers.

2.1 Purpose of Document

The main purpose of this document is to describe the modelling of solar water heating systems. The goals and theoretical models used in the SWHS code are provided, with an emphasis on explicitly identifying assumptions and unambiguous definitions. This document is intended to be used as a reference to provide ad hoc access to all information necessary to understand and verify the model. The SRS is abstract because the contents say *what* problem is being solved, but do not say *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 process is not waterfall, as Parnas and Clements [4] point out, 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 is limited to thermal analysis of a single solar water heating tank. Given the appropriate inputs, the code for SWHS is intended to predict the temperature and energy histories for the water.

2.3 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 approach, they can start reading the instance models in Section 4.2.5 and trace back to find any additional information they require. The instance model provides the Ordinary Differential Equation (ODE) that models the solar water heating system. SWHS solves this ODE.

The goal statements are refined to the theoretical models, and theoretical models to the instance models. The instance model (Section 4.2.5) to be solved is referred to as IM1.

3 General System Description

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

3.1 System Context

Figure 1 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.

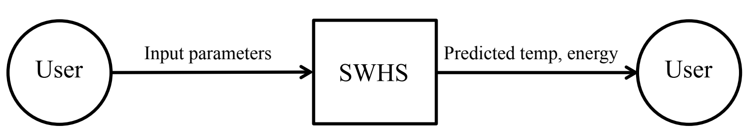

Figure 1: System Context

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, definitions and finally the instance model (ODE) that model the solar water heating tank.

4.1 Problem Description

SWHS is a computer program developed 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 heat energy transfer per unit area.

- Specific Heat: heat capacity per unit mass.
- 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 Figure 2, includes the following elements:

PS1: Tank containing water.

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

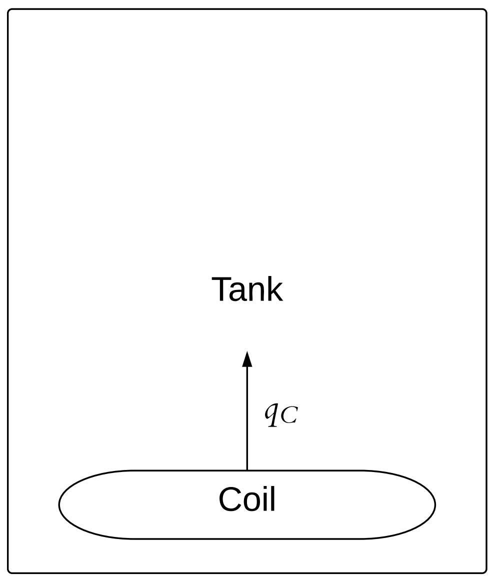

Figure 2: Solar water heating tank, with heat flux from coil of q_C

4.1.3 Goal Statements

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

GS1: predict the water temperature over time;

GS2: predict the change in the energy of the water over time;

4.2 Solution Characteristics Specification

The instance model (ODE) that governs SWHS is presented in Subsection 4.2.5. The information to understand the meaning of the instance model and its derivation is also presented, so that the instance model can be verified.

4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [T], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

A1: 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 [T1].

A2: All heat transfer coefficients are constant over time [GD1].

A3: The water in the tank is fully mixed, so the temperature is the same throughout the entire tank [GD2].

A4: Density of the water has no spatial variation; that is, it is constant over the entire volume [GD2].

A5: Specific heat capacity of the water has no spatial variation; that is, it is constant over the entire volume [GD2].

A6: Newton's law of convective cooling applies between the coil and the water [DD1].

A7: The temperature of the heating coil is constant over time [DD1, LC1].

A8: The temperature of the heating coil does not vary along its length [DD1, LC2].

A9: The model only accounts for charging of 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 coil [IM1, LC3].

A10: The operating temperature range of the system is such that the water is always in liquid form. That is, the temperature will not drop below the melting point of water, or rise above its boiling point [IM1].

A11: The tank is perfectly insulated so that there is no heat loss from the tank [IM1, LC4].

A12: No internal heat is generated by the water; therefore, the volumetric heat generation is zero [IM1].

A13: The pressure in the tank is atmospheric, so the melting and boiling points of water are 0^oC and 100^oC, respectively [IM1, IM2].

A14: When considering the volume of water in the tank, the volume of the coil is assumed to be negligible [R2].

4.2.2 Theoretical Models

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

Number	T1
Label	**Conservation of thermal energy**
Equation	$-\nabla \cdot \mathbf{q} + g = \rho C \frac{\partial T}{\partial t}$
Description	The above equation gives the conservation of energy for time varying heat transfer in a material of specific heat capacity C and density ρ, where $\mathbf{q}$ is the thermal flux vector, g is the volumetric heat generation, T is the temperature, t is time, and ∇ is the gradient operator. For this equation to apply, other forms of energy, such as mechanical energy, as assumed to be negligible in the system (A1).
Source	http://www.efunda.com/formulae/heat_transfer/conduction/overview_cond.cfm
Ref. By	GD2

4.2.3 General Definitions

This section collects the laws and equations that will be used in deriving the data definitions, which in turn are used to build the instance models.

Number	GD1
Label	**Newton's law of cooling**
SI Units	$\mathrm{W\,m^{-2}}$
Equation	$q(t) = h\Delta T(t)$
Description	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. $q(t)$ is the thermal flux ($\mathrm{W\,m^{-2}}$). h is the heat transfer coefficient, assumed independent of T (A2) ($\mathrm{W\,m^{-2}\,°C^{-1}}$). $\Delta T(t) = T(t) - T_{\text{env}}(t)$ is the time-dependent thermal gradient between the environment and the object (°C).
Source	[1, p. 8]
Ref. By	DD1

Number	GD2
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	The basic equation governing the rate of change of temperature, for a given volume V, with time. m is the mass (kg). C is the specific heat capacity ($\mathrm{J\,kg^{-1}\,°C^{-1}}$). T is the temperature (°C) and t is the time (s). q_{in} and q_{out} are the in and out heat transfer rates, respectively ($\mathrm{W\,m^{-2}}$). A_{in} and A_{out} are the surface areas over which the heat is being transferred in and out, respectively ($\mathrm{m^2}$). g is the volumetric heat generated ($\mathrm{W\,m^{-3}}$). V is the volume ($\mathrm{m^3}$).
Ref. By	IM1

Detailed derivation of simplified rate of change of temperature

Integrating (T1) over a volume (V), we have

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

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 $\hat{\mathbf{n}}$ is a unit outward normal for the surface,

$$-\int_S \mathbf{q} \cdot \hat{\mathbf{n}} dS + \int_V g dV = \int_V \rho C \frac{\partial T}{\partial t} dV. \tag{1}$$

We consider an arbitrary volume. The volumetric heat generation is assumed constant. Then (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 GD2. Assuming ρ, C and T are constant over the volume, which is true in our case by assumption (A3), (A4), and (A5), we have

$$\rho C V \frac{dT}{dt} = q_{\text{in}} A_{\text{in}} - q_{\text{out}} A_{\text{out}} + gV. \tag{2}$$

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

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

4.2.4 Data Definitions

This section collects and defines all the data needed to build the instance models. The dimension of each quantity is also given.

Number	DD1
Label	**Heat flux out of coil**
Symbol	q_C
SI Units	$\mathrm{W\,m^{-2}}$
Equation	$q_C(t) = h_C(T_C - T_W(t))$, over area A_C
Description	T_C is the temperature of the coil. T_W is the temperature of the water. The heat flux out of the coil, q_C, is found by assuming that Newton's Law of Cooling applies (A6). This law (GD1) is used on the surface of the coil, which has area A_C and heat transfer coefficient h_C. This equation assumes that the temperature of the coil is constant over time (A7) and that is does not vary along the length of the coil (A8).
Sources	[3]
Ref. By	IM1

4.2.5 Instance Models

This section transforms the problem defined in the Section 4.1 into one which is expressed in mathematical terms. It uses concrete symbols defined in Section 4.2.4 to replace the abstract symbols in the models identified in the Sections 4.2.2 and 4.2.3.

Number	IM1
Label	**Energy balance on water to find T_W**
Input	m_W, C_W, h_C, A_C, t_{final}, T_C, T_{init} The input is constrained so that $T_{\text{init}} \leq T_C$ (A9)
Output	$T_W(t)$, $0 \leq t \leq t_{\text{final}}$, such that $\frac{dT_W}{dt} = \frac{1}{\tau_W}(T_C - T_W(t))$, $T_W(0) = T_{\text{init}}$
Description	T_W is the water temperature (°C). T_C is the coil temperature (°C). $\tau_W = \frac{m_W C_W}{h_C A_C}$ is a constant (s). The above equation applies as long as the water is in liquid form, $0 < T_W < 100^o$C, where 0^oC and 100^oC are the melting and boiling points of water, respectively (A10).
Sources	Original SRS with PCM removed
Ref. By	

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 coil as q_C, over area A_C. No heat transfer occurs to the outside of the tank, since it has been assumed to be perfectly insulated (A11). Assuming no internal heat is generated (A12), $g = 0$. Therefore, the equation for GD2 can be written as:

$$m_W C_W \frac{dT_W}{dt} = q_C A_C.$$

Using DD1 for q_C, this can be written as

$$m_W C_W \frac{dT_W}{dt} = h_C A_C (T_C - T_W). \tag{3}$$

Dividing (3) by $m_W C_W$, we obtain

$$\frac{dT_W}{dt} = \frac{h_C A_C}{m_W C_W}(T_C - T_W). \tag{4}$$

Setting $\tau_W = \frac{m_W C_W}{h_C A_C}$, Equation (4) can be written in its final form as:

$$\frac{dT_W}{dt} = \frac{1}{\tau_W}(T_C - T_W).$$

Number	IM2
Label	**Heat energy in the water**
Input	C_W, m_W, T_{init}, $T_W(t)$
Output	$E_W(t)$, $0 \leq t \leq t_{\text{final}}$, such that $E_W(t) = C_W m_W (T_W(t) - T_{\text{init}})$
Description	The above equation is derived using T??. E_W is the change in thermal energy of the liquid water relative to the energy at the initial temperature (T_{init}). C_W is the specific heat capacity of liquid water and m_W is the mass of the water. The change in temperature is the difference between the temperature at time t, T_W, and the initial temperature, T_{init}, this equation applies as long as $0 < T_W < 100^o$C (A10).
Sources	[3]
Ref. By	–

4.2.6 Data Constraints

Table 1 and 3 show the data constraints on the input and output variables, respectively. The column physical constraints gives the physical limitations on the range of values that can be taken by the variable. The column for software constraints restricts the range of inputs to reasonable values. 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 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 specification parameters in Table 1 are listed in Table 2.

(*) These quantities cannot be equal to zero, or there will be a divide by zero in the model.

(+) These quantities cannot be zero, or there would be freezing (A10).

(**) The constraint on the maximum time at the end of the simulation is the total number of seconds in one day.

Table 1: Input Variables

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

Table 2: Specification Parameter Values

Var	Value
L_{min}	0.1 m
L_{max}	50 m
$\frac{D}{L}_{\text{min}}$	0.002
$\frac{D}{L}_{\text{max}}$	200
h_{min}	0.001 m
A_C^{max}	$\pi(\frac{D}{2})^2$ m^2
ρ_W^{min}	950 $\text{kg}\,\text{m}^{-3}$
ρ_W^{max}	1000 $\text{kg}\,\text{m}^{-3}$
C_W^{min}	4170 $\text{J}\,\text{kg}^{-1}\,{}^{\circ}\text{C}^{-1}$
C_W^{max}	4210 $\text{J}\,\text{kg}^{-1}\,{}^{\circ}\text{C}^{-1}$
h_C^{min}	10 $\text{W}\,\text{m}^{-2}\,{}^{\circ}\text{C}^{-1}$
h_C^{max}	10000 $\text{W}\,\text{m}^{-2}\,{}^{\circ}\text{C}^{-1}$
$t_{\text{final}}^{\text{max}}$	86400 s

Table 3: Output Variables

Var	Physical Constraints
T_W	$T_{\text{init}} \leq T_W \leq T_C$ (by A9)
E_W	$E_W \geq 0$

5 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

5.1 Functional Requirements

R1: Input the following quantities, which define the tank parameters, material properties and initial conditions:

symbol	unit	description
L	m	length of tank
D	m	diameter of tank
A_C	m^2	coil surface area
T_C	°C	temperature of coil
ρ_W	kg/m^3	density of water
C_W	J/(kg °C)	specific heat capacity of water
h_C	$\text{W}/(\text{m}^2\,°\text{C})$	convective heat transfer coefficient between coil and water
T_{init}	°C	initial temperature of water
t_{final}	s	time at end of simulation

R2: Use the inputs in R1 to find the mass needed for IM1, as follows:

$$m_W = V_W \rho_W = \pi (D/2)^2 L \rho_W$$

where V_W is the volume of water in the tank.

R3: Verify that the inputs satisfy the required physical constraints shown in Table 1.

R4: Output the input quantities and derived quantities in the following list: the quantities from R1, the mass from R2 and τ_W (from IM1).

R5: Calculate and output the temperature of the water ($T_W(t)$) over the simulation time (from IM1).

R6: Calculate and output the energy in the water ($E_W(t)$) over the simulation time (from IM2).

5.2 Nonfunctional Requirements

Given the small size, and relative simplicity, of this problem, performance is not a priority. Any reasonable implementation will be very quick and use minimal storage. Rather than performance, the priority nonfunctional requirements are correctness, verifiability, understandability, reusability and maintainability.

6 Likely Changes

LC1: A7 - The temperature of the heating coil will change over the course of the day, depending on the energy received from the sun.

LC2: A8 - The temperature of the water in the coil will actually change along its length as the water cools.

LC3: A9 - The model currently only accounts for charging of the tank. A more complete model would also account for discharging of the tank.

LC4: A11 - Any real tank cannot be perfectly insulated and will lose heat.

References

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