Effect of Tank Size on the Temperature Distributions for Solar Water Heaters

Ayoola Olamide Afolayan

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Prof. Dr. Elvan Yilmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Prof. Dr. Uğur Atikol
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Prof. Dr. Uğur Atikol
Supervisor

Examining Committee

1. Prof. Dr. Fuat Egelioğlu
2. Prof. Dr. Ibrahim Sezai
3. Prof. Dr. Uğur Atikol

ABSTRACT

The objective of the present study is to investigate the effect of tank size on the temperature distributions as well as the availability of hot water in the storage tanks of solar water heaters with two-stage usage. A usage pattern is assumed, where the first discharge is 50 L of hot water at 7:00 pm (representing two persons taking showers in succession) and the second discharge is 25 L of hot water at 7:00 am (representing one person taking a shower). The standing time between the two draw-offs is fixed at 12 hrs. The investigation is carried out by considering different tank sizes namely: 80 L, 121 L, 150 L and 200 L. TRNSYS program is used for the simulation. Results show that the optimum tank size for solar water heaters is 150 L with high quality solar collectors for the described scenario of the daily hot water usage.

Keywords: Temperature distributions, storage tank, hot water, simulation.

ÖZ

Bu çalışmanın amacı, güneş enerjili su ıstma sistemlerinde depo kapasitesinin, depolanan suyun sıcaklık dağılımı ve kullanılabilir sıcak su mevcudiyetinin üzerindeki etkisini iki aşamalı kullanım şartlarında incelemektir. Varsayılan kullanım şablonunda ilk kullanım akşam 7:00'de 50 L, ikinci kullanımın ise sabah 7:00'de 25 L olarak belirlenmiştir. İlk kullanım iki kişinin sırayla duş almasını, ikinci kullanım ise bir kişinin duş almasını temsil ediyor. İki aşama arasında geçen bekleme süresi 12 saat olarak sabitlenmiştir. Araştırmada 80, 121, 150 ve 200 L ebatlalarında su tankları kullanılmıştır. Simulasyonlar TRNSYS programı kullanarak yapılmıştır. Bulgular, yüksek kaliteli güneş panelleri ie kullanılmak kaydı ile, bahsedilen senaryo için, en optimum tank kapasitesinin 150 L olduğunu gösteriyor

Anahtar Kelimeler: sıcaklık dağılımları, depolama tankı, sıcak su, simülasyon

Dedicated to God Almighty

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LIST OF ABBREVIATIONS

TRNSYS	Transient System Simulation
SDHW	Solar Domestic Hot Water

NOMENCLATURES

Q_u	Useful energy gain
$\dot{m}$	Mass flow rate
C_{pf}	Specific heat of collector fluid
T_o	Outlet temperature of fluid from collector
T_i	Inlet temperature of fluid to collector
A	Total area of the solar collector array
T_a	Ambient (air) temperature
F_R	Overall collector heat removal efficiency factor
U_L	Overall thermal loss coefficient of the collector per unit area
I_T	Global radiation incident on the solar collector (Tilted surface)
$U_{L/T}$	Thermal loss coefficient dependency on T
ΔT	Temperature difference
a_0	Intercept (maximum) of the collector efficiency
a_1	Negative of the first-order coefficient in collector efficiency equation
a_2	Negative of the second-order coefficient in collector efficiency equation
T_h	Temperature of the water going into the storage tank from the heat source
T_L	Temperature of the replacement water
T_{env}	Temperature of the environment surrounding the tank
T_i	Temperature of the ith tank segment
$\dot{m}_L$	Fluid mass flow rate to the load
$\dot{m}_h$	Fluid mass flow rate to tank from the heat source

N	Number of fully mixed (having the same temperature) tank sections
P	Power

Greek Symbols

η	efficiency
$\tau\alpha$	transmissivity-absorptivity product
τ	transmissivity
γ	control function

Subscripts

c	collector
s	storage tank
i	inlet
o	outlet
max	maximum
a	ambient
L	load
h	heat source
T	tilted surface
f	fluid
w	water
env	environment
z	height
t	time
min	minimum

Chapter 1

INTRODUCTION

1.1 Background

Thermal stratification of water occurs in a storage tank when cold water with high density accumulates at the lowest part of the tank, and less dense hot water rises to the top due to gravity effect. As water heats and cools, it expands and contracts leading to a change in its density. Each layer of water in the tank is stacked above or below the others with the hottest water on top and the coldest water at the bottom.

It is important to study the temperature distribution in hot water tanks in order to identify the factors which enhance or decline stratification within the tank [1]. By enhancing the thermal stratification, hot water at a temperature suitable for domestic usage can be provided especially in the morning and evening when solar radiation is not effective or unavailable. Some of the factors that determine the rate at which cooling of hot water occurs in a storage tank is the volume of the tank, the time that is waited before the discharging of water takes place after heating, the quantity of hot water being drawn for consumption and the initial temperature of the cold water that charges in through the bottom of the tank [2]. The appropriate tank size needs to be correctly-sized to ensure an optimum performance of a hot water solar heating system. Selecting the proper tank capacity will in turn enhance the performance of the system.

The amount of hot water extracted from the tank at different intervals also contributes to the stratification that occurs within storage tanks. Therefore, there is a need to study the withdrawal of hot water intermittently and at different draw-off volumes, in order to be able to plan the availability of useful hot water inside the tank.

1.2 Scope and Objectives

The aim of the present study is to investigate the effect of storage tank size on the temperature distributions of water inside the cylinders of solar water heaters under Cyprus conditions. The investigation will also focus on the possibility of two-stage usage pattern; first period in the evening and the second period in the morning, with a standing time between them. This will enable us to have a better knowledge of the thermal behaviour in domestic hot water-storage tanks and most importantly to determine the optimum tank size for different usage patterns. TRNSYS software (Version 16) is utilized for running the simulations.

1.3 Organization of Thesis

This dissertation is divided into seven chapters. In Chapter 2, a literature review was conducted where previous experiments and researches on temperature distributions in storage tanks were studied.

The methodology is presented in Chapter 3. The procedure of data gathering and process analysis are given in detail.

In Chapter 4, the governing equations for each of the components used in the computer program to conduct this investigation are revised.

TRNSYS simulation procedure is explained in Chapter 5

In Chapter 6, the results of the investigation are discussed in detail.

Finally conclusive remarks are made in Chapter 7.

Chapter 2

LITERATURE REVIEW

2.1 Solar Water Heating System

A solar domestic water heating system is made up of a storage tank, a solar thermal collector, an auxiliary heater, a pump and layers of pipes that links the collector into the tank. Figure 2.1 (re-displayed from Ref. [3]) shows a typical set up of solar water heating system. Water is heated in this system through the solar energy received by the collector. The cold water circulating through the collectors receives heat through solar radiation, where it turns to hot water and goes back to the storage tank [4]. The hot water which can be used for domestic purposes is taken from the topmost part of the tank and is restored with the cold water coming in through an inlet pipe situated at the lowest portion of the tank.

The main purpose of heat storage tank in solar water heating systems is to supply the adequate quantity of hot water at a suitable temperature. To achieve this objective, cold and hot fluids have to be separated in the right manner by developing a means which will prevent mixing in the tank in order to maintain stratification as hot water is being drawn or stored.

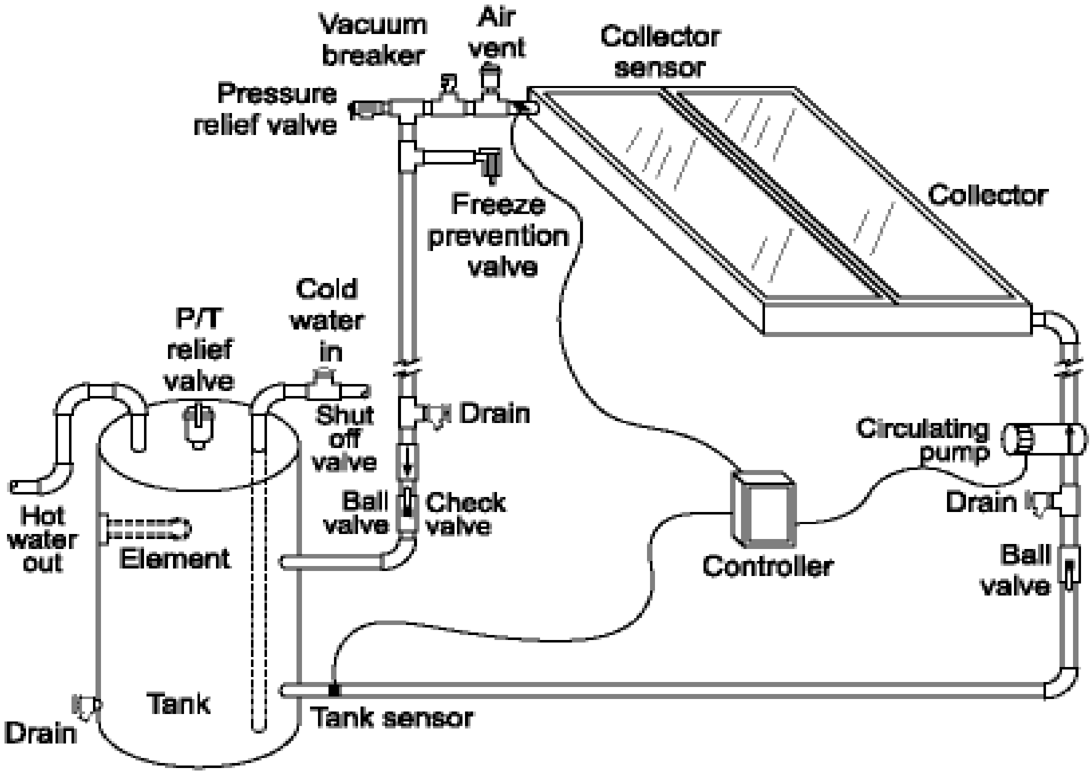

Figure 2.1: Schematic Diagram of a Solar Hot Water Heating System as displayed in Ref. [3].

2.2 Thermally Stratified Storage Tanks

Thermally stratified storage tanks to a great extent have been used in solar domestic hot water (SDHW) heating systems. Thermal storage tank is an essential component which also determines the performance of a solar water heater. Computer simulation also helps to determine the efficiency of this system. In a stratified tank, the masses of hot and cold water are separated. Stratification helps to ensure that the hot water stays at the top to meet the load and the cold water is retained at the bottom. Therefore, it is important to maintain the stratification in the tank, and also in the solar collector to ensure an efficient system. Figure 2.2 explains the phenomenon of stratifications as it occurs in thermally stratified storage tanks.

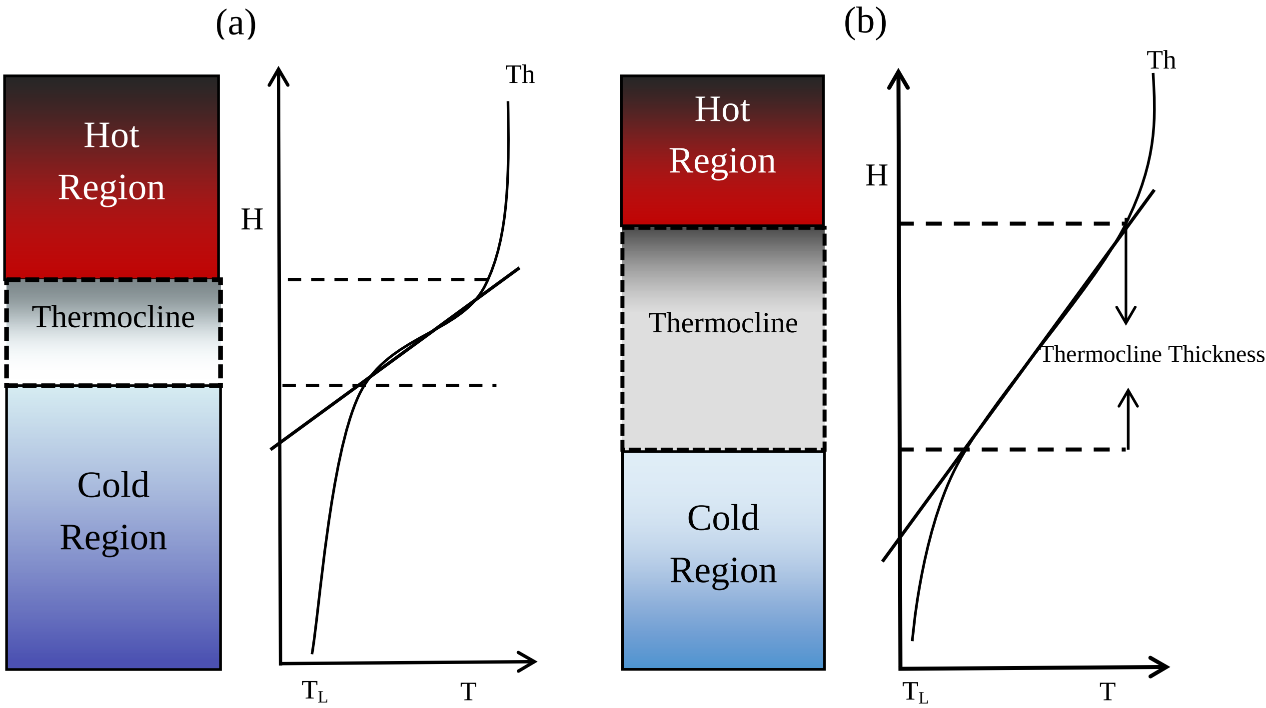

Figure 2.2: (a) Highly Stratified Storage Tank, (b) Moderately Stratified Storage Tank.

Figures 2.2 (a) and (b) indicate two separate levels of stratification of water in a storage tank. Thermocline is a region of steep temperature gradient formed between the hot and cold water masses thus preventing the mixing of the hot and cold water. The amount of hot water that can be drawn from this tank is largely dependent on the thermocline thickness as indicated in the diagrams above.

Some of the factors that influence the degrading of thermal stratification in solar storage tanks include: conduction within the tank walls induced by natural convective flow, mixing between the inlet cold and hot water in the tank, heat loss to the ambient and diffusion of heat which occurs within the tank as a result of the temperature gradient within the fluid [5].

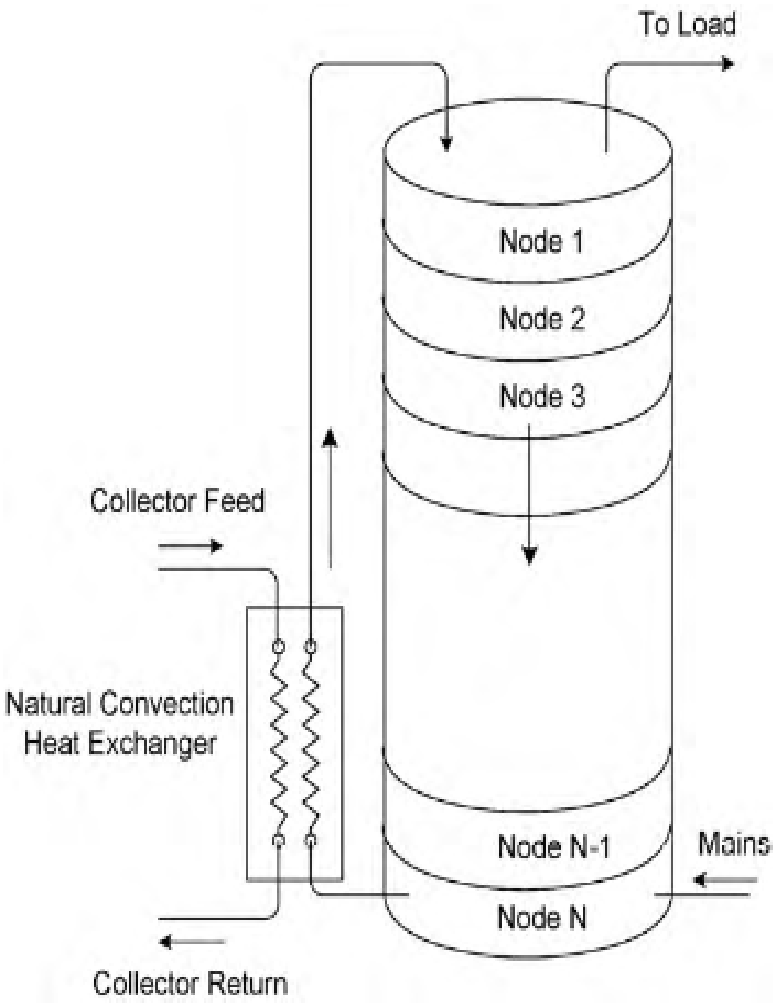

Figure 2.3: Schematic of a Water Storage Tank Divided into Sections for the Purpose of Modeling Stratification as displayed in Ref. [6].

Figure 2.3 [6], shows a schematic of storage tank divided into segments. The cold water comes in through the mains to heat exchanger by natural convection. The temperature of water in each node varies and it decreases gradually from the top of the tank specified as node 1 to the bottom specified as node N. In order to maximize the amount of water above 40^{o}C which is assumed to be the minimum water temperature for a comfortable shower, it is important to control the mixing between the hot and cold water in the tank.

2.3 Historical Review

A number of experiments, researches and numerical studies have been conducted on temperature distributions in storage tanks for domestic water heaters from different perspectives. Some of these papers which are relevant to the study will be reviewed and analyzed for similarities and differences pertaining to this present work.

Cynthia A.C and Stephen J.H, in “2010”, [6], carried out an investigation to determine the magnitude of heat loss from a typical hot water storage tank designed specifically for domestic purposes. A test was also performed on the rate at which of cooling of hot water takes place in the storage tank. An electric water heater storage tank of 270 L capacity insulated with fiberglass was used to conduct the test. The schematic of the experimental system (re-displayed from Ref. [6]), is given in Figure 2. It shows a vertical storage tank of 9 temperature levels (nodes) with an interval of 0.15m between each node. The tank is 1.50m high and is incorporated with a heat exchanger. The values obtained from these tests were compared to that of computer simulations. Also the basic assumptions used in the computer modeling of solar storage heat losses such as minimal wall conduction, temperature profile and uniform heat loss were investigated. It was observed that there were virtually no temperature gradients in the horizontal direction, and it was determined that to adequately produce acceptable predictions, it is necessary to use a heat loss parameter that accurately represents the thermal storage tank as installed.

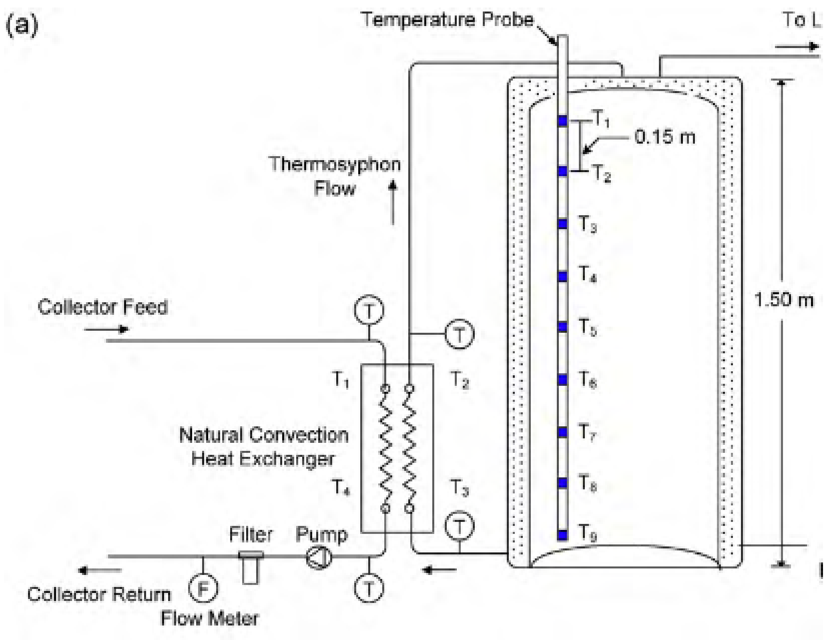

Figure 2.4: Schematic of Experimental Rig Showing the Vertical Temperature Probe as displayed in Ref. [6].

It was observed from the cooling test carried out on the tank that the huge proportion of heat that was lost to the surrounding occurs at the base of the tank. This was as a result of the poor insulation at the lowest part of the tank.

Fang et al, in "1989" [7], conducted a study on the declining stratification in stratified storage tanks. The study was carried out experimentally and theoretically. The effect of insulations and tank wall thickness on the thermal behaviour of a stratified tank was also discussed. It was discovered from the experiment that one of the factors which leads to degrading stratification in a storage tank is the tank wall axial conduction, and this can be improved on by insulating the outside of the tank. It thus helps to prevent the heat loss in the storage tank. It was also observed that by insulating the inside of the tank, stratification can also be maintained this way. The study was however, concluded by developing a model which explains temperature distributions inside storage tanks and compared the experimental result obtained with their numerical values to verify the model.

Ulrike Jordan and Simon Furbo, in “2005”, [8], carried out an experiment to reveal the impact of draw offs on thermal stratification in small solar domestic storage tanks. Two storage tanks were investigated in their experiment. In tank 1, the bottom and top parts was incorporated with a coil heat exchanger and a mantle heat exchanger was applied in the second tank. The storage tanks size used in their experiment were 144 L and 183 L. The investigation was carried out experimentally and also by computer simulation. TRNSYS program was used for the simulation. In the system simulation, a storage tank with multi-node was employed to model the rate of mixing with respect to the condition of operation. The simulated and measured data were then compared. They found out from their investigation that the effects of flow rate, draw-off volume and the initial temperature of the water on the rate of stratification inside the two tanks are different. They also discovered that the inlet design of the tanks which comprises of a curved and flat plate in the shape of a half ball placed above the inlet pipe, and incorporated into the system have a fairly large effect on the performance and that large flow rates in comparison to a small withdrawal will reduce the efficiency of the inlet pipe for the specified load pattern of domestic hot water usage.

In “1999” Shahab Alizadeh, [9], carried out an investigation on the thermal behaviour of a cylindrical solar storage tank in a horizontal position. He carried out four sets of experiments by injecting cold water into the tank initial with three types thermal field. A thermosyphon solar energy system was employed. A horizontal cylindrical tank of 292L capacity made of plexiglass material was used to view the mixing process. It contains a total number of 38 thermocouples which are used to monitor the temperature level in the model. Alizadeh discovered from the experiment that better stratification can be achieved in the tank if a conical tube having the tendency to move in different direction is used as the inlet nozzle in the system. It was also discovered that the tank performance can be improved when the temperature of the cold water that goes into the tank is lower compare to initial temperature at the bottom part of the tank.

Helwa et al, in “1995”, [10], conducted an experimental study to assess the performance of solar water heating system with a horizontal storage tank. A number of factors which influences stratification in the inner surface of the tank were also carefully measured. The efficiency of this system was investigated by measuring the temperature distributions inside the tank during the usage and non-usage period of hot water. It was discovered that the hot water usage pattern has a considerable impact on the storage tank thermal behaviour. Therefore, hot water demand in summer period can be adequately met but to achieve similar efficiency during winter, the system has to be equipped with an electric heater.

Khammas et al, in “2011”, [11], investigated the thermal behaviour of hot water storage tanks during stagnation mode. The experimental study was carried out for three different aspect ratios of the tank, namely ½, 1 and 2. The variation in stratification of water which might occur as the cooling of water begins in the tank was also investigated for the specified aspect ratios. The tank used to carry out their experiment was made from an un-insulated steel sheet with 1mm-thickness. From their experiment, it was observed that the tank with aspect ratio ½ was slightly more stratified due to heat loss to the surrounding. Stratification in the tank with aspect ratio 1 was found to be weak as well, but better compare to the former. They finally concluded that the tank with aspect ratio 2 produces clearer stratification. This is as a result of the heat that is been lost to the surrounding, which in turn induces degrading thermal stratification inside the tank.

A literature review shows that several studies have been performed numerically and experimentally on the temperature distributions in a storage tank but the impact of the tank size on the temperature distributions have received negligible attention. In this present study, this effect will be investigated considering different tank capacities namely; 80 L, 121 L, 150 L and 200 L respectively. The investigation will also focus on the possibility of two-stage usage with a standing time between them. TRNSYS simulation program will be used for the computer modeling.

Chapter 3

METHODOLOGY

The study is conducted on a forced circulation solar water heating system (such as the one shown in Figure 4.1) assumed to be located in Cyprus. A stratified storage tank with 15 nodes of equal segments was modeled considering the solar heating process and two-stage usage patterns simultaneously. The auxiliary heater in the modeled tank was disabled to ensure that heating of water is solely from the solar energy received.

The discharging pattern in Ref. [2] and that of practiced in the present work are displayed in Figure 3.1. In Ref. [2], the water was discharged at a flow rate of 5 L/min (300 L/h) until 21.4 L of water for one person or 42.8 L of water for two persons was extracted. This extraction process took 4.28 minutes for one person and 8.56 minutes for two person's needs. In TRNSYS however, it was not possible to set the simulation timing below one hour during discharging. Therefore, flow rate was set to 50 L/h indicating that 50 L of hot water is extracted in 1 hour between 7pm and 8 pm and the second discharge of 25 L of hot water is also carried out in 1 hour between 7am and 8am at a flow rate 25 L/h as shown in Figure 3.1. In Ref. [2] the standing time (t_s) is defined as the static period between the dynamic (discharging) periods and the data associated with t_s = 12 is used in the present work.

The present work does not attempt to validate the present simulation by the experimental results of Ref. [2]. However, the two studies are compared to explore the differences in temperature distributions inside the tanks of the two different systems. In Ref. [2], the water in the tank is heated once before the discharging procedure is started, whereas with a solar water heating system, the heating process continues throughout the day-time as long as the solar radiation is available.

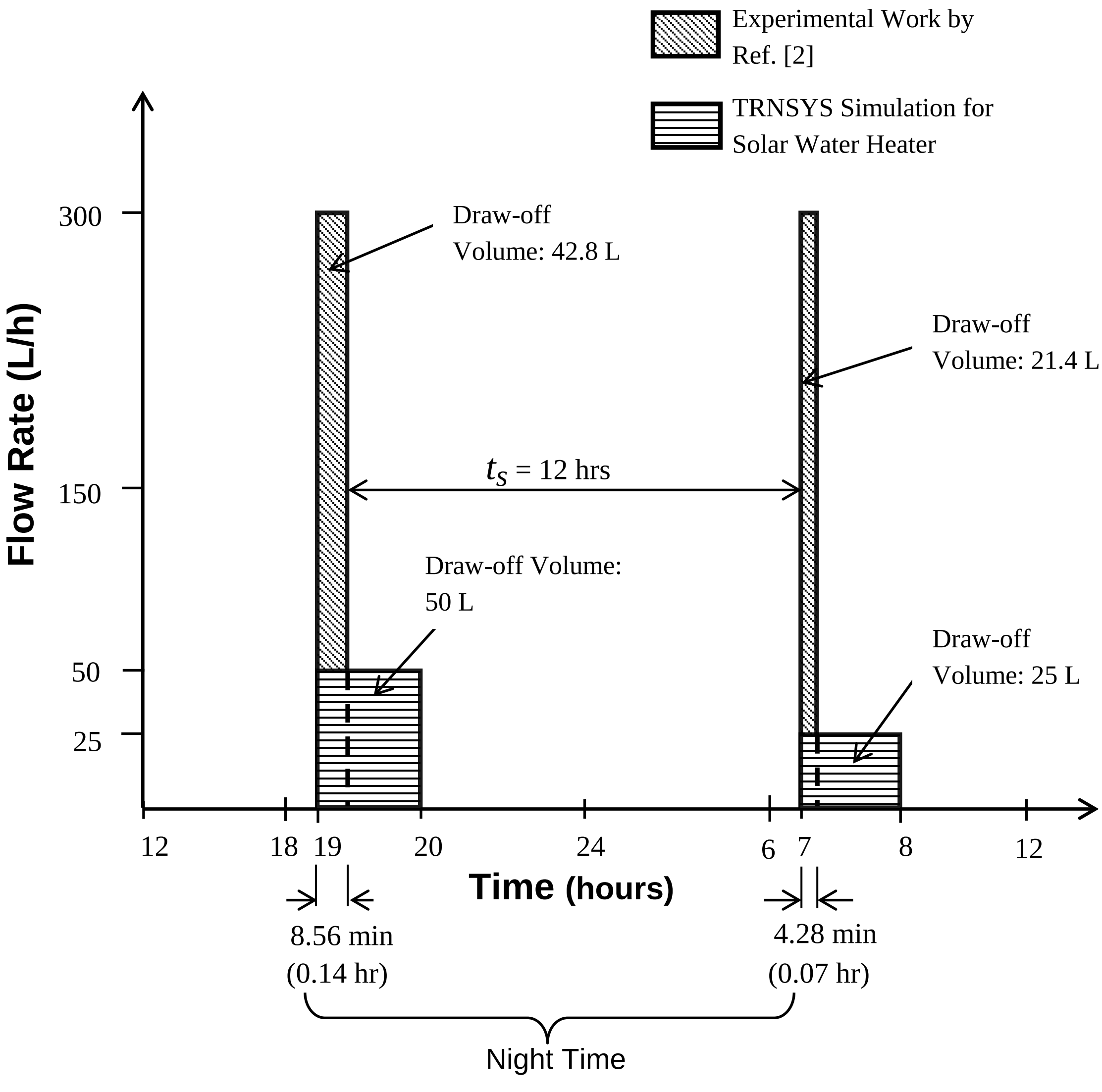

Figure 3.1: Hot Water Discharging Procedure in the Experimental and Simulation Study.

Figure 3.2 describes the procedure of the methodology adopted in this work. The water in the tank is heated whenever solar energy is available, while at the same time a two-step discharging scenario is followed. An instance of the temperature distributions inside a tank during the first and the second discharge stage represented in terms of the dimensionless height versus the dimensionless temperature is shown in the figure.

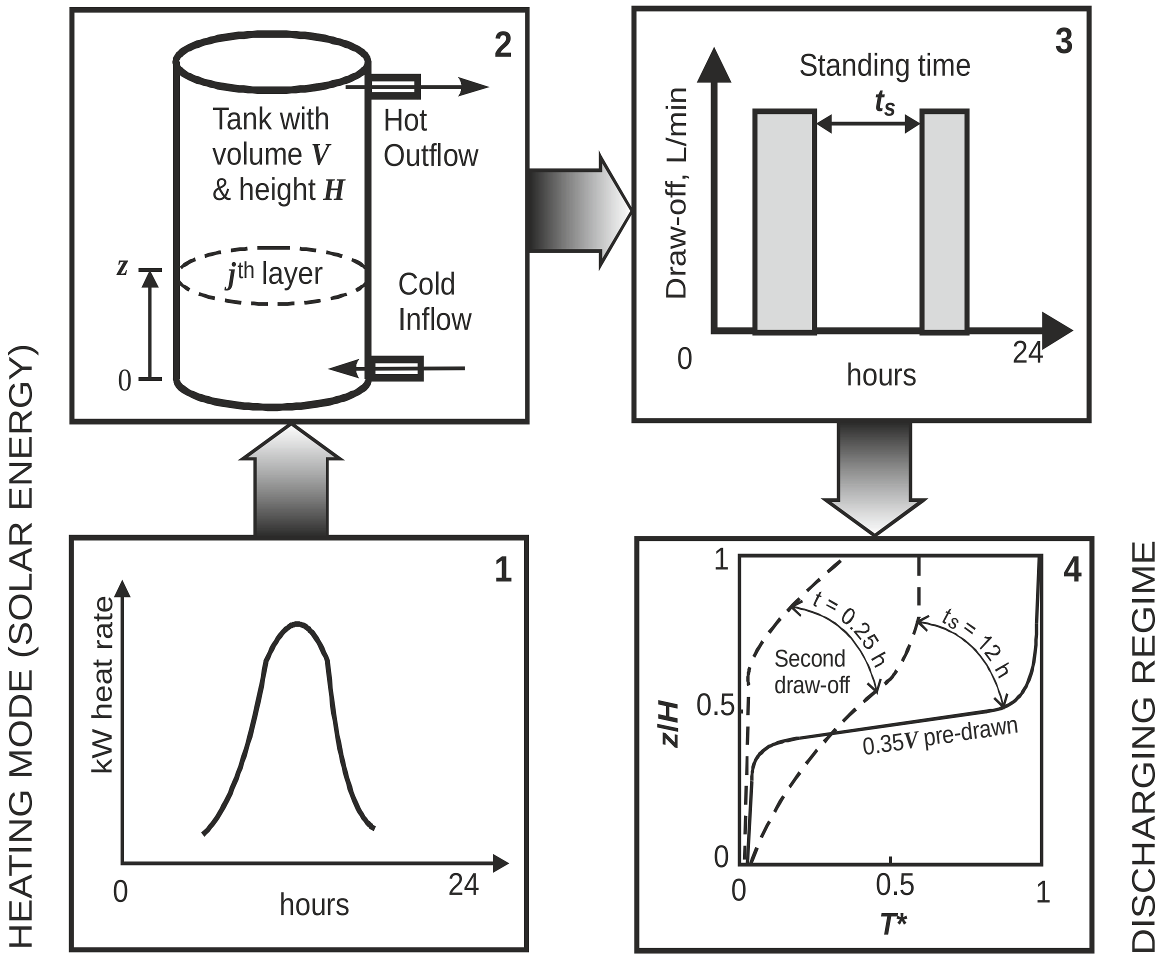

Figure 3.2: The heating-discharging process and the graphical analysis of the temperature distributions in the tank.

The 15 nodes specified in the modeled tank are used to measure the temperature level in the tank. To better understand the temperature distributions inside the tank, the temperature profile is hereby presented in terms of dimensionless height z/H and dimensionless temperature T^*:

$$T^* = \frac{T(z,t) - T_{in}}{T_{max} - T_{in}} \tag{3.1}$$

where:

T_{in} = Inlet cold water temperature

T_{max}= Maximum Temperature

$T(z,t)$ = Height z and time t of the water temperature

H is the height of the tank and z represents the height from the bottom of the tank. T_{max} is equal to the maximum temperature of the discharged hot water during the first and second draw off, while *T(z,t)* represents the hot water temperature in each node at a particular time as obtained from the simulation. T_{in} is assumed to be constant at 10 ^{0}C. The solar intensity and the temperature of the environment (Cyprus) under study were measured in the TRNSYS program. Figure 3.3 shows the ambient temperature curve and the solar radiation versus the elapsed time as obtained from the computer simulation.

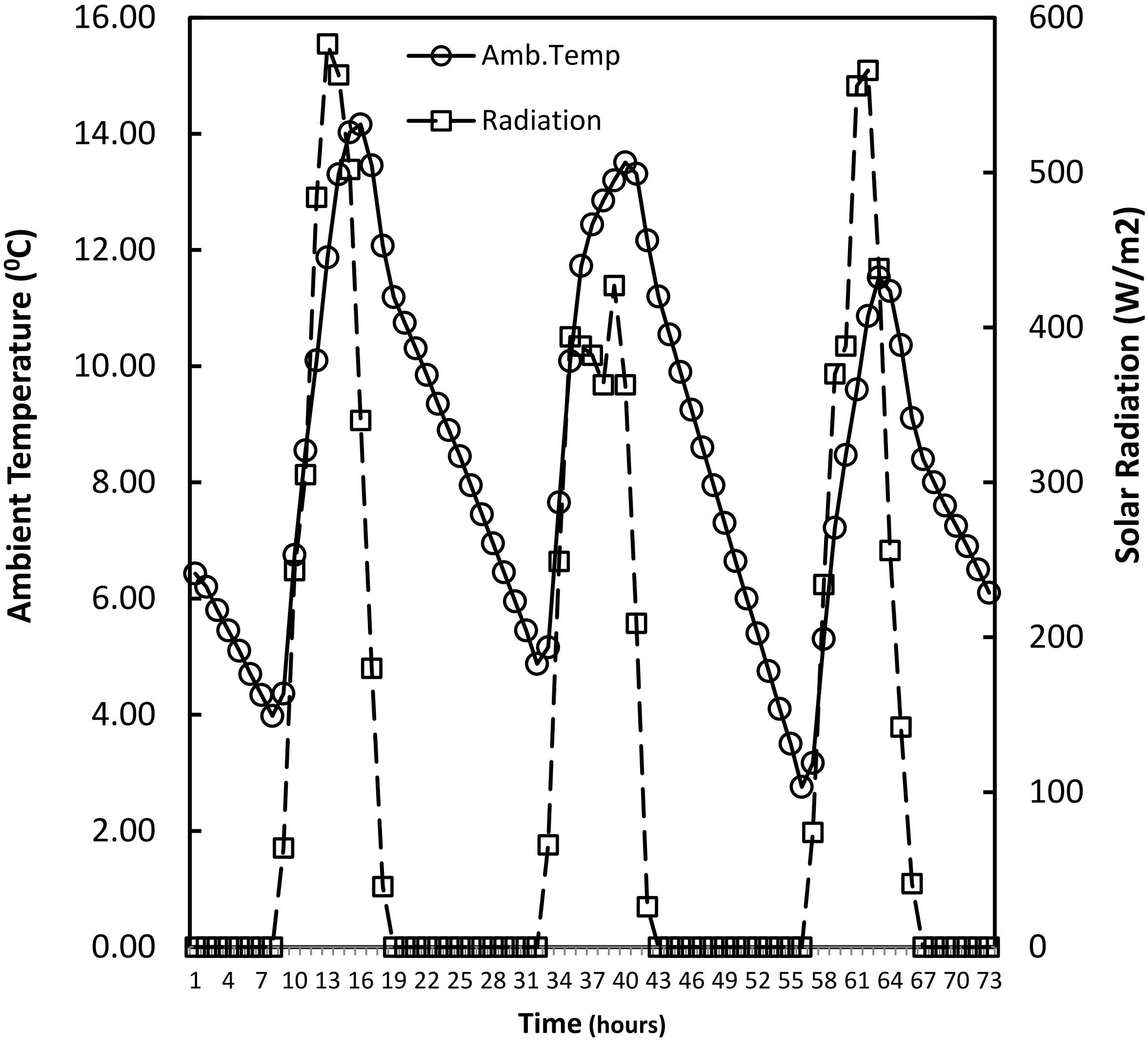

Figure 3.3: Temperature and solar radiation data for January 12-14 provided for Larnaca in TRNSYS

Chapter 4

GOVERNING EQUATIONS

4.1 Introduction

A forced-circulation solar water heating system, shown in Figure 4.1 is used as a basis of the present study. The components investigated include: a stratified storage tank, a solar collector, a pump, and a controller. The governing equations for each of these components will be discussed in this chapter.

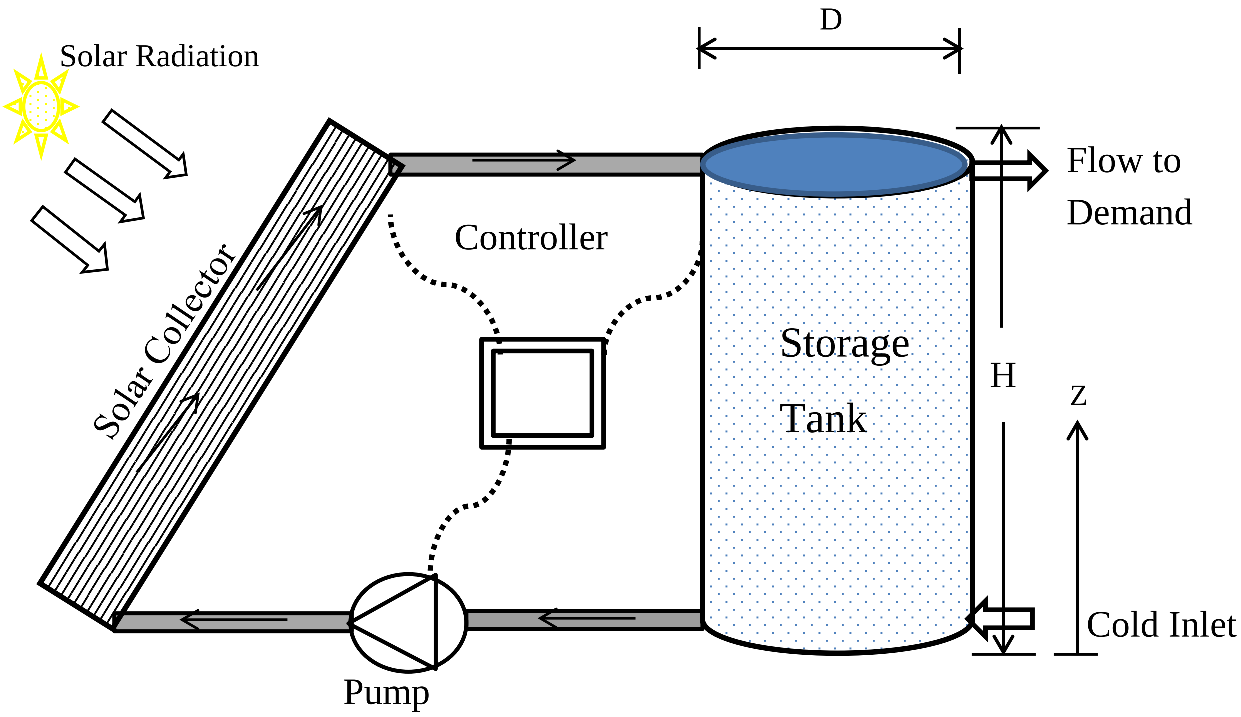

Figure 4.1: Schematic View of a Forced Circulation Solar Water Heating System.

4.2 Flat Plate Collector

This component models the thermal performance of a flat-plate solar collector. The solar collector array may consist of collectors connected in series or in parallel. The thermal performance of the collector array is determined by the number of modules in series and the characteristics of each module [12]. The temperature of the fluid from the standard test results of the collector efficiency may be the inlet temperature or the outlet temperature. Figure 4.2 represents a distinctive flat plate solar collector.

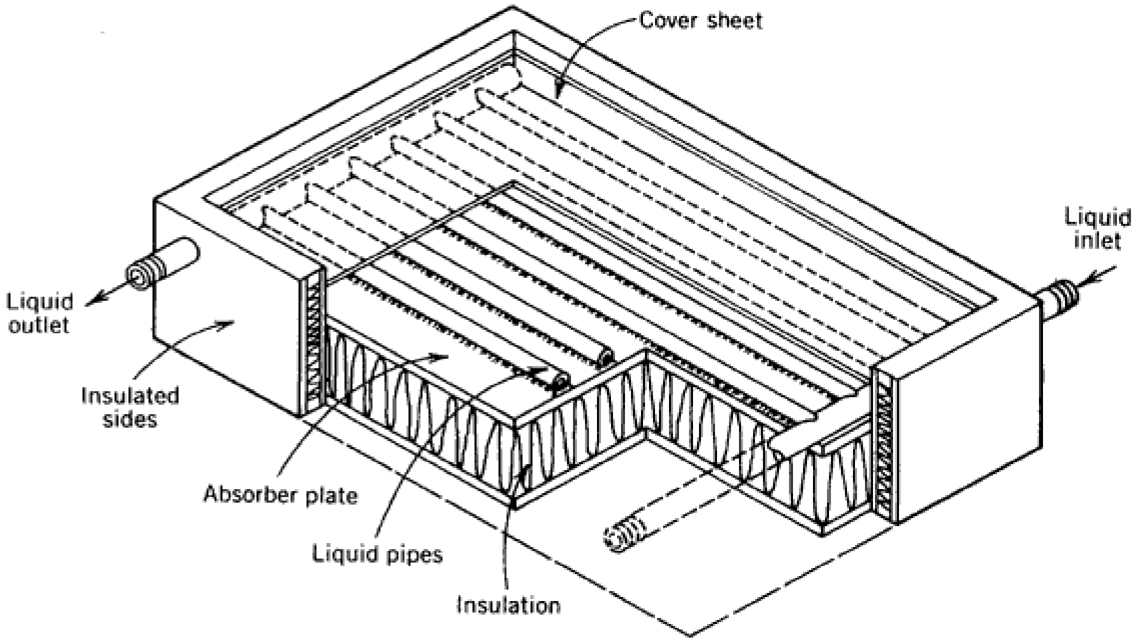

Figure 4.2: Flat Plate Solar Collector as displayed in Ref [13]

4.2.1 Energy Balance

The outlet temperature of the fluid exiting the solar collector array can be determined by applying energy equation on each part of the collector. The rate of useful energy gain by the solar collector is given by [14]:

$$Q_u = \dot{m} C_{pf} (T_0 - T_i)$$

where:

Q_u = Total rate of useful energy gain, [W]

$\dot{m}$ = Flow rate at use conditions, [kg/h]

C_{pf} = Collector fluid Specific Heat, [kJ/kg-K]

T_o = Temperature of the fluid exiting the collector, [°C]

T_i = Temperature of the fluid going into the collector, [°C]

A general equation for solar thermal collector efficiency can be obtained from the Hottel-Whillier equation [14] as:

$$\eta = \frac{Q_u}{AI_T} = \frac{\dot{m}C_{pf}(T_0 - T_i)}{AI_T} = F_R\,(\tau\alpha)_n - F_R\,U_L\frac{(T_i - T_a)}{I_T} \tag{4.1}$$

where:

η = Collector Efficiency

A = Total area of the solar collector array, [m²]

T_a = Ambient (air) temperature, [°C]

F_R = Total heat extraction efficiency factor of the collector

U_L = Total coefficient of heat loss per unit area of the collector, [kJ/h-m²-K]

I_T = Global radiation falling on the solar collector, [kJ/h-m²]

$\tau\alpha$ = Product of the absorber and cover transmittance

$(\tau\alpha)_n$ = (τα) at normal incidence

The loss coefficient U_L is not exactly constant, so a better expression is obtained by taking into account a linear dependency of U_L versus (T_i - T_a):

$$\eta = \frac{Q_u}{AI_T} = F_R\,(\tau\alpha)_n - F_R\,U_L\frac{(T_i - T_a)}{I_T} - F_R\,U_{L/T}\,\frac{(T_i - T_a)^2}{I_T} \tag{4.2}$$

where:

$U_{L/T}$ = Thermal loss coefficient dependency on T, [kJ/h-m²-K²]

Equation 4.2 can be rewritten as:

$$\eta = a_0 - a_1 \frac{(\Delta T)}{I_T} - a_2 \frac{(\Delta T)^2}{I_T} \tag{4.3}$$

where:

ΔT = Temperature difference

a_0 = Efficiency of the collector at intercept

a_1 = Negative of the first-order coefficient in collector efficiency equation, [kJ/h-m²-K]

a_2 = Negative of the second-order coefficient in collector efficiency equation, [kJ/h-m²-K²]

Equation 4.3 represents the efficiency equation of solar collectors generally used in flat plate collector of quadratic efficiency (Type 1).

4.3 Controller

This component is used to control fluid flow through the solar collector based on the principle of two temperature inputs. Duffie and Beckman, [14], show that for stable operation of a solar collector loop without heat exchanger, the following inequality must be satisfied:

$$\Delta T_1 \geq \frac{\dot{m}C_p}{AF_R U_L} \Delta T_2 \tag{4.4}$$

where:

ΔT_1 = Temperature difference at which the pump is turned on

ΔT_2 = Temperature difference at which the pump is turned off

4.4 Stratified Fluid Storage Tank

The thermal performance of a fluid-filled sensible energy storage tank, subject to thermal stratification, can be modeled by assuming that the tank consists of N

($N \leq 15$) fully-mixed equal volume segments, as shown in Figure 4.3. The degree of stratification is determined by the value of N. If N is equal to 1, the storage tank is modeled as a fully-mixed tank and no stratification effects are possible [12].

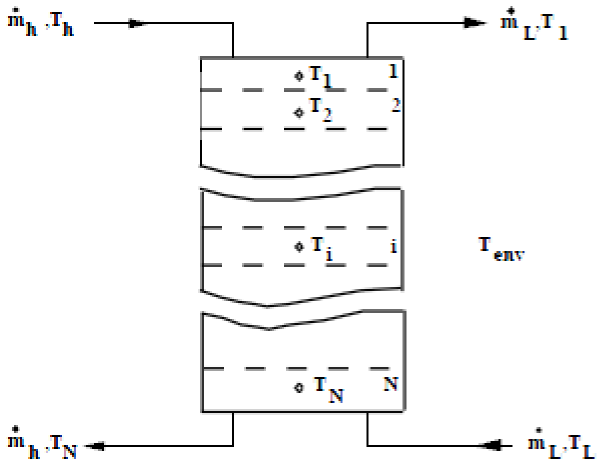

Figure 4.3: Stratified Fluid Storage Tank as displayed in Ref. [12]

T_h = Temperature of the water going into the tank from the collector

T_L = Temperature of the replacement water

T_{env} = Environment temperature which the tank is located

T_i = ith tank segment temperature

$\dot{m}_L$ = Mass flow rate of water to the load

$\dot{m}_h$ = Mass flow rate water to tank from the heat source

N = Number of nodes in the tank with the same temperature ($N \leq 15$)

The following equations are essential to formulate the energy balance on node i of the modeled tank at time t [14]:

$$(m_s C_p)_i * \frac{dT_{s,i}}{dt} = F_i \dot{m}_c * C_p * (T_{co} - T_{s,i}) - L_i * \dot{m}_L * C_p * (T_{s,i} - T_L)$$
$$-(UA)_i * (T_{s,i} - T_a) + \begin{cases} \dot{m}_{m,i} * (T_{s,i-1} - T_{s,i}) & if\ \dot{m}_{m,i} > 0\} \\ \dot{m}_{m,i+1} * (T_{s,i} - T_{s,i+1}) & if\ \dot{m}_{m,i} < 0\} \end{cases} \quad (4.5)$$

where:

C_p = Specific heat capacity of water, [J/kg.K]

m_s = Mass of water in the storage tank, [kg].

$\dot{m}_L =$ Hot water demand, [kg/s].

U = Overall heat transfer coefficient of the storage tank at outer radius, [W/m^2 K].

A = Outer area of the storage tank including insulation, [m^2].

T_s = Instantaneous tank temperature, [^{0}C]

Control function of a collector F_i^c, determines which node receives water from the collector.

$$F_i^c = \begin{cases} 1\ if\ i = 1\ and\ T_{co} < T_{s,i} \\ 1\ if\ T_{s,i-1} \geq T_{co} > T_{s,i} \\ 0\ if\ i = 0\ or\ if\ i = N+1 \\ 0\ otherwise \end{cases} \quad (4.6)$$

The water returning from the load can be controlled in a similar manner with load return control function F_i^L

$$F_i^L = \begin{cases} 1\ if\ i = N\ and\ T_L < T_{S,N} \\ 1\ if\ T_{S,i-1} \geq T_L > T_{S,i} \\ 0\ if\ i = 0\ or\ i = N+1 \\ 0\ otherwise \end{cases} \quad (4.7)$$

Subscripts

c represents the data related to the solar collector panel.

N represents total number of nodes in the storage tank.

s represents the storage tank.

4.5 Pump

This pump computes a mass flow rate using a variable control function, which must be between 0 and 1, and a fixed or user specified maximum flow capacity [15]. Pump consumption may also be calculated, as a linear function of mass flow rate. The outlet temperature is calculated as:

$$T_o = T_i + \frac{P * f_{par}}{\dot{m} C_p} \quad (4.8)$$

where:

T_i = Inlet fluid temperature

T_o = Outlet fluid temperature

C_p = Specific heat of water, [J/kg.K]

f_{par} = Fraction of pump power converted to fluid thermal energy

$\dot{m}$ = Pump mass flow rate

P = Power consumption of pump

The outlet mass flow rate is given as:

$$\dot{m}_o = \gamma \dot{m}_{max} \quad (4.9)$$

where:

γ = control function ($0 \leq \gamma \leq 1$)

$\dot{m}_{max}$ = maximum flow rate (when $\gamma = 1$)

4.6 Temperature Profile

The temperature profile in a storage tank can be presented in terms of the dimensionless height z/H and dimensionless temperature T^* defined by,

$$T^* = \frac{T(z,t) - T_{in}}{T_{max} - T_{in}} \quad (4.10)$$

where:

$T(z,t)$ = Water temperature at time t and height z.

T_{max} = Maximum temperature.

T_{in} = Inlet cold water temperature

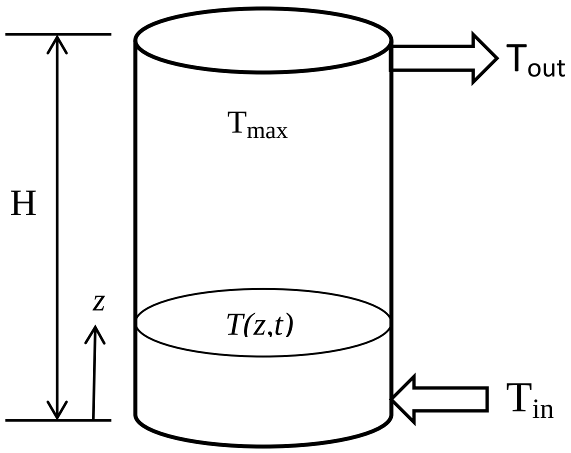

Figure 4.4: Temperature Profile Measurement in a Stratified Tank

The total height of the tank is *H* while the height from the bottom of the tank increases by *z*. Temperature profiles presented in terms of their dimensionless values helps to show the simulation result on a graph by normalizing the level to which the maximum values are attained during the simulation.

Chapter 5

TRNSYS PROCEDURE

5.1 TRNSYS Program Description

TRNSYS is an acronym for “transient simulation program”. This program has been in existence for over 30 years. It was developed by the members of the Solar Energy Laboratory in the University of Wisconsin, US [15]. Several energy concepts like power generation system, domestic hot water systems can be validated using this program. To setup a TRNSYS project, the system components are interconnected in the simulation studio in a desired manner. TRNSYS components are often referred to as Types [15]. A mathematical model in the simulation engine is used to represent each of the components which have a distinct TYPE number. Input file which is also referred to as the deck file is being generated in the simulation studio for the program simulation engine. Projects are created in the simulation studio by simply dragging and dropping the required components to the workspace, linking them together and running the simulation. Information on the simulation time step, start time and stop time are found in the control card. Another significant feature in the TRNSYS simulation studio is the list file which provides the details on errors that might occur while running a simulation and an output manager that controls which variables are plotted or printed.

5.2 System Model

In order to carry out this investigation successfully, it is important to have a proper knowledge of the entire water heating system operation, understand the working principle of all the components required to run the simulation and be able to interpret the results of the simulation.

The assembly of the components which were modeled for the simulation is shown in Figure 5.1.

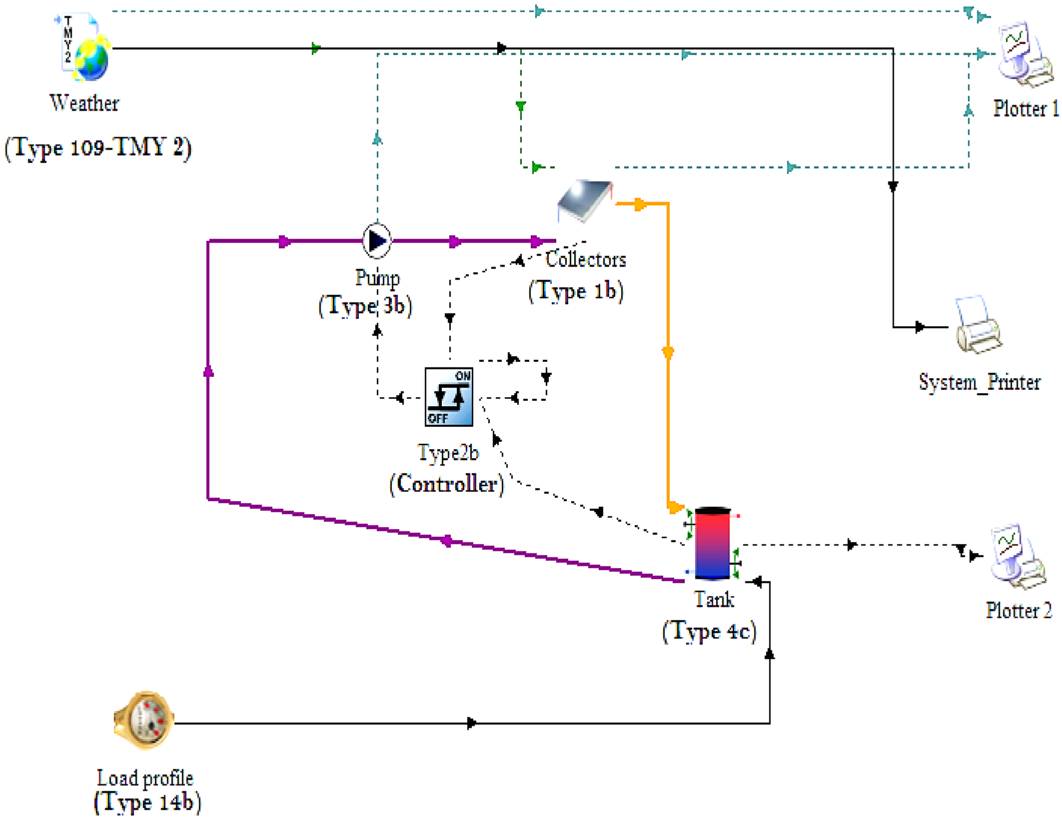

Figure 5.1: TRNSYS Components Assembly [15]

Components used in the modeling of the system are discussed briefly in this section.

5.2.1 Stratified Storage Tank

This type of storage tank is also referred to as Type 4c in the TRNSYS component library. The tank utilized in this work is an open or direct heating type (see Figure 4.3). The tank can be divided into 15 equal segments at most, in which thermal analysis can be conducted separately.

Table 5.1 Characteristics of the Modeled Stratified Tank

Parameter	Tank Size	80L/121L/150L/200L
Parameter	Specific Heat of Fluid	4.190 kJ/kg.K
Parameter	Fluid Density	1000 kg/m^3
Parameter	Tank Loss Coefficient	2.5 kJ/hr.m^2.K
Parameter	Number of Nodes (N)	15

5.2.2 Flat Plate Collector

A flat plate solar collector of quadratic efficiency which is also referred to as Type 1b in Trnsys program is modeled. This component is widely used in solar water heating system. The characteristics of the solar collector modeled are shown in Table 5.2. The intercept efficiency value of the collector was set to 0.8. This parameter is the y-intercept of the collector efficiency versus the temperature difference divided by radiation ratio curve.

Table 5.2 Characteristics of the Modeled Flat Plate Solar Collector

Parameter	Collector Area	4m^2
Parameter	Fluid Specific Heat	4.190 kJ/kg.K
Parameter	Tested Flow rate	40 kg/hr.m^2
Parameter	Intercept Efficiency	0.800000
Parameter	Efficiency Slope	0.635 BTU/hr.ft^2.R
Input	Inlet Temperature	Linked
Input	Inlet Flow rate	Linked
Input	Ambient Temperature	Linked
Input	Collector Slope	40

Output	Outlet Temperature	Linked
Output	Outlet Flow rate	Linked

Figure 5.2 below shows the efficiency curve of the modeled solar collector. The vertical axis shows efficiency while the horizontal axis shows the temperature difference (temperature of the fluid entering the solar collector minus the ambient temperature) divided by the incident solar radiation. The slope of the line in the graph represents the heat loss factor. The steeper the slope, the more the collector loses heat as temperature increases. The highest efficiency of the collector is when the fluid entering the collector is the same temperature as the ambient environment.

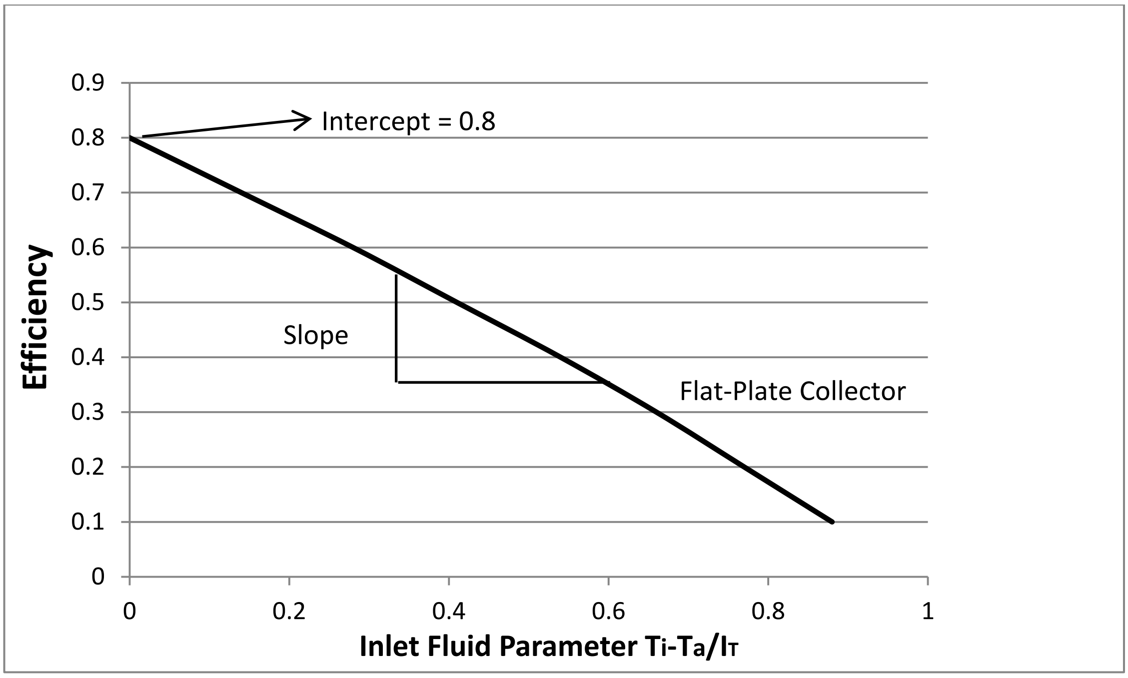

Figure 5.2: Solar Collector Efficiency Plot

5.2.3 Pump

The solar pump is also referred to as Type 3b in the TRNSYS component library. The features of the solar pump modeled are shown in Table 5.3. A control function with varying capacity, whose value must be kept in the range of 0 and 1, is used to determine the mass flow rate of this modeled pump [15]. It also helps to circulate water in the closed loop.

Table 5.3: Characteristics of the Modeled Pump

Parameters	Maximum Flow rate	100 kJ/hr
Parameters	Fluid Specific Capacity	4.19 kJ/kg.K
Parameters	Maximum Power	60 W
Parameters	Inlet Fluid Temperature	10 ^{0}C
Parameters	Conversion Coefficient (f_{par})	0.05

5.2.4 Forcing Function

The component is also referred to as Type 14b in the TRNSYS component library. It is a time dependent forcing function used to estimate the water draw or load profile. This component helps to control the average water drawn per time. The value of the function at different times in the entire cycle is created by separate data points in this forcing function.

Table 5.4 Characteristics of the Forcing Function (Load Profile)

Parameters	Initial Value of Time	0 hr
Parameters	Initial Value of Function	0 L/hr
Parameters	Time at Point-1	19 hr
Parameters	Water Draw at Point-1	50 L/hr
Parameters	Time at Point-2	7 hr
Parameters	Water Draw at point-2	25 L/hr
Parameters	Time at Point-3	24 hr
Parameters	Water Draw at Point-3	0 L/hr

5.2.5 Weather Data

The role of this component in TRNSYS simulation is to read the weather at regular time interval from a data file. Typical Meteorological Year (TMY) weather data file from TRNSYS for Larnaca Airport-Cyprus was used for the simulation.

5.2.6 Controller

This component is also referred to as Type 2b in the TRNSYS component library. It is used to generate an ON/OFF signal which operates the pump. It also helps to control the temperature of the hot water in the storage tank as well as the collector to ensure that it does not exceed the stipulated temperature for safety reasons.

5.3 Simulation Procedure

A solar water heating system is modeled in a computer program called TRNSYS. In this simulation program, all the features of each of the components required for the simulation were carefully observed and the necessary adjustments were made. In the modeled tank, 15 temperature level (nodes) was defined which is the maximum number of nodes in the modeled tank. The auxiliary heater was disabled, and the control signal input for each of the elements was set to 0 since an auxiliary heater is not desired for the simulation. The initial temperature for each node was set to 10 ^{0}C which is also equivalent to the inlet cold water temperature value set for the simulation. The initial tank volume was set to 80 L for the first scenario but was later changed in the cause of the investigation for subsequent tank sizes.

The collector area of the modeled flat-plate collector was set to 4m^2. Collector slope was set to an angle of 40^0 which is consistent with the latitude of Cyprus. The input of the inlet temperature and ambient temperature were linked to their corresponding output and the values were overridden during the simulation when connected to other components. The monitoring temperature in the controller unit (Type 2b) was set to 80 ^{0}C. The control signal will be set to OFF if the temperature should exceed 80 ^{0}C. In the forcing function (water draw) component, 9 points were defined. The time at point 1 which is the starting time for the first draw of 50 L was set to 19 which also imply 9pm in the evening and stopping time to 8pm at point 3. The starting time for the second draw of 25 L was set to 7 at point 6 which imply 7am in the morning, and the stopping time to 8 at point 8 which also imply 8pm. The initial value of time and function was set to 0 and the time at point 9 was set to 24 so that the cycle will repeat every 24 hours. A graphical representation showing the working principles of the forcing function (load profile) obtained as output from the simulation is displayed in Figure 5.2.

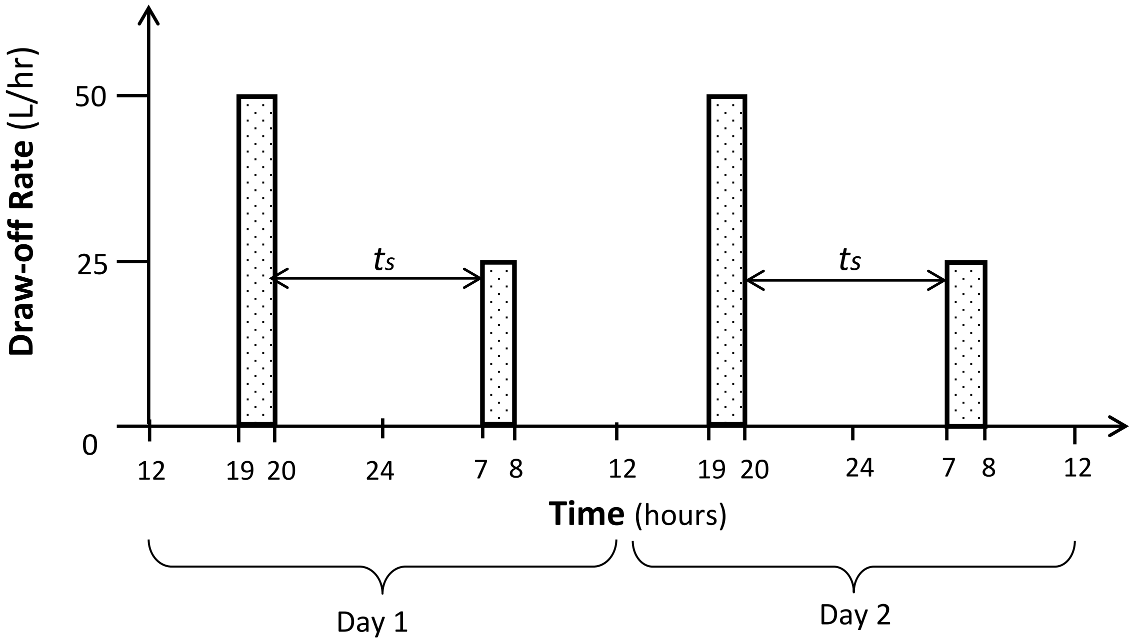

Figure 5.3: Graphical representation of the average value of water draw function which is used as the forcing function in the simulation. Due to a discharging period of 1 h, the effective standing time is 11 h in the case of TRNSYS simulation.

The model was then simulated with the weather data for Larnaca-Cyprus in the TRNSYS program. This procedure was repeated for different tank capacities namely; 80 L, 121 L, 150 L and 200 L respectively. The simulation was conducted for 3 days from January 12 to 14. Some of the data obtained as output from the simulation are the water temperature in each node of the tank, ambient temperature and the hourly solar radiation of the environment under study. These data were extracted from an external file in the simulation studio and copied to an excel sheet to carry out proper analysis of the system. The water temperature in each node of the tank was chosen to validate the model. The effect of the two-stage draw-off with respect to different tank sizes on the temperature distributions in the solar water heating system during the simulation was taken into account and the results presented graphically.

Chapter 6

RESULTS AND DISCUSSION

6.1 Cooling Behaviour in 121 L Storage Tanks

The temperature distributions inside the 121 L storage-type electrical water heater in the experimental work of Ref.[2] as 42.8 L of hot water is drawn off at a flow rate of 5 L/min and the temperature distributions inside a tank with the same storage capacity with solar water heating as 50 L of water is drawn off is shown in Figure 6.1. The temperature distributions inside the tank during the second draw-off at 5 L/min after the initial draw-off of 42.8 L of hot water in the experimental study and the temperature distributions inside the 121 L storage tank for solar water heater as the second withdrawal of 25 L of hot water takes place after a standing time of 12 hrs elapses is also shown in Figure 6.2. The present work does not attempt to validate the present simulation by the experimental results of Ref. [2]. However, the two studies are compared to explore the differences in temperature distributions inside the tanks of the two different systems. The dimensionless temperature is obtained by calculating the difference between the temperature of water in each node of the stratified tank and the inlet cold water temperature, divided by the difference between the maximum temperature and inlet cold water temperature. In Figure 6.1, it can be seen that in the solar system, the desired temperature (which is the same as the maximum 80^{o}C in the case of electrical water heater) is reached. Also as the discharging is continuing a steep temperature gradient at the bottom region of the tank which resulted in a rise in the thickness of the thermocline as the withdrawal of hot water continues in both cases. However, the temperature difference between the solar and electrical systems observed at the lower end of the tanks is due to the differences in their flow rates and the slightly different draw-off volumes.

In Figure 6.2, it can be seen that the thermocline is well defined in the simulation curve thereby causing the hot and cold water in the tank to be properly separated. In this case, hot water suitable for a comfortable shower can be drawn after a standing time of 12 hrs elapses. The decrease in the maximum temperature observed in the experimental curve is due to the poor insulation of the experimental tank resulting to heat loses during the static standing period which is slightly shorter in the case of the simulation. However, the temperature of the water in both cases drops gradually from the top to bottom.

Figure 6.3 shows the temperature distributions inside the tank (121 L) as a function of time during the test days as observed in TRNSYS. The temperature of the water flowing from the top of the tank to supply the load is reperesented as Ttop while the temperature of the water in the pipe connecting the outlet of the tank to the collector is represented as Tbottom. The maximum temperature inside the tank prior to the first draw-off is about 80 ^{0}C. As the discharge of 50 L of hot water begins at 7pm in the evening, the top node temperature drops to 76 ^{0}C and the temperature in node 8 (T8) drops to 49 ^{0}C. However, after a standing time of 12 hrs elapses and the withdrawal of 25 L of water is carried out at 7am in the morning, the temperature of the water in the top node is at 67 ^{0}C and a temperature above 40 ^{0}C is maintained in the tank until the 6th node (T6) where the temperature drops to 38 ^{0}C.

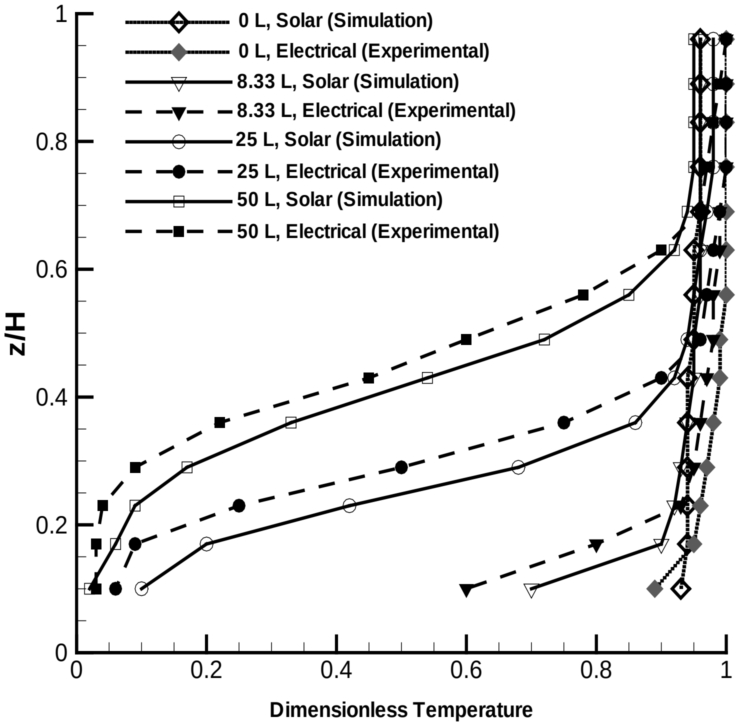

Figure 6.1: Transient Temperature Distribution as the Hot Water is drawn off from a Fully-Heated 121 L Storage Tank.

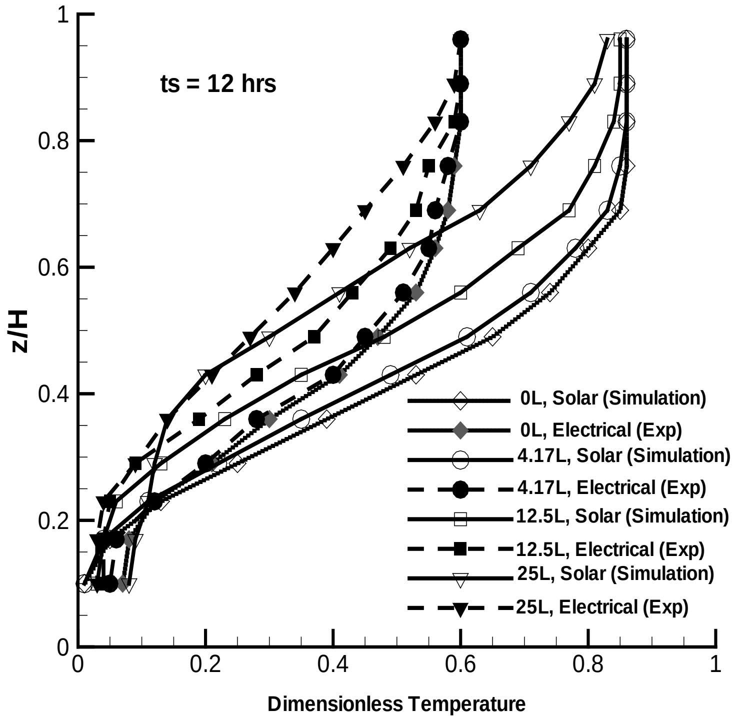

Figure 6.2: Transient Temperature Distribution in the 121 L Storage Tank as Hot Water is drawn off after a Standing Time of 12 hrs.

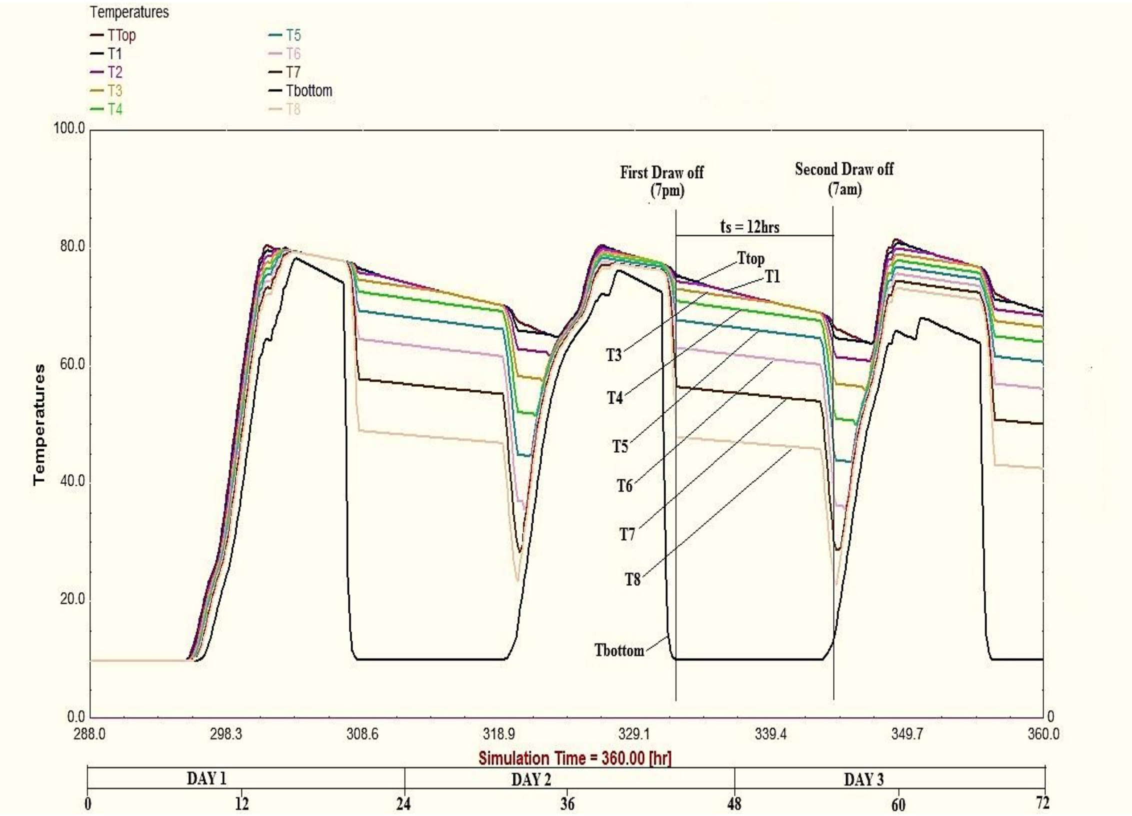

Figure 6.3: Temperature Distributions inside the 121 L Tank Volume as a Function of Time during the test days (indicated as January 12, 13 and 14 in TRNSYS).

6.2 Cooling Behaviour for Different Capacities of Storage Tanks using Solar Energy

Different tank sizes are tested by using the same solar energy system. The temperature profiles represented in terms of dimensionless height versus the dimensionless temperatures and the temperature distributions in each tanks during the first withdrawal of 50 L of water at 7pm in the evening and a second discharge of 25 L of water at 7am after a standing time of 12 hrs elapses between the first draw-off and second draw-off as observed in TRNSYS simulation will be analyzed in this section.

Figure 6.4 shows the temperature distributions as a function of time from a heated 80 L storage tank as indicated in TRNSYS. The maximum temperature in the tank prior to the first draw-off is about 82 ^{0}C but drops to 68 ^{0}C as the first discharge of hot water begins. The temperature of water at the top of the tank as the second draw-off begins is around 45 ^{0}C. A significant drop in the temperature at each node is observed in this tank due to its small size and a large draw-off volume.

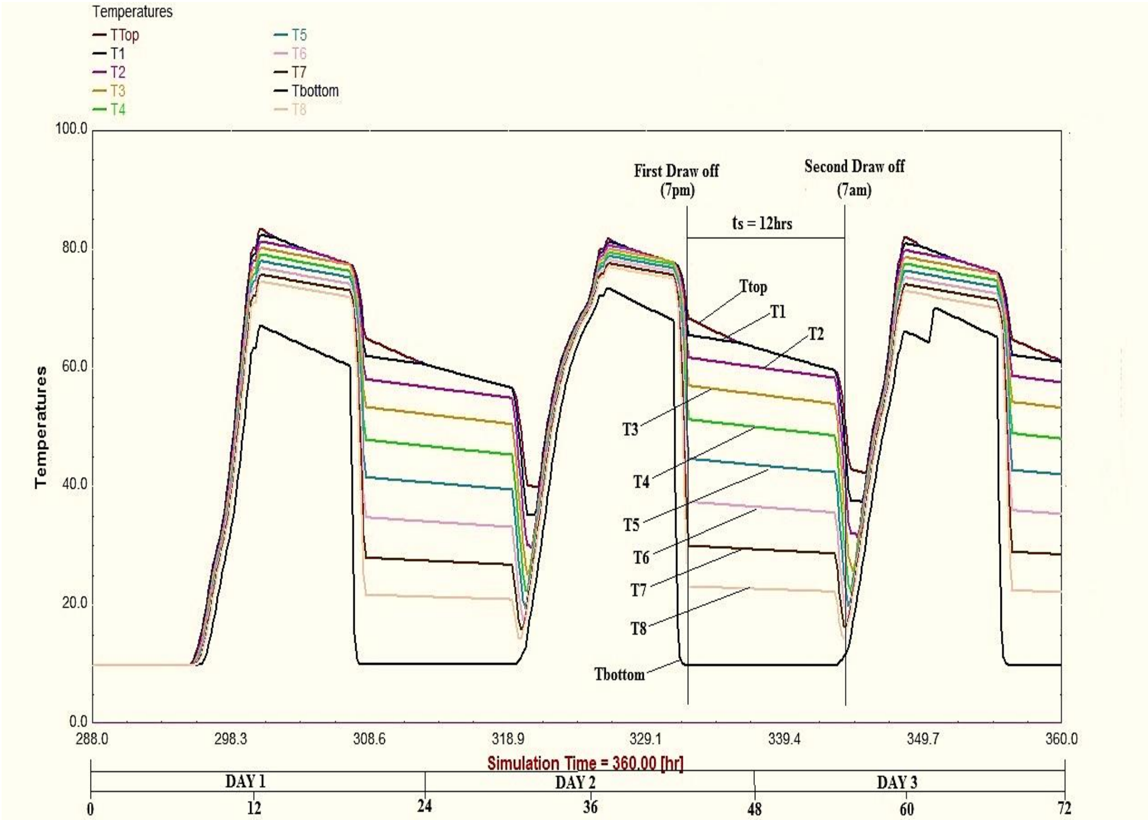

Figure 6.4: Temperature Distributions inside the Tank of 80 L as a Function of Time during the test days (indicated as January 12, 13 and 14 in TRNSYS).

Figure 6.5 shows the transient temperature distributions in the tank with a storage capacity of 80 L during the first discharge at a draw-off rate of 0.833 L/min in the evening. The temperature distributions as the withdrawal is about to start is also uniform during the first draw-off but the thermocline is not well defined and a steep temperature gradient is observed from the bottom part to the top part of the tank. This could be due to the amount of water that is being drawn in comparison to the size of the storage tank and the time of draw as solar radiation is not available for heating of water in the tank. Also the cold and hot water inside this tank are fully mixed.

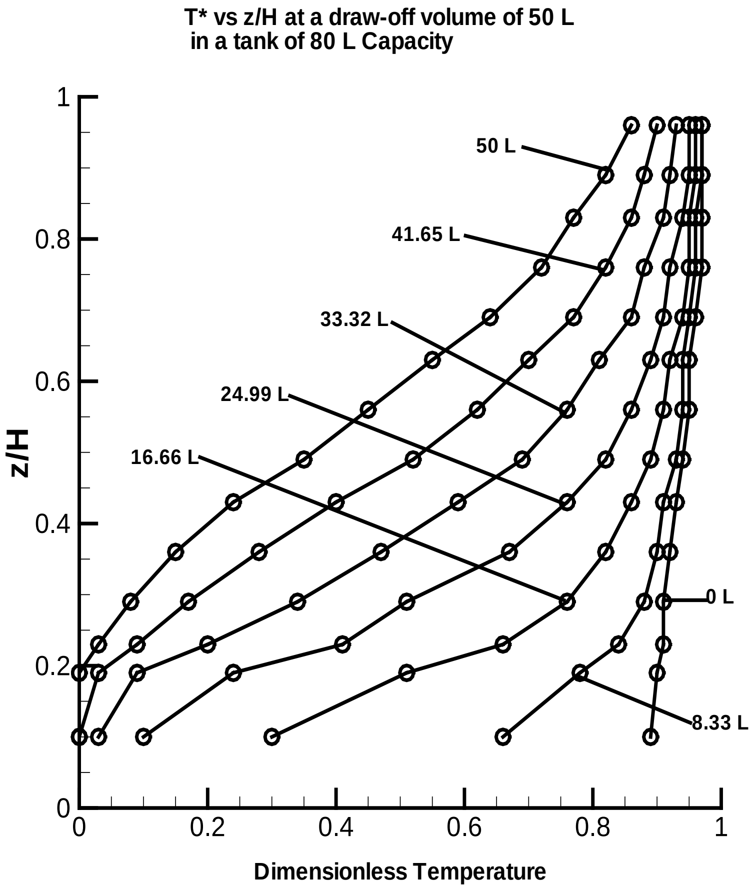

Figure 6.5: Transient Temperature Distributions in the Storage Tank as the Hot Water is drawn off at 0.833L/min.

Figure 6.6 shows the distributions of temperature in a tank that has a storage capacity of 80 L as 25 L of hot water is discharged at a draw-off rate of 0.417 L/min by morning. The thermocline moves upward from the bottom to the top part of the tank during discharge. A sharp decrease in the temperature of water after a static period of 12 hrs is observed in this tank. As the draw-off process begins, it is shown in the curve that de-stratification occurs sharply in the upper part of the tank resulting to a loss in the tank performance.

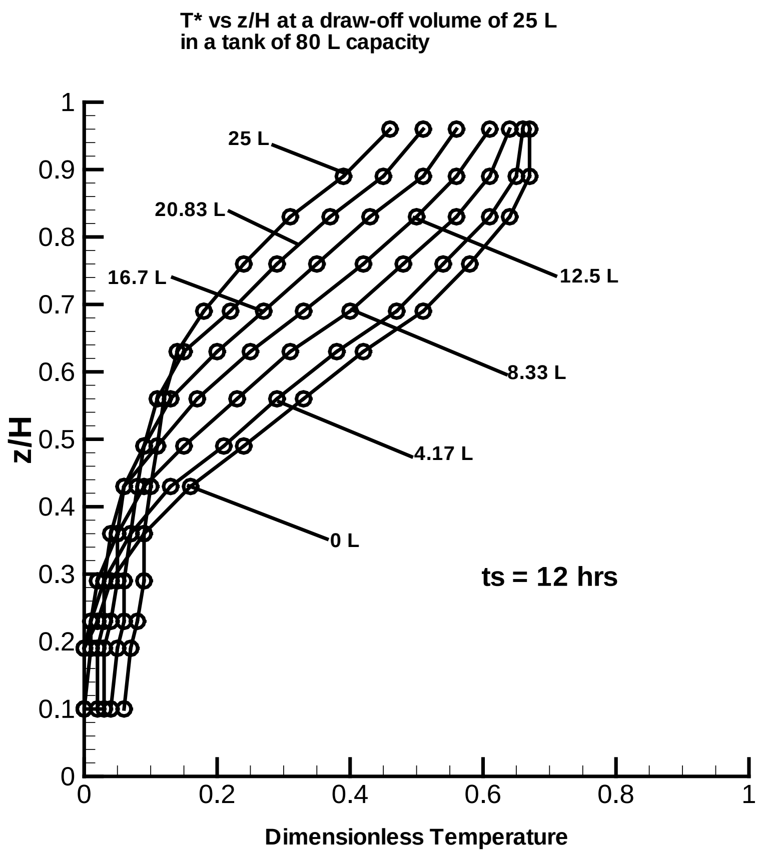

Figure 6.6: Temperature Distribution inside the Tank as Hot Water is discharged at a flow rate of 0.417 L/min.

The distribution of temperature as a function of time from a heated 150 L tank as indicated in TRNSYS is presented in Figure 6.7. A maximum temperature of 80 ^{0}C was attained in this tank as well prior to the first discharging process. However, the temperature of water at the top of the tank drops slightly to 78 ^{0}C due to standing time of 2 hrs between the heating and the discharging period at 7pm as observed in Figure 3.3. The temperature of water in this tank is nevertheless maintained after the first draw-off. Hot water suitable for one or two person to take a shower can be drawn off from this tank in the morning even after a standing time of 12 hrs has been observed after the first draw-off.

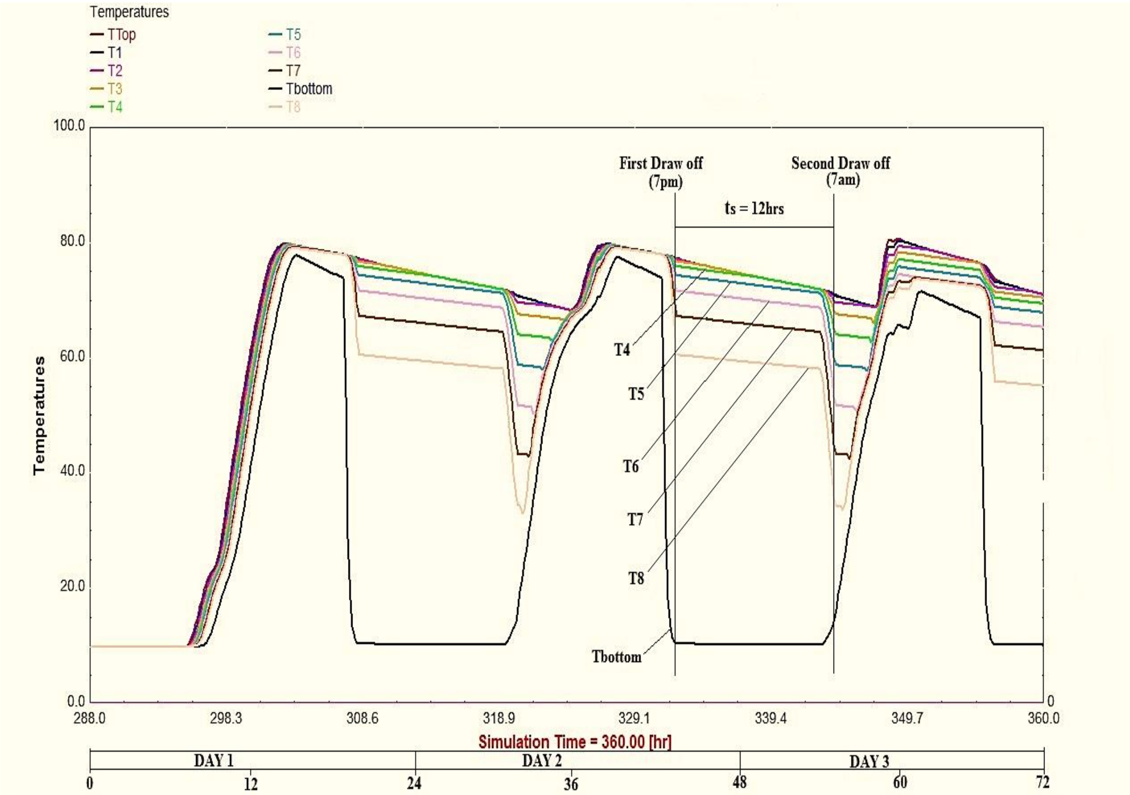

Figure 6.7: Temperature Distributions inside the Tank of 150 L Capacity as a function of Time during the Test Days (indicated as January 12, 13 and 14 in TRNSYS).

The temperature distribution in a tank of 150 L volume as 50 L of hot water is discharged at a draw-off rate of 0.833 L/min in the evening is shown in Figure 6.8. The initial temperature distribution as the draw is about to take effect is the same but a steep temperature gradient, exist at the base of the tank. The cold region temperature gradient is increased while the temperature of water available in the hot region reduces as the usage of hot water continues. The thermocline position moves upward from the bottom part of the tank during discharge.

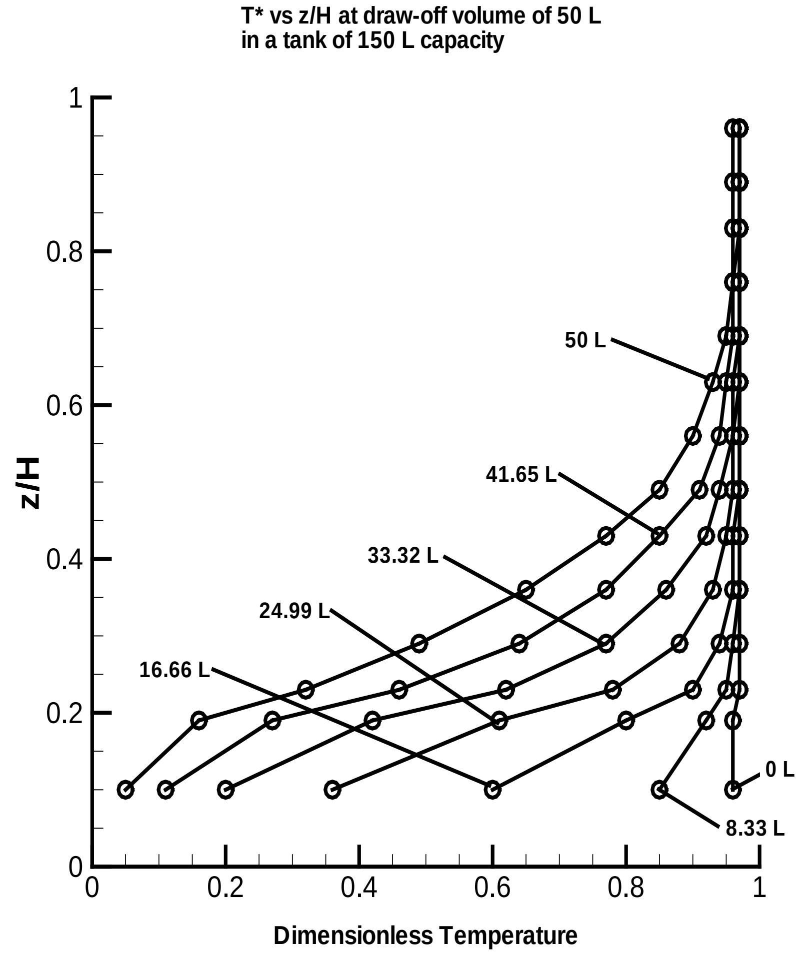

Figure 6.8: Transient Temperature Distributions inside the Tank as the withdrawal of Hot Water takes place at a draw-off rate of 0.833 L/min.

Figure 6.9 shows the distributions of temperature in a storage tank of 150 L capacity when hot water is discharged at a rate of 0.417 L/min which is equivalent to 25 L in the morning. Temperature gradients start increasing during the discharging process due to mixing of hot and cold water at the bottom of the tank. It however, becomes uniform at the top part of the tank. The thermocline thickness changes with respect to time. The cold and hot water are separated properly, thus stratification is well preserved in this tank.

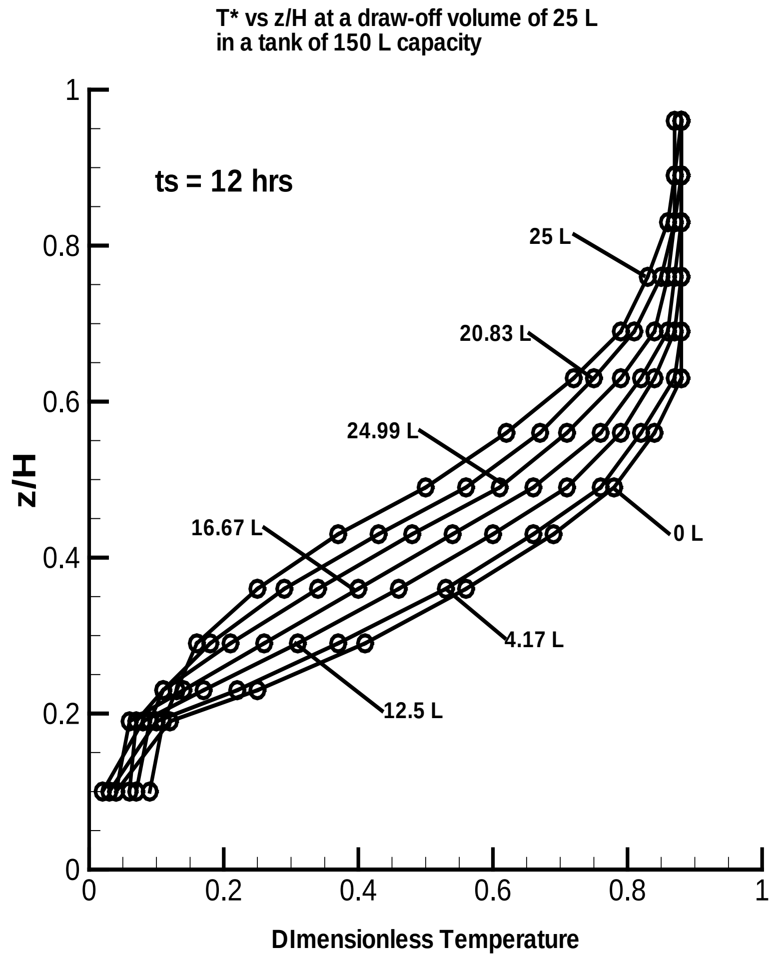

Figure 6.9: Transient Temperature Distributions inside the Tank as the withdrawal of Hot Water is carried out at draw-off rate of 0.417 L/min.

Figure 6.10 shows the temperature distributions as a function of time in a heated 200 L tank as indicated in TRNSYS. The maximum temperature inside this tank prior to the first discharge of 50 L of hot water in the evening is about 73 ^{0}C. This temperature is less compare to what was obtained in the other tank sizes under study. Although more hot water can be drawn in this tank but at a temperature lower than what was obtained in a tank with 150 L capacity.

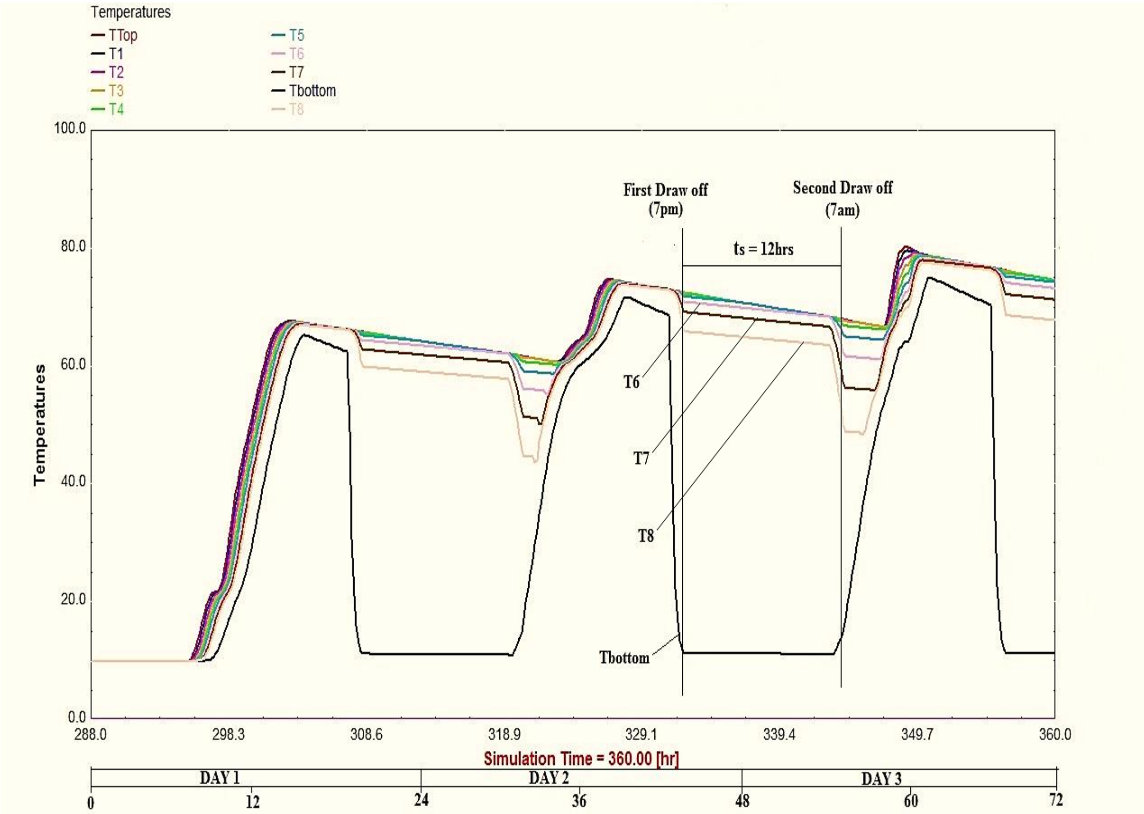

Figure 6.10: Temperature Distributions inside the Tank (200L) as a function of Time during the Test Days (indicates as January 12, 13 and 14 in TRNSYS).

Figure 6.11 shows the temperature distribution in a storage tank of 200 L capacity when the rate of discharge of hot water is 0.833 L/min equivalent to a draw-off volume of 50 L in the evening. The temperature distributions at the beginning of the discharge process are also the same in this case. The thermocline is however reformed as the withdrawal takes place and the temperature gradients begin to increase due to mixing of hot and cold water at the lowest part of the tank.

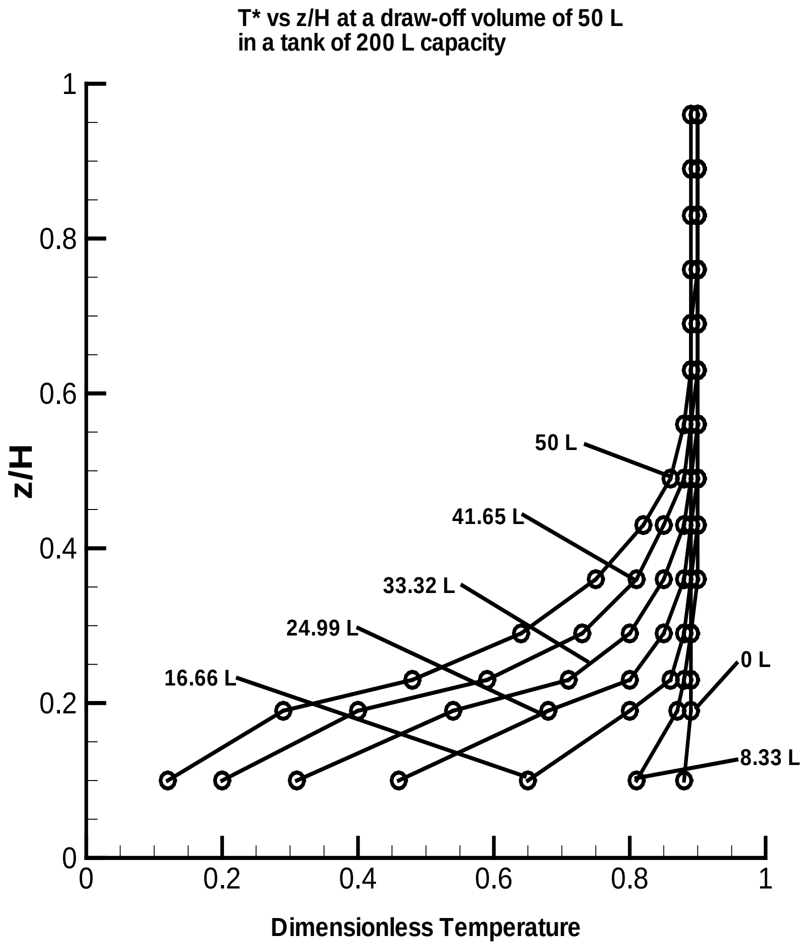

Figure 6.11: Transient Temperature Distributions in the Storage Tank as the Hot Water is drawn off at 0.833 L/min.

The temperature distribution of water in a storage tank of 200 L capacity as 25 L of hot water is discharged at a draw-off rate of 0.417 L/min in the morning is shown in Figure 6.12. In this case, there occurs a decrease in the magnitude of temperature inside this tank as the water is been drawn and the water temperature reduces slowly from the upper part of the tank to the base. As observed in the dimensionless temperature profile, more people can take a shower even after the second draw-off of 25 L but at a lower temperature.

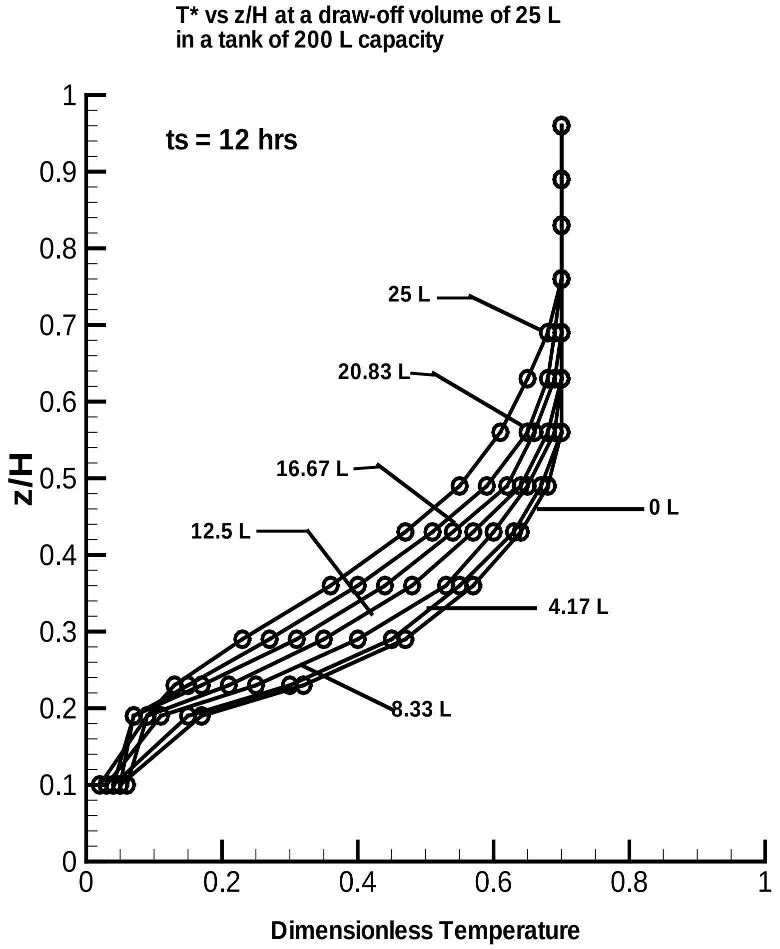

Figure 6.12: Transient Temperature Distributions in the Storage Tank as the Hot Water is drawn off at 0.417 L/min.

Stratification is better preserved in the tank with 150 L storage capacity compared to the other specified tank sizes and more hot water can be drawn at a desired temperature as the second discharge takes place as observed in Figure 6.9. Although the tank with a storage capacity of 200 L shows a similar behaviour with this usage pattern but the temperature of the water drawn inside this tank is lower compared to the with 150 L storage capacity.

The outlet temperatures of different tank capacities at the beginning of the first draw-off and second draw-off, and the maximum temperatures of water in the tank before the discharging process as obtained from the simulation are presented in Table 6.1. Comparing the outlet temperatures at the beginning of the first and second discharge for the different tank sizes in the table below, it was observed that the tank of 150 L capacity produce the highest temperatures of water. Also the minimum temperature of 40 ^{0}C is attained in the different tank sizes after the second draw-off takes place.

Table 6.1: Outlet Temperature of Different Tank Sizes

Tank Size (L)	T_{max} (^{0}C)	T_{out} at the beginning of the first draw-off (^{0}C)	T_{out} before the beginning of the second draw-off (^{0}C)	T_{out} > 40 ^{0}C ?
80	82	68	45	Yes
121	80	76	67	Yes
150	80	78	73	Yes
200	75	73	68	Yes

Chapter 7

CONCLUSIONS

The present study is conducted to investigate the effect of tank size on the temperature distributions for solar water heaters and the possibility of two-stage usage with a standing time of 12 hours between them. The study was carried out under Cyprus winter conditions. The result of the experimental work of Ref. [2] was compared with the simulation results in order to explore the differences in temperature distributions inside the tanks of the two different systems. There exist some similarities between the experimental and simulation curve inside the tank having a storage capacity of 121 L during the second draw-off but the differences in the maximum temperature observed at the top of the tank is due to heat loss in the experimental tank as the standing time elapsed. Hence, the second draw-off of 25 L of hot water takes place at a significantly lower temperature. Proper insulation of the tank used in the experiment will improve the system thermal performance. During the first discharge of 50 L of water in the evening, the main deviation in the experimental and simulated curve observed at the lower part of the tank is due to the differences in their flow rate and draw-off volume.

Looking at the cooling behaviour for different tank sizes using solar energy, the results indicates that the temperature of water drawn from the tank is largely dependent on the draw-off volume, size of the tank and the time of draw especially in situations where a standing time of 12 hours elapses before the second discharging takes place. The worst case was when 50 L of hot water was discharged in a tank of 80 L capacity in the evening and the discharging of 25 L of hot water was started again after 12 hours. In this case, due to the large amount of hot water drawn off in relation to the small tank size, less amount of hot water for a comfortable shower is produced during the second discharge. In the 150 L capacity tank, the maximum temperature of 80 ^{0}C was attained before the discharging process and hot water at desired temperature for one or more persons to take a shower can be drawn even after the first draw-off of 50 L was carried out in the evening before the second draw-off takes place after 12 hours. Although, the tank with a capacity of 200 L shows similar behaviour but the temperature of water drops sharply after the first draw-off and the temperature of water during the second discharge is lower compared to what was obtained in the 150 L tank size for the same scenerio as observed in Table 6.1. This is as a result of the large tank size in relation to the collector area specified in the present work.

In this study, it is assumed that high quality solar collectors with a total area of 4 m^2 are used. In Cyprus, the solar collectors are manufactured with efficiencies of 55-60 % and gross area of 2.7 m^2 and the solar storage tanks are at a standard size of 120 L. This investigation shows that the optimum tank size for solar water heaters should be 150 L with high quality solar collectors for the specified usage pattern.

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