Addis Ababa University
Addis Ababa Institute of Technology
School of Mechanical & Industrial Engineering

Assessment of Thermal Stratification Impact in a Storage Tank on the Performance of PV/T and Hybrid PV/T-Heat Pump System using Computational Method

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Mechanical Engineering (Thermal Engineering)

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Addis Ababa, Ethiopia

July 2023

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Assessment of Thermal Stratification Impact in a Storage Tank on the Performance of PV/T and Hybrid PV/T-Heat Pump System using Computational Method" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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ACKNOWLEDGMENT

First and foremost, I would like to acknowledge the Almighty God with His Mother, St. Marry and His Archangel St. Gabriel for granting me the perseverance to complete this thesis. This thesis has taken me more time than expected.

My advisor, Dr. Ing. Demiss Alemu, has been relentless in encouraging and guiding me throughout the course of my thesis work. Hence, I am grateful for your mentorship. I would like to thank Dr. Alemayehu Tenaw for providing the necessary documents of his research work including the solar data which simplify my entire work.

I am also thankful for my father, Gashe Dereb Hailemariam, my beloved mother W/ro Tafesech Getachew, and my siblings Brook, Tizeta, Merry, and Rediet for their financial and emotional support. My acknowledgement also extends to my relatives and all friends who have helped me by providing resources and emotional supports.

Lastly, but not least, I acknowledge Addis Ababa University for sponsoring my MSc study and granting research funds and staff of school of Mechanical and Industrial Engineering for their managerial guidance.

ABSTRACT

In solar thermal systems, hot water storage tanks are employed to store the heat energy extracted from multiple energy sources and to balance the supply/demand of thermal energy requirements. One of the main challenges of these systems is the mixing of hot and cold water in the storage. Though several storage utilization methods were adopted, identifying the best approach to utilize the stored heat energy effectively and efficiently is still critical. Hence, this study has focused on modelling thermal stratification in a storage tank to assess its positive impact on the performance of existing hybrid PV/T and heat pump water heating system.

One-dimensional multi-node model was simulated in MATLAB, with implicit finite-difference scheme, for evaluating temperature distribution and annual efficiencies of the system after the thermal stratification is applied. Details of the fluid flow stored in the stratified storage were studied in two dimensional CFD model using ANSYS Fluent. Both models were validated with experimental results from literature.

Compared to the system with mixed storage, the stratified storage enhanced the annual solar fraction to 0.73. Thermal and overall efficiencies were also elevated with 14.8% and 15.6% respectively. Both the collector and storage heat losses were diminished with significant figures. Performance analysis was also done on geometrical parameters like H/D ratio, insulation, inlet locations, and operational conditions such as collector flow rates, heat removal factor and hourly hot water consumption fraction.

The results of the CFD model showed that the temperature gradient differences in increasing storing time. Applying improved quality of model is still needed for simulating a better appropriate thermally stratified storage tank model in a solar thermal system technology.

Key words

Solar thermal energy storage, thermal stratification, hot water storage tank, multi-node model, CFD Model

Contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

1D= One- Dimensional

2D= Two- Dimensional

CFD= Computational Fluid Dynamics

COP= Coefficient of Performance

DHWC= Daily Hot Water Consumption

HP= Heat Pump

PV/T= Photo-Voltaic Thermal Collector

TES= Thermal Energy Storage

NOMENCLATURE

Ac	Function of the collector area(m^2)
A_c	Contact area between nodes of the tank (m^2)
ΔA_s	Surface area of the node (m^2)
${c_p}_C$	Specific heat of water from collector [J/ (kg °C)]
${c_p}_L$	Specific heat of water to the load [J/ (kg °C)]
${c_p}_{in}$	Specific heat of water from mains [J/ (kg °C)]
${c_p}_n$	Specific heat of water in the node [J/ (kg °C)]
${c_p}_s$	Specific heat of water to the collector [J/ (kg °C)]
d	Internal diameter of the storage (m)
d_{in}	Diameter of the inlet pipes(m)
d_{out}	Diameter of the outlet pipes(m)
E	Total specific energy (J/kg)
F	Collector efficiency factor
F_R	Collector heat removal factor
f	Body Forces (N/m^3)
$f.U$	Dot product of the velocity and force vector
G	Solar Irradiance (W/m^2)
g	Gravitational acceleration (m/s^2)
h	Height of the tank (m)
Δh	Node size (m)
k	Thermal conductivity of water(W/m-K)

k_{eff}	Effective thermal conductivity (W/m.°K)
L	Characteristic linear dimension (m)
$\dot{m}_C$	Mass flow rate of water from collector (Kg/s)
$\dot{m}_{in}$	Mass flow rate of water from the mains (Kg/s)
$\dot{m}_{in,n}$	Mass flow rate across the bottom of the node (Kg/s)
$\dot{m}_L$	Mass flow rate of water to the load (Kg/s)
$\dot{m}_s$	Mass flow rate of water to the collector (Kg/s)
$\dot{m}_{out,n}$	Mass flow rate across the top of the node (Kg/s)
Δm_n	Total mass present in the node (Kg)
N_{epv}	Nominal efficiency of PV module
n	Number of nodes
P	Pressure (Pa)
P_f	Packing Factor
Q_u	Useful heat gain (W/m^2)
$\dot{Q}_{hp}$	Heat input from the heat pump (W)
$\dot{q}$	Heat transferred (J/kg)
Re	Reynolds number
S	Absorbed solar energy (W/m^2)
S_e	Enthalpy of Source (J/kg)
T	Temperature (^{o}K)
T_a	Ambient temperature (^{o}C)
T_C	Temperature of water from collector (^{o}C)
T_{fp}	Temperature coefficient of PV module
T_L	Temperature of water to the load (^{o}C)
T_n	Nodal temperatures (^{o}C)
T_{n-1}	Temperature of water in the previous node(^{o}C)
T_{n+1}	Temperature of water in the next node(^{o}C)
T_o	Reference temperature (^{o}K)
T_p	Temperature of PV (^{o}C)
T_{rf}	Reference temperature (^{o}C)
T_s	Temperature of water to the collector (^{o}C)
T_{wba}	Temperature of back up water from mains (^{o}C)

T_{wi}	Temperature of water into the collector (^oC)
T_{wo}	Temperature of water out of the collector (^oC)
t	Time (s)
Δt	Time step (s)
U	Total Velocity (m/s)
U_L	Overall collector heat loss coefficient of the collector ($W/m^2 \cdot °C$)
U_t	Heat transfer coefficient of the node($W/m^2 \cdot °C$)
u_o	Velocity of a fluid with respect to the object tank (m/s)
u,v	X and Y components of velocity (m/s)
$\dot{V}$	Volume flowrate (m^3/s)
V_s	Volume of the storage (m^3)

Greek Symbols

β	Coefficient of thermal expansion (K^{-1})
ρ	Density (kg/m^3)
ρ_o	Density at the operating temperature T_o(kg/m^3)
τ	Shear stresses (N/m^2)
τ_{eff}	Effective Shear stress (N/m^2)
ϑ	Kinematic viscosity(m^2/s)
μ	Dynamic viscosity [kg (m.s)]
η_{th}	Thermal efficiency
$(\tau\alpha)_{PV}$	Product of Transmittance & Absorptance of the PV module

CHAPTER ONE

INTRODUCTION

Since solar energy is the most abundant source of energy on earth, it can be harnessed for various applications like water heating, electricity generation, space heating, and distillation. This can be done by using either photovoltaic or solar thermal conversion systems with minimal greenhouse gases during its collection. From the above applications, nowadays, the most popular one is utilization of solar energy for cogeneration of hot water and electricity due to its low investment and maintenance cost [1]. This chapter overviewed one of those solar thermal systems and thermal stratification application in its storage tank. The motivation for doing the research, objectives, and other research contents are also included.

1.1 Background

Different energy storage systems have recently been developed to a point where it can have a significant impact on modern technology. The standard book, Thermal Energy Storage Systems and Applications, explained types, techniques, and methods of various energy storage systems with their benefits on a detailed basis [2]. According to the book, from those different types, thermally stratified storage tanks are classified under sensible thermal energy storages. To attain the desired performance of a system, careful design, simulation, and accurate component models of the system's components is needed [3]. This section provides background information about the existing hybrid PV/T-Heat pump system and some features of thermally stratified storage tanks.

1.1.1 Overview of the existing PV/T assisted Heat Pump System

Photo voltaic thermal collector (PV/T) represents the device with photo voltaic (PV) panel and solar thermal collectors to obtain solar energy. Unlike the conventional solar thermal collectors, photovoltaic solar thermal collectors (PV/T) have an amazing feature of gaining high energy outputs per unit surface area due to the conversion of solar radiation into usable heat (hot water) and electrical energy simultaneously. Combination of PV/T systems with other efficient energy systems like heat pump systems will give globally efficient hybrid system that can be even installed either for domestic or large scale without an additional alternative source of energy applications.

The warm water from the PV/T can be used as an input to the heat pump water heater to attain the required temperature of water by the end-user. The application of photovoltaic-thermal system is not only for pre-heating water, but also the electrical energy generated by the PV/T system would cover the electrical energy demand for the heat pump water heater [4].

PV panel collector, thermal storage tanks, heat pump, piping, mains supply, and load are some components of PV/T-assisted heat pump domestic hot water storage system. The panels use solar radiation to heat the water for the collection of useful solar energy and the hot water is sent directly into the storage tank. If auxiliary heating is required for the end use or load, heat pumps can be used. For a storage contains cold water initially, the processes in the system are:

- The initial cold water is pumped to the collector through first storage outlet at the bottom and heated by the PV/T.
- The hot water from PV/T is sent to the storage tank inlet at the top.
- When required, the hot water from the first storage tank is sent to the heat pump system for additional heating through an outlet at the top of the tank and is stored in the second storage.
- Coldwater from the main supply enters the tank at bottom to replace hot water left.
- Hot water is drawn from the hot water storage tank when heating load is required.

Figure 1.1 shows the system schematics with its components and processes adopted from the existing hybrid PV/T-Heat pump water heating system. It is shown that the storage tanks are involved in every process, from the components of the system, this research focuses on the modelling of the storage only.

There are three distinct steps (dynamic operational modes) in a complete storage process called charging, storing, and discharging [2,3]. From these processes, the first two are categorized under charging and the other is considered as discharging. These steps may also occur simultaneously as hot water is added from the PV/T and extracted to be sent to the load or storing and charging at the same time.

Thermal energy storage, simply water storage tank, has two important roles as an energy reservoir and redistribution. From the lower temperature section of the water storage tank, the cold water circulating through the PV/T collectors is heated by solar radiation, where it becomes the hot water and returns to the storage tank.

Storages can be broadly classified based on different factors incorporated as tabulated as in Table 1.1.

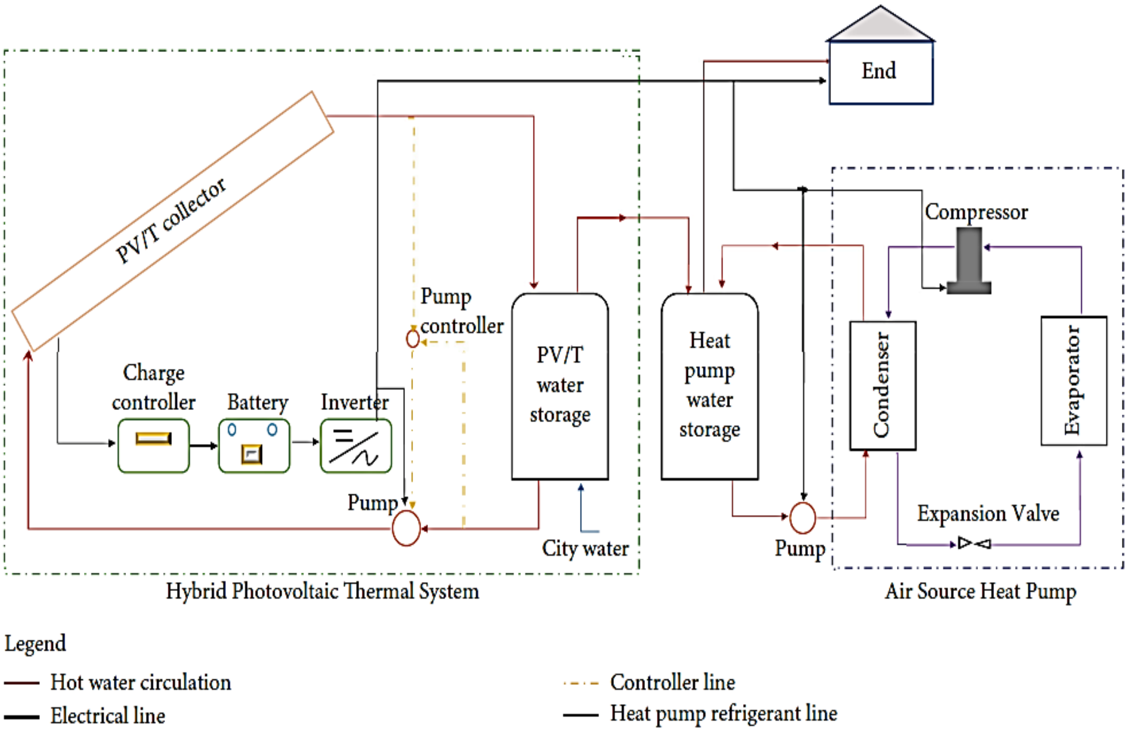


Figure 1. 1 Schematic of the existing Hybrid PV/T-Heat Pump System [80]

Table 1. 1 Behavioral classification of storage tanks [11]

Connections with loads	**Material**	**Geometry (orientation and location)**
Series	Fluid	tank port
Parallel	Tank	internal or external heat exchangers
Hybrid	Insulation	electrical heaters

It is known that, for residential applications, hot water loads are higher during night than daytime which is opposite to solar availability. Main function of the thermal storage tank is, therefore, to store absorbed solar energy for use during periods of low and no insolation. Generally, thermal energy storage has the following advantages [11].

- balancing the energy supply and demand, which often do not occur at the same time.
- shifting the energy usage from off-peak demand to on-peak demand requirement.
- degrading energy losses by decreasing the number of starts and stops of the heating system.
- upgrading system reliability.
- increasing heating generation and deliverable storage capacity.
- shifting energy purchases to lower cost periods.

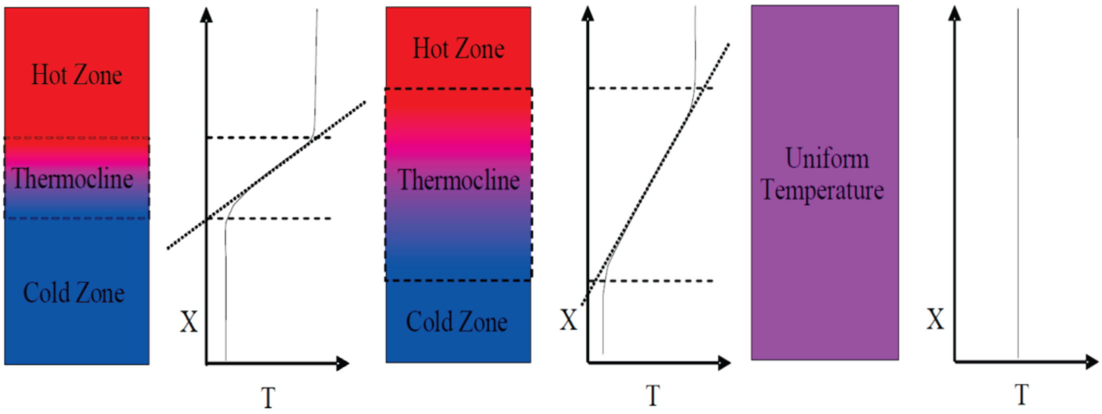
Storage tank material, wall and insulation thickness, thermal capacity, temperature range, means of heat addition or removal, thermal loss, and circulating fluid flow rate are some factors which influence thermal storage effectiveness. Optimization of these factors with good storage tank stratification can enhance high energy extraction efficiency [5]. Consequently, the concern of this thesis is on the phenomenon of thermal stratification in water storage tanks.

1.1.2 Stratified thermal energy storage tanks

Stratified thermal energy storage tanks (TES) operate based on the principle of thermal stratification. Thermal stratification is a phenomenon of the vertical layering of water due to the density difference between hot and cold water. It is also the ability of buoyancy or floating impact of the hot water over the cold water which causes the cold water to sink at the bottom and the hot water floats to the top of the tank. Thermal stratification in the storage tank allows for the greatest amount of energy to be extracted when hot water is desired by the load. This is because the temperature of the water in the hot region of the tank would not significantly change.

The first method of thermal stratification is to divide the tank into three zones or layers during operation. These are the top layer with the warmest water, the bottom layer with the coldest water and the interface between them which indicates the degree of stratification. Thermocline is the intermediate temperature region that can be used as an index of the temperature stratification of the stored water as shown in figure1.2. Most of the time, for stratified storage tank is full, thermocline will move up and down depending on whether the system operation is charging or discharging.

When the storage tank has no inside partitions, it is regarded as a natural thermal stratification system. Since the warmth and density of water are inversely proportional properties, its principle of operation is simply based on the density gradient of the lower density warm water and higher density cold water. Compared to other systems, the storage volume of this type is reduced, because the dead water volume is relatively low, and the energy efficiency is relatively high [3].



(a) Moderate stratification with small thermocline width

(b) Low stratification with large thermocline

(c) No stratification/ fully mixed tank

Figure 1. 2 Differing levels of stratification within a tank [6]

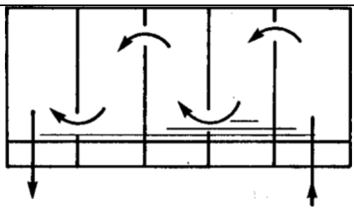
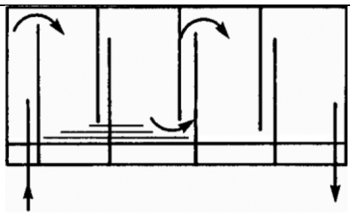
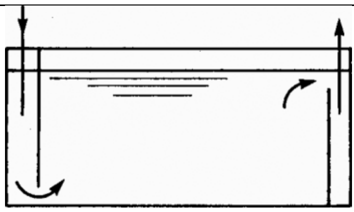
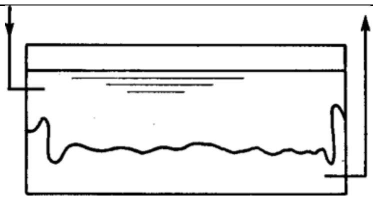
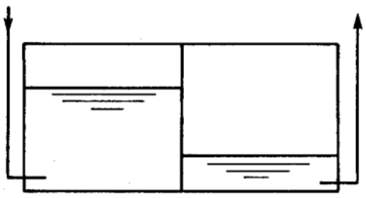
It is also indicated that degree of stratification applied in storages is dependent on the factors such as tank volume and configuration, location, design of the inlets and outlets, the flow rates, and durations of the charging, storing, or discharging periods [2]. Various types of stratified thermal energy storage tanks are presented in table 1.2.

1.1.3 Benefits of thermal stratification

Applying and maintaining thermal stratification on storage tanks of solar thermal systems has numerous advantages. Some of them are:

- **High Solar fraction:** Solar fraction means the ratio of the energy provided to the load by the solar thermal system and the load energy requirements. If the temperature of the water at the top of the tank is high, a higher solar fraction would be obtained in which a larger portion of the energy required is supplied to the load by the system [6, 9].
- **High utilization of solar collectors:** Maikel [8] asserted that well stratified storage tanks enhance solar collector efficiency. This is because the cold water at the bottom of the tank enters the collector which reduces collector heat losses to the environment. When the temperature of water in the collector is higher than the temperature at the bottom of the tank, the collector starts to charge the storage tank.
- **Reduced heat loss from the system:** The lower the temperature of the circulated water is, the lower the heat loss from the system will be [10]. A stratified tank with lower average circulation temperature results a lower heat loss from the system than mixed tank.

Table 1. 2 Types and features of various stratified TES tanks [2]

Type	**Schematic representation of cross-section**	**Efficiency**	**Remarks**
Continuous multi-tank type		Medium	Underground beam space can be used effectively. Insulation is difficult to install
Improved dipped weir type		Medium-High	Construction is difficult
Thermally Stratified type		High	Best suited for large-size tank built aboveground
Movable diaphragm type		High	Diaphragm material is problematical. Not easily adapted to tanks with internal pillars and beams
Multi-tank water renewing type		High	Underground beam space can be utilized to some extent. Heat loss is large

Applying thermal stratification within a thermal storage tank can improve the entire system performance by up to 37% depending on the nature of the load when compared to a fully mixed tank [5,6]. A well stratified tank will retain warmer fluid at the top and will discharge it eventually to the loads which reduce the need for auxiliary heating. Therefore, assessing the impact of thermal stratification on PV/T assisted heat pump domestic hot water storage system using computational simulation model has a great significance on the proper utilization of solar energy with reduced heat losses. In this typical work, the concept of thermal stratification is expected to be applied on the PV/T storage with single medium storage, the heat-transfer fluid, water, is also used as a storage medium in which no internal heat exchanger is needed.

1.2 Statement of the problem

As discussed earlier, the temporal mismatch between the availability of variable solar energy and hot water demand needs the allocation sustainable energy in the thermal energy storage tanks. The mixing of hot and cold water in the tank is the main problem that reduces supplied temperature and useful quality of energy to the load. Since the collector inlet fluid temperature due to the even whole water temperature in the tank caused by mixing is higher than the unmixed temperature, the amount of energy collected might also be lowered. This problem of mixing can be removed by applying thermal stratification technology.

The initiation for doing this thesis originated from the recommendation of PHD-dissertation [4] which modeled a PV/T and hybrid PV/T-heat pump system with fully mixed storage tank. The annual performance of the storage tank and the whole system has been predicted using computational method. From the results, it is observed that the temperature of the water in the tank and the load energy is lowered which encountered higher heat losses.

The prediction of the water temperature inside the storage tank represents the most important goal to reach in the evaluation of the thermal energy system. Though many numerical studies have been carried out around thermal stratification, a comprehensive approach for PV/T- heat pump water heating system with annual performance prediction has not explicitly been published so far. Hence, an appropriate computational modelling approach must be developed. By using the data of the existing thesis, this paper has simulated PV/T- heat pump water heating system with stratified thermal storage using the one-dimensional method in MATLAB.

The impact of thermal stratification on the proposed system must be investigated by comparing the stratified storage model with the existing mixed storage. Identifying the major parameters which affect the energy extraction efficiency using performance analyses is also an essential task for optimizing the model.

To improve the efficiency of the system, an accurate model of the water storage tank and its stratification is necessary [11]. Consequently, this research is extended to model the thermal energy storage tank using a two-dimensional approach with experimental validation from literature. This helps to select the more accurate thermally stratified storage model for the system.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis is to assess the impact of thermal stratification on the performance of PV/T and hybrid PV/T-heat pump system compared to a system with mixed storage.

1.3.2 Specific Objectives

The specific objectives of the study are to:

- derive mathematical transient differential equations to describe the processes occurring in the stratified storage.
- apply some modifications to the existing reference model for the undergoing investigation on thermal stratification.
- model a thermally stratified storage for a PV/T and hybrid PV/T-heat pump water heating and electrical energy generation system.
- compare the models of the existing non-stratified model with the new stratified model by analyzing the changes in solar fraction, heat loss and hot water efficiency.
- perform parametric study to provide information about those factors which affect thermal stratification.
- validate the models using an experimental model and recommend the more appropriate thermally stratified tank model.

1.4 Scope and limitations

Thermal stratification is a complex physical process that is affected not only by geometrical structure, but also operation conditions which cannot be described in the modeling. To achieve the desired thesis objectives, this research focused on developing a precise model for a typical thermally stratified tank. It applies theoretical, mathematical, and computational analyses for modelling the thermal storage tank and uses experimental data from literature for comparison.

It is possible to model a system to a high degree of accuracy to extract the required information. In practice, however, it may be difficult to represent in detail some of the phenomena occurring in real systems. The analyses on this study are limited to one- and two-dimensional system analyses only. This is due to the complication of three-dimensional analyses on both proposed modelling tools. But one-dimensional models cannot describe flow structure in detail within the tank, especially under high flow rate and complex tank structure conditions.

Though the main objective of the thesis is to study the effect of stratification on the tank performance, assessing the quality, level, or degree of the stratification itself using evaluating index is omitted in this current study. Because many authors studied, the paper excludes the recommendations for optimizing the model. The entire study is based on the theoretical application of stratification (natural stratification) on the storage tank, inability to investigate the actual stratifying tools like baffles, diffusers and stratifies is the other delimitation.

1.5 Significance of the study

The previous research project was aimed to solve the hot water production and electrical generation limitations in the off-grid areas of Ethiopia using one integrated system (hybrid PV/T-heat pump system). The improved PV/T collector efficiency due to thermal stratification leads to a high domestic water heating performance of heat pump. After implementation of this research, performance increment of the existing entire system would be observed as with the real application of the improved thermal storage system. It also has a great significance in the advancement of solar thermal systems technologies with reduced deforestation and environmental pollution which help many beneficiaries for long term.

1.6 Thesis organization

The thesis is organized into seven chapters including the previous introductory chapter. The second chapter included the review of the literature on modelling thermal stratification and its impact on system performances followed with chapter three which gives the overview of research methods, approaches, and mathematical modelling.

One dimensional multi-node and two dimensional CFD modellings are involved in chapter four and five respectively. The result and discussion section, chapter six, presented the research findings, parametric analysis, and comparisons in the two proposed models. The last chapter indicated the conclusions and necessary recommendations of the researcher based on the modelling outcome.

CHAPTER TWO

LITERATURE REVIEW

According to E. Andersen [12], the effect of thermal stratification in hot water storage tanks on the performance of solar thermal systems has been primarily investigated in the 1960s for improving the overall efficiency of the systems. But Y.M. Han [13] argued that intensive research about thermal stratification was made in 1970s by stating two-dimensional model paper which has been done in 1975 [14]. Some researchers asserted that stratified thermal storage tanks were applicable in 1970s and 1980s because of their low cost and simplicity [2,19]. In the 1980s, the first commercial application of stratification technology was applied in areas like industries and power plants.

Continued studies have been published on thermal stratification analysis and modelling with different systems, configurations, and techniques until now. Almost all of them indicated that applying temperature thermal stratification in hot water storage tanks can effectively improve the performance of the storage. The researchers also established that stratified storage tanks can have a significant positive influence on the overall efficiency of solar heating system [15-18]. Due to rapid change and growth of solar systems technology, this research area still demands more advancement of knowledge, investigation, and analysis.

In the evaluation of thermal energy storage systems, predicting the temperature profile in the storage is prioritized to reach the objectives. Since the importance of temperature stratification started to be known, several one-dimensional and two-dimensional models have been developed. [6,12,20]. Therefore, the following section discusses the state of the art of theoretical, mathematical, and computational modelling of thermal stratification.

2.1 Modelling of thermal stratification

Describing the physical processes (heat losses to the environment, heat transfer between the different temperature nodes, mixing due to inlet flow) occurring in the storage tank with mathematical equations is the primary step in studying thermal stratification. Taking all the processes into account, these equations couldn’t be solved mathematically without considerable simplifying equations and formulations [11].

Therefore, developing a mathematical model is an integral part of stratified storage tanks analysis. Important investigations on storage tank models and the physical mechanism of thermal stratification are summarized in this section.

2.1.1. Modelling Analysis

Several authors studied thermal stratification with different levels of modelling analyses sophistication to investigate the performance of thermal energy storage systems. The analyses include one-dimensional, two-dimensional, and three-dimensional models. The main constraints to select the proper modelling analysis are degree of precision, simplicity, and speed. However, at least one energy interaction was eliminated in these models for the sake of computational simplicity [30].

2.1.1.1.One-dimensional model

As E. Kleinbach [21] discussed, in the earlier time, one-dimensional models of thermally stratified storage tanks were described by dividing the tanks with fixed or variable location disks that have uniform temperatures. Though different researchers proposed several one-dimensional models [23-27], the important and relevant ones will be only discussed.

Y.M. Han [13] classified one-dimensional modelling types as temperature stratified, heat balance, turbulent mixing, and displacing mixing models. The first model type uses a coefficient which enables the water to find the corresponding position based on value of temperature. The heat balance transient model calculates the temperature of water at each time step by balancing all heat interactions in the storage [26]. In the turbulent mixing and displacing mixing models, analytical equations for each equal tank volume division layer were used with and without mixing between the layers, respectively.[29]

One of the most prominent books on solar storage tanks is the text of Duffie and Beckman [31]. The one-dimensional model of a stratified storage tank stated in this book is simple, magnificent, and base model for other studies. But, according to experimental evidence of some authors, their model doesn't represent high stratification. Even if the heat losses through the storage wall were figured in this model, R. Buckley [30] quoted that the model exclude the heat transfer within the fluid column with constant density and specific heat.

C. Unrau [3] developed one-dimensional models using analytical techniques for accurate prediction of the temperature profiles within a storage tank. Mixing mechanisms like increasing inlet temperatures with time, heat losses to the surroundings, tank wall heat conduction and inlet jet mixing were considered individually. Though the models are simple, they do not always perform well due to numerical error and the inherent simplifications of the physical mixing mechanisms.

A performance study of one-dimensional TRNSYS tank models using experimental data from low and high heat source flow rates was also done [21]. Validation of the models with experimental data was done with for a wide range of conditions to give some recommendations as to which tank model should be used under which operating conditions. The recommendations were based on the accuracy of predicting the experimental data and the computational efficiency of the models.

2.1.1.2. Two-dimensional model

Since one-dimensional models cannot describe flow structure in detail within the tank, after the 1990s, two or more dimensional models were developed gradually. It is already stated that minimization of the mixing of the hot and cold water in the storage maintains thermal stratification. Numerical approaches by Navier–Stokes equation showed the outline of the mixing process can be examined using a two–dimensional method. [13]. The two- dimensional model of A. Cabelli [14], examined the effect of the entrance Reynolds number and the contribution of buoyancy in promoting stratification of both horizontal and vertical tank configurations. The study also made a comparison of the two-flow circuit model with a simple and approximated one-dimensional model.

R. Oliveski, A. Krenzinger and H. Vielmo [32] performed a numerical analysis using a two-dimensional approach in cylindrical coordinates through the finite volume method. The results were compatible with the results from the experimental analysis carried out both under laminar and turbulent conditions. According to the authors, comparing to one dimensional model, the two-dimensional models are suitable for the understanding of the thermal phenomena in the hot water storage tank.

2.1.1.3. Three-dimensional model

According to literature, three dimensional models help to understand the reasons of some deviations between the simulated and experimental results [33]. They are also able to obtain fine details about the performance of the storage tank, such as flow patterns and temperature profiles at different locations and times. One of the exemplary studies on these models was made by O. Abdelhak, H. Mhiri and P. Bournot [34] which examined thermal behavior of a vertical storage tank during the dynamic mode. The paper included calculation of discharge efficiency, Richardson number and stratification efficiency and shows the decrement of overall efficiency due to mixing. Though these models are powerful tools for simulations, real results couldn't be accessed because of assumption of erroneous constants or neglecting factors. Therefore, a high level of skill and scientific judgment is desired to produce correct results [35]. The following table summarizes the comparison between the above modelling analyses.

Table 2. 1 Strengths and weaknesses of the modelling analyses [33]

	One-dimensional	Two-dimensional	Three- dimensional
Strength	good quality of the results	better quality of the results	best quality of the results
	simple to formulate	few simplifications	
	not time-consuming	detailed information on the motion of the fluid	Give more précised information [34]
		consider for the turbulence condition	Clear temperature and velocity distribution
Weakness	Inconsistencies because of artifices	time-consuming	more computing time
	many simplifications of the real physical system	complex in formulation	more complicated
	deficient information about the fluid	not recommended for long term simulations	due to the large number of nodes required, impossible for long term simulations

2.1.2. Modelling approaches of thermally stratified energy storages

In practice, the behavior of hot water storages is not trivial for modeling. In the last decades, a considerable number of models have been developed to analyze thermal energy storage using various modelling techniques. This section recapitulates these modelling techniques conducted so far by different researchers. Some of them compare the techniques with their respective advantages and limitations in terms of application, computational time, and accuracy [11].

Duffie [31] traditionally categorizes previous models in two groups called multi-node and plug flow models. They sorted the approaches with many variations, and the selection depends on its application. The modelling techniques might also extend to three with the addition of plume-entrainment model [21]. Analytical models called Quasi and Adaptive-grid one-dimensional models were also introduced [3].

Another generic review on modelling approaches was presented by A. Soomro and his colleagues [20], considering other studies, they categorized them as numerical, analytical, and artificial neural network (ANN). Depending on this review, the modelling approaches can be described in table 2.2.

Table 2. 2 The three common modelling approaches of thermal energy storages [20]

Numerical modelling	**Analytical modelling**	**Artificial Neural Network**
provide detailed insights	provides the exact solutions	black box model
based on physical laws	Based on some assumptions	based on data-driven
require specific software tool	make the system unrealistic in some cases	
computationally very complex and expensive	computationally easy and flexible	simple and low cost

A brief review of O. Dumont [11] discussed eight modelling approaches to select the optimal thermal energy storage modeling method for a given application. The approaches are analytical, fully mixed, black box, moving boundary, plug flow, multi-node, zonal and CFD in which some of them are illustrated in the next figure.

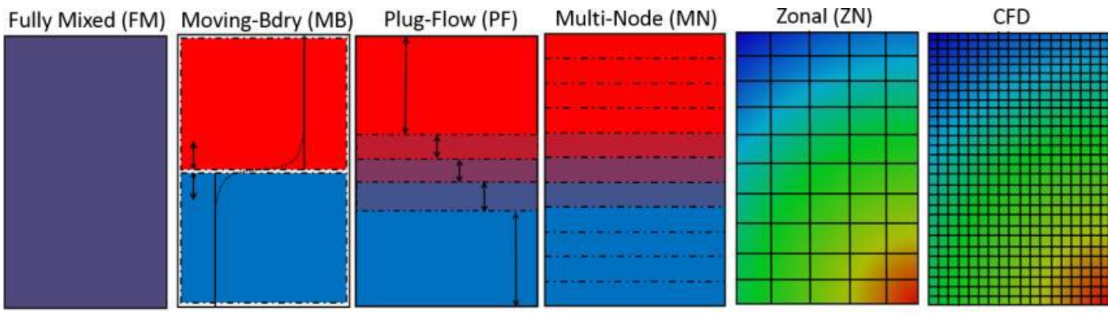


Figure 2. 1 Different modeling approaches to model temperature distribution in hot water storages [11]

i. Analytical Method (AM)

This method describes the system with analytical functions by using Laplace transformation technique to predict the thermocline based on three hypotheses [10,35]: the tank is modelled as a one-dimensional semi-infinite body to make the problem mathematically tractable; no mixing or ambient heat losses are considered; and thermo-physical properties (inlet temperature and mass flow rate) are kept constant. Though this model is simplified model and obtains exact solutions in a short time, it has a narrow range of applications and mostly used to model ideally stratified or fully mixed tanks [43].

ii. Blackbox (BB) Method

The black box model is one of statistical learning models which uses artificial neural network methods that can be validated with a database which could be either experiments or complex models. Inputs with hidden functions are used to evaluate outputs [37]. Though this approach is fast and has been validated for different geometries based on CFD models, it is very dependent of the database.

iii. Plug Flow (PF) Method

One of the most common modelling approaches is called a plug flow method in which N-variable volume isothermal disks are assumed to move through the tank with different temperature and without any mixing between them. The size of each disk depends on the velocity of fluid within the tank and the entering fluid temperature [21]. Many authors affirmed that this method is a bookkeeping method to keep track of the size, temperature, and the position of a section which is faster than multi-node mode [30,38]. Since it requires a lower number of nodes (less complex model) in the case of high stratification [31], this model particularly simulates the tank with a lower time. In addition, plug flow model with variable inlet is interesting because it gives the upper limit of deliverable thermal energy causing perfect stratification.

iv. Multi-Node (MN) Method

Multi-Node method is the other alternative modelling approach for simulating stratified storage tanks that is widely used technique to obtain temperature profiles or temperature distribution [25,41].

This method considers assumptions like:

- The tank is to be made up of N nodes/ slabs/ sections/ layers/ segments/ cells/ zones with horizontal uniform temperature and fixed location disks [30,38].
- The flow inside is one-dimensional with no radial temperature variation [11].
- Before fluid streams flowing up and down from each node enter each node, they are fully mixed [21].

The temperature profile can be found by applying energy balances for each node that involves entering and leaving streams from heat sources and load, ambient losses and, if any, energy inputs of auxiliary. As a result, a set of N simultaneous partial differential equations are used to solve the temperatures of the nodes as functions of time. This model also discretizes the equations into a set of one-dimensional, isothermal nodes along the height of the tank [30].

Selection of node number amount is essential to determine the degree of the thermal stratification. The higher the number of nodes, the more stratification level [41]. But increasing the number of nodes escalates the computational complexity and to overcome this issue, the following model is proposed.

v. Adaptive Grid (AG) Method:

This model was first introduced by Powell and Edgar [42] which combines the advantages of the multi-node and the plug flow models and eliminates some of the challenges. Because of this, the adaptive grid model is also called the combination of the multi-node and plug flow models.

The authors used the technique of reducing the number of nodes in the regions of the tank with a more uniform temperature and used more nodes in the thermocline region to predict temperature profile accurately. Therefore, nodes upper and lower the thermocline region (hot and cold regions) are considered as single nodes. Like the movement of the nodes in the plug flow model, the nodes in the thermocline region move with the thermocline location. The main drawback of this model is that, since the top of the tank is represented with a single node, it couldn’t account for mixing effects caused by the inlet jet [3].

vi. Fully Mixed (FM) method

In this method, homogenous temperature is considered in the whole storage tank in which thermal stratification couldn’t be maintained. Even though it is the simplest and fastest method, the system will achieve poor performance due to mixing and it could be seen as a Multi-Node (MN) model with one node.

vii. Moving Boundary (MB) Method

The simulation in this method divides the storage tank into two zones with fixed temperatures using an ideal thermocline of negligible thickness. The energy balance including ambient losses, heat input and output helps to identify position of the thermocline or temperature profile as a function of time and flow. Compared to a multi-node model, this model obtains a more accurate stratification with low CPU time [38]. This model was developed by Dickes [44] with assumptions such as that it does not take mixing into account, no mass transfer between the two zones and the position of the thermocline determines the volume of the two zones.

viii. Computational Fluid Dynamics (CFD) Method

CFD modelling is the most exact and accurate method used today to model real physical phenomena. Finite Element or Finite Volume solution methods can be used to better understand the flow field inside the solar storage tanks. This modelling technique takes less assumptions and empiricism compared to one-dimensional modeling. Though it is the most recent realistic and accurate method, the simulation could be time-consuming and for long simulations such as annual, a simple model should be chosen. The most recent research regarding the simulation with the CFD method was presented by P. Dzierwa and other researchers [65] based on an axial-symmetric model of a hot water tank for the process of charging using ANSYS Fluent R19.2 software.

ix. Zonal (ZN) Method

Blandin and his colleagues [45] proposed a pressure zonal model to predict annual performances of a generic solar tank. The model used a 3D finite-volume method with a large mesh where mass and energy balance are verified. The advantage of the large mesh leads the computation to have less time. In terms of physical phenomena considered and computational time, this model is an intermediary between CFD model and multi-node model. It is roughly seven times slower than the multi-node model and it is not as precise as CFD. Table 2.3 presented the above modelling approaches with different respective comparison criteria.

Table 2. 3 Modelling approaches comparison [11]

Criterion	**AM**	**FM**	**BB**	**MB**	**PF**	**MN**	**ZN**	**CFD**
Ambient losses	-	*	-	*	*	+	+	+
Conduction (water + wall)	-	-	-	*	-	+	+	+
Mixing due to T^{o} inversion	-	-	-	+	*	*	+	+
Quilting (heat loss due to hydraulic connection)	-	-	-	*	*	*	+	+
Convective current induced by parietal heat transfer	-	-	-	*	-	*	+	+
Jets mixing (during direct charging or discharging)	-	-	-	-	-	*	+	+
Heat transfer through exchanger or resistor	-	-	-	*	*	+	+	+
Navier-stokes + obstacles	-	-	-	-	-	-	-	+
CPU time	+	+	+	+	+	o	-	-
Determinist	+	+	-	+	+	+	+	+

The above table shows the comparison between the modelling approaches based on criteria like physical processes which occur in the storage, CPU time and the need to have a database to fit parameters (not determinist). It uses the designation '+' for 'is good', '-'for 'bad', 'o' for 'is intermediate' and * means that it can be integrated in the model but not systematically.

Though some studies compare the results from the above modeling approaches [47,48], to select the optimal storage tank model, criteria like application, accuracy, computational time, and database availability must be considered. The selection tree to pick appropriate model is summarized with Figure 2.2.

2.2 Effect of thermal stratification on performance of storage tanks

Many researchers affirmed the positive impact of thermal stratification on the performance of storage tanks as well as the whole solar thermal systems [3,15,20]. In many solar utilization systems, comparing the fully stratified and fully mixed water tank, the energy storage efficiency and the whole system may be increased up to 6%

and 20% [13]. The researchers state the two influencing parameters called collector flow rates and solar fraction on the overall system efficiency.

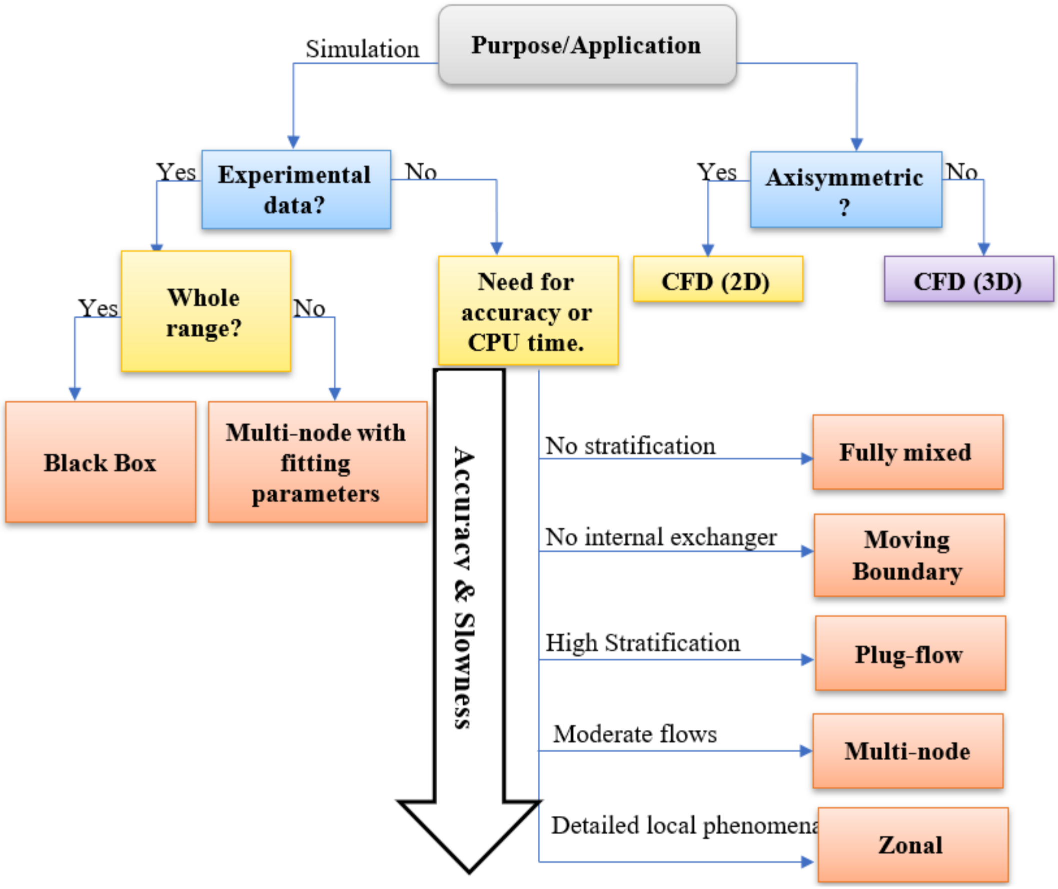


Figure 2. 2 Tree of selection for optimal storage tank modelling approach [11]

2.2.1 Collector loop flow rates

Solar thermal system's performance is influenced by the tank temperature distribution which is affected mainly by the flow rate of the collector. This flow rate is a nominal flow rate of the water from the solar collector to the storage tank. The ranges for high and low-flow solar hot water systems are 10 to 20 and 2 to 8 g/s per $m^2$of the collector area respectively [6,38,49]. V. Dwivedi [39] verified that low-flow design in the collector panel and thermal stratification inside the storage tank are the prominent factors in enhancing the system performance. E. Kleinbach [21] also showed that the stratification importance on tanks with high and low collector flowrates.

a) High-flow solar water heating system

High collector flow rates (about 13 g/s per m^2 of collector area) improve the collector efficiency by increasing the collector heat removal factor (ratio of the actual useful energy gain of a collector to the theoretical useful gain) which improves collector flow factor [31]. However, due to the high amount of mixing in tanks with high collector flow rates, the temperature distribution becomes more uniform.

Even if, the lowered temperature difference across the collector panels in high flow systems lowers the collector losses and improves the efficiency, it requires pumping system. This is more useful for multi-collector systems [39].

b) Low-flow solar water heating systems

Low collector flow rates increase the efficiency of the collector by reducing collector heat removal factor and supplying the collector with cold water from the bottom of a stratified tank because of lower collector thermal losses. Opposite to high-flow systems, low-flow systems have higher collector temperature difference that leads to higher losses. However, higher outlet temperature would enable to supply the hot water directly to the load without significant auxiliary heating [39].

Comparing to a system having a fully mixed tank and a high flow rate, using low collector flow rates (roughly one-seventh of the standard value) with thermally stratified storage tanks can improve the performance of solar hot water for domestic, commercial, and industrial systems by as much as 38% [7].

2.2.2 Solar fraction

Thermal stratification impact on system performance could be depicted by using a factor called solar fraction that is solved by dividing the energy delivered to the load to the solar thermal system, by the required load total energy [3]. The temperature of the water at the top of the tank would affect the energy delivered by the system, so that, a higher solar fraction would be obtained for high water temperature at the top. In addition, low temperature of water at the top (lower stratification) decreases the solar fraction in which additional amount of auxiliary energy is needed. This means the contribution of solar fraction in low-flow systems would be higher than high-flow systems. Wuestling [50] demonstrated the comparison of the expected yearly solar fraction versus the system flow rate for a perfectly stratified and fully mixed tank by using the following figure.

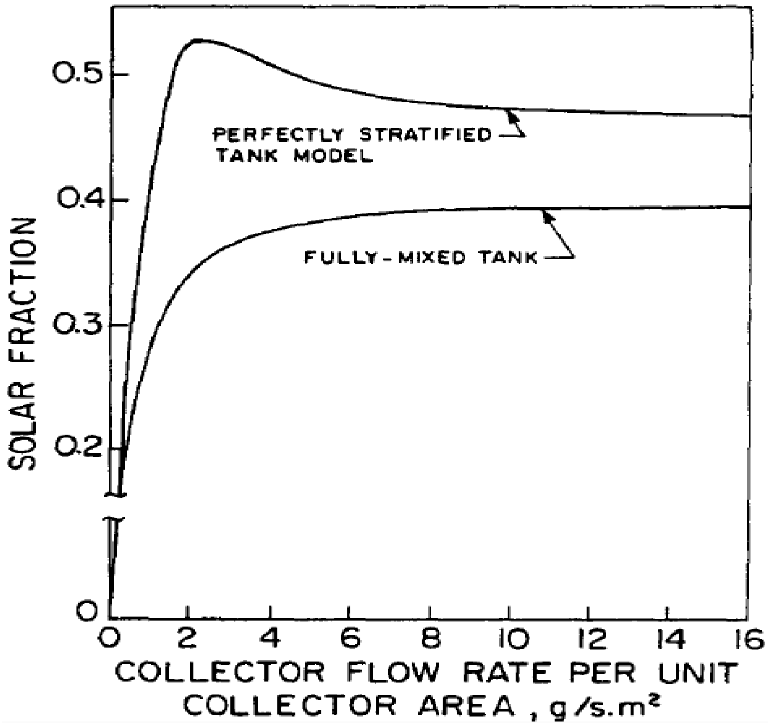


Figure 2. 3 Annual solar fraction versus the collector flow rate of perfectly stratified and fully mixed tanks [50]

Most previous literature indicates the performance improvement by calculating and comparing the thermal performance of stratified storages with those fully mixed ones as shown in Table 2.4. These improvements are calculated in relation to the percentage of the heating demand covered by solar thermal energy. Since the improved performance through stratification is connected to the solar fraction, it is difficult to indicate the exact percentage of performance improvement. Therefore, most of the time performance improvement is expressed in intervals [9].

2.3 Chapter Summary

For simulating annual performance of energy systems, the simpler and computationally less expensive model is more suitable [21]. Referring to the objectives of this thesis, one-dimensional model technique is chosen for the annual analysis and two-dimensional model for the short-term simulation. The multi-node model is chosen for the one-dimensional modelling since it is the most classical choice for the annual simulations with good accuracy [11]. And, for the two-dimensional analysis, CFD design model is selected because it is preferable to model complex flow field inside the storage with a wide range of configuration.

It is stated above that the existing PHD-thesis which modeled PV/T and hybrid PV/T-heat pump system with fully mixed storage tank with low flow rate is the inspiration of this study. Usually, low-flow systems are preferred for domestic application from the thermal performance and pumping point of views. Therefore, in this research, thermally stratified, low-flow solar hot water storage system design is applied to get more improved performance than the previous studies.

From the reviewed literatures, it can be concluded that applying thermal stratification on hot water storage tanks has a magnifying effect on the performance of the system. However, the assessment of thermal stratification effect in PV/T and hybrid PV/T-heat pump systems had not yet studied so far. Annual simulations were also overlooked in previous studies on thermally stratified storages of these systems. Hence, this research will contribute to further technology advancement of annual performance prediction and short-term simulation of PV/T and hybrid PV/T- heat pump systems.

Table 2. 4 Previous studies on efficiency improvement due to thermal stratification

Author	**Storage applied/ application**	**Performance improvement (%)**
Han & Wu, 1978 [22, 23]	residential storage	6
Duffie & Beckman, 1974 [9, 31]	solar water heating	9
Koppen, Fisher & Dijkmans [22]	solar heating	15
Sharp & Loehrke, 1979 [58]	sensible heat storage	5–15
Koppen & Veltkamp, 1979 [46]	pebble bed storage	5–10
Veltkamp, 1981 [49]	real system storage	10–20
Cole & Bellinger, 1982 [26]	residential storage	5–20
Wuestling, 1985 [50]	systems utilizing control strategy	12–15
Hollands & Lightstone, 1989 [7]	low collector flow rate system	38
N. K. Ghaddar, 1994 [59]	active solar water heating system	20
Furbo, 2014 [9]	Low flow solar heating systems	10 – 25

CHAPTER THREE

METHODOLOGY

The previous chapter discussed different existing thermally stratified storage tank models. The overall approaches and methods for this thesis are included in this chapter.

3.1 Research Approaches

This research would apply theoretical and simulation scientifical approaches. The theoretical section includes problem definition, objective specification, literature reviewing, mathematical modelling and selection of numerical methods and solution packages. The simulation approach involves 1D and 2D computational modelling methods with experimental validation. Then, considering the determined and expected outcome, conclusions and recommendations would be suggested. The following diagram shows the key tasks and methods included in the study.

1. Problem formulation
- Define research problem, specify objectives and scope.

2. Literature Review
- Collect data related to the study from previous books, journals, articles

3. Method selection
- Select suitable numerical methods and techniques
- Select compatible commercial softwares

4. Mathematical modelling
- State respective governing differential equations

5. One-dimensional modelling
- Develop a numerical algorithm and formulate simplifying assumptions
- Solve the system by creating one-dimensional multi-node models

6. Two-dimensional modelling
- Create and run CFD model by applying boundry conditions and assumptions

7. Discussion
- Validate the models with an experimental results from literature.
- Compare the results of 1D stratified storage model with mixed system.
- Perform parametric analysis.

8. Summary
- Draw conclusions, give recommendations and indicate future works

Figure 3. 1 Basic research approach steps of the study

3.2 Research Methods

As stated above, the major solving methods of this research are mathematical and computational modelling techniques. These methods have a significant role in the whole solving process that enables us to meet the research questions and objectives.

The mathematical or thermal modelling method explained the system from a conceptual or theoretical point of view to describe and analyze the water storage system. It includes representation of the processes in the storage through governing differential equations and simplifying assumptions.

One-dimensional computational modelling was used to assess how the system will perform over time by solving the differential equations of the mathematical model. It simulated the thermally stratified system for the manipulation of annual performance compared to existing fully mixed storage tank. This method generated solutions by using numerical method algorithm and properly selected computer program.

The multi-computational modelling is also used in the two-dimensional analysis for the sake of obtaining approximate solutions under different conditions. Geometrical modelling, mesh settings, applying boundary conditions and obtaining solutions are the major procedures in the computational method.

Both methods were validated with experimental results from literature. A flowchart that describes sequence of the modelling methods is indicated on Figure 3.2.

3.2.1 Mathematical modelling of the stratified storage tank system

In the investigation of thermally stratified storage tank system, mathematical models are developed to accurately capture the impact of stratification on the storage tank efficiency. It describes the physical mechanisms of thermal stratification by using governing equations on thermal modelling basis. Thermal modelling obtains these governing differential equations by applying conservation laws of mass, energy, and momentum.

3.2.1.1 Basics of governing equations of thermally stratified storage tanks

For formulating the governing equations, different possible physical processes which can occur in a thermally stratified hot water storage tanks must be identified. These processes are [11]:

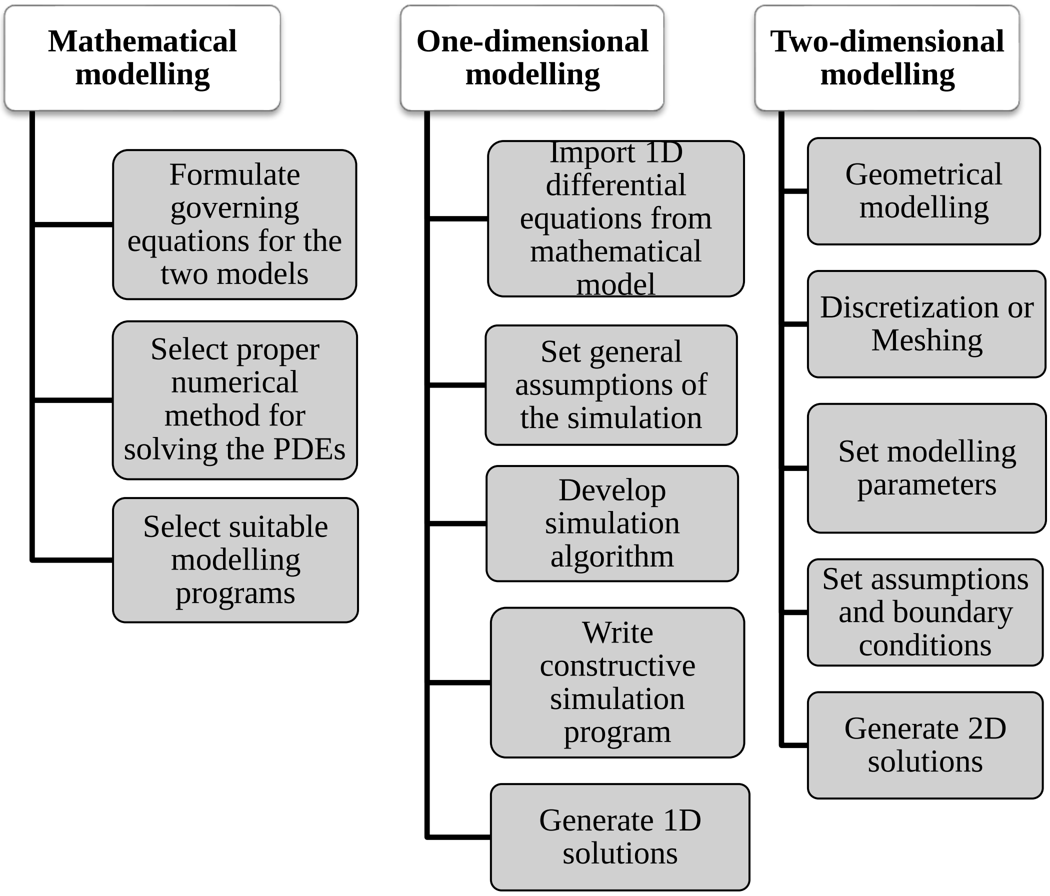


Figure 3. 2 Basic detail research methods of the current study

i. **Natural convection:** It is method of heat transfer in which natural means the influence motion of the water. It causes the temperature of the water at the bottom of the tank to be lower than the water at the top of the tank at later times [3].

ii. **Buoyancy and plume entrainment:** Buoyancy induced flow is caused by temperature inversion due to loading conditions occurred when cold or hot water enters warm or cold layer like using the solar heating system in the late afternoon [44]. If the momentum and buoyancy forces have the same and opposite directions, positive and negative buoyant plume entrainment occurs respectively [3]. The positive one occurs when the cooler water with a higher density enters the top of the tank, the inlet water falls until it reaches same water density tank level. But if the inlet water is hotter than adjacent inlet water, negative buoyant plume occurs because the buoyancy force which opposes the momentum of the flow will direct the water upwards [55].

iii. **Water conduction (diffusion):** It is a flow of energy exchanged by conduction in the water due to temperature gradient. In this heat transfer, thermal energy will be diffused from the hot water region to the cold-water region, and therefore, the main cause of energy transfer between these regions is thermal diffusion [52].

iv. **Heat losses to surroundings:** These are ambient losses due to the heat flux exchanged by convection between the storage medium and the environment which caused decrement of temperature of the water in the near wall region [53].

v. **Tank wall conduction:** This conductive heat transfer is created through storage tank wall which causes the temperatures of the hot regions to decrease, and the cold regions would increase over time. Lavan and Thompson [16] studied that heat conduction through the tank wall is considerably larger than the heat loss through the tank insulation and the heat transfer by water conduction.

vi. **Parietal heat transfer:** This is caused by convective currents when the tank wall cools a thin vertical layer of water adjacent to the wall which becomes denser than its surroundings and slips towards the bottom of the tank [54].

vii. **Heat transfer through heat exchanger or resistor:** This is a heat flow flux produced by the internal heat exchanger.

viii. **Inlet Jet Mixing:** It is created because of the water entering during direct charging or discharging of the tank [3].

ix. **Quilting**: It is a heat loss due to recirculation of water in the tank from hydraulic connections.

x. **Obstacles**: Better thermal stratification is provided by placing obstacles in the tank which decreases momentum driven jets [56].

The selected heat transfer modes and processes for this simulation are discussed in section 3.3.3.

3.2.1.2 Selection of proper numerical method for modelling storage tanks

The common numerical methods that are used for modelling and solving partial differential equations are finite element method, finite difference method, finite volume method and boundary element method. From these methods, most of the time, finite element and finite difference method are the frequently used techniques for modelling thermal stratification. R. Buckley [30] made a brief comparison between both methods for selecting the proper numerical method based on its application.

i. Finite-Difference Method (FDM)

Finite difference method reduces partial differential equations to algebraic equation and solves them either iteratively or simultaneously after discretizing the domain into grid points. It is the most appropriate method for long term applications to observe the temperature distribution in the tank over time and hourly energy additions, subtractions, and losses. Explicit and implicit differentiations are the fundamental solving ways of this method.[57] The following table contains the basic differences of these methods.

Table 3. 1 Explicit Vs Implicit method

Explicit method	**Implicit method**
The temperature at a node at a time t+1 is a function of the temperature of the node and the surrounding nodes at time t	The temperature of the node at a time t+1 is a function of the temperatures of the adjacent nodes at time t+1
is simple to solve	requires much more effort to solve for a single time step
has a stability criterion which places an upper limit on the size of the time step	not constrained by a stability criterion
use smaller time step size	larger time step size is used to overcome the computational losses
trivial heat transfer problems take a longer time to solve computationally	trivial heat transfer problems take fewer time to solve computationally

ii. Finite-Element Method (FEM)

In finite element method, the domain is divided into a set of volumes or finite elements connected to one another by nodes, and the conservation equations are applied for each element. The equations are then multiplied by a weight polynomial function that approximates values of a certain function for each element before being integrated over the entire domain. This method is more advantageous to examine the fluid dynamics and interactions within the tank during certain specific conditions.

Therefore, in this paper, finite difference method is chosen for solving one-dimensional multi-node annual model based on its application. An implicit FDM solving method is also selected because of its ability simulate the storage system for a period of weeks or months with a fewer time than an explicit method. In addition, finite volume method is preferable for investigating two-dimensional CFD model to more study the fluid dynamics in the tank.

3.2.2 One-dimensional analysis governing equations

3.2.2.1 General conditions of the equations

Since the one-dimensional analysis applies the concept of multi-node modelling approach, the storage tanks are modelled by dividing the storage tank with 'N' number of nodes of volumes at constant temperatures. It applies the conservation of mass and energy for each node which consider all mass and energy flows in and out of a node to calculate nodal temperatures or simulate the temperature distribution within the tank. This temperature distribution is estimated based on the node temperatures that existed at the beginning of the time step. Thus, the change in the energy of the node per time is the difference between the sum of the rates of energy entering and the sum of the rates of energy leaving the node.

$$\frac{dE}{dt} = \sum \dot{E}_{in} - \sum \dot{E}_{out} \tag{3.1}$$

In the previous existing model, the equation applied for fully mixed tank or multi-node with one node (single node) uses heat balance by applying first law of thermodynamics as represented by equation 3.2 [39].

$$m_s c_p \frac{dT_s}{dt} = Q_c - Q_l - Q_{loss} \tag{3.2}$$

where the left-hand side term corresponds to the heat energy stored in the tank with m_s is mass of water in the storage tank, c_p is heat capacity of water, T_s is the instantaneous tank temperature, Q_c is heat addition from the solar collector or heat pump, Q_l is heat removal from the storage tank to load utility and Q_{loss} is heat loss to the environment. But, for a one-dimensional multi-node model with finite number of nodes, once all the required inputs are determined, the temperature of node n would be calculated by combining all the terms into the differential equation. Then, a set of n first-order, ordinary differential equations resulting from each node's energy balance are used to solve for the temperature distribution in the storage tank [60].

3.2.2.2 Assumptions for one-dimensional simulations

a) Number of nodes

For annual calculations, more than 10 nodes are not necessary and, usually, 3 to 5 nodes are sufficient [31,62]. Therefore, based on storage height, for this prediction, 5 number of nodes are selected for the PV/T storage.

b) Inlet and outlet position mode

A multi-node model has the option of fixed or variable inlet positions. For fixed inlet positions, the heat flow from collector enters at the top and water from mains or pre-heated storage at the bottom of the tank. But, for variable ones, the flows enter the nodes that are closest in density and no temperature inversions are created. Multi-node model with variable inlets predicted higher values for the energy input to the tank than the multi-node model with fixed inlet options. Even if this model preserved the maximum possible degree of stratification, it still mostly underpredicts the measured energy input to the tank [21]. The location of the inlet has a stronger influence on thermal stratification than outlet location [11,15].

c) Flow of water

For this simulation, the flow of water within the tank is one-dimensional in which one-dimensional temperature distribution is created, while there are radial losses through the side of the tank to the environment. And the temperature of water in each node is uniform with standard assumption that the net mass flow across the interface between the nodes is upward. The sign convention for upward flow to be positive because the load return flow is reinserted at the bottom of the tank [30].

d) Operating mode

As the existing system has considered all the three operating conditions, charging, discharging, and storing, the thermal behavior of the storage is on dynamic mode in the operation period which has a great relation with real time analysis.

e) Material properties of the water

Material properties of the water such as density and specific heat are dependent on water temperature. To make the system equation linear, nodal constant properties over time step are mostly considered. This is an appropriate assumption for certain storage media in certain applications with low range of temperatures. If these properties are modeled as functions of temperature, non-linear systems of equations are inherently generated. R. Buckley [30] referenced the book of Özisik [61] which states the method of linearization of the equations is to “lag” the value of the properties by assuming that the property at time t can be used to represent the density at time t+1. However, this method is more reasonable for systems with small time step. The equations that describe density and specific heat as function of temperature can be seen in these equations [30].

$$\rho_w = 0.000015451T^3 - 0.0059003T^2 - 0.019075T + 1000.3052 \quad (3.3)$$

$$C_{p,w} = 0.00000321T^4 - 0.0007986T^3 + 0.078029T^2 - 3.0481T + 4217.73 \quad (3.4)$$

As the temperature range is low, substituting random possible temperatures in the above equations didn't reflect high variations. Therefore, in this modelling, density, specific heat, and thermal conductivity are considered as constant over the temperature range.

f) Mass in each node

During an individual time-step, because small change in mass makes a negligible contribution to the total energy of the node, the amount of mass present in each node is assumed to be constant in the energy balance. The change of mass in each node makes the energy balance equation non-linear [30].

g) Loss from collector or heat pump to the storage

The loss occurred due to the heat flow from the PV/T collector or heat pump to the stratified storage is considered as negligible. The heat loss due to recirculation of water in the tank from hydraulic connections is also ignored for both storages.

h) Flow regime

Since the simulation applies to a low-flow system, the fluid flow regime in the storage is assumed to be laminar. Hence storage tank's entering and exiting fluid velocities are low enough in which they do not promote extensive mixing within the storage.

i) Volume of water and pressure of the tank

Although there is slight expansion of the water, constant volume of water is assumed in the storage. And the pressure in the tank remains at atmospheric pressure [53].

j) Tank wall conduction

The heat loss through storage wall conduction is low enough for promoting de-stratification [6], same temperature of wall of the tank and water are taken at each node.

k) Tank insulation:

To decrease heat losses, the storage is modelled assuming good insulation.

3.2.2.3 PV/T System Storage Modelling

i. Features to be included in the model.

For describing the energy balance for the nth node, we must specify the sources of the main flows of energy additions, subtractions, and losses. For this simulation, the basic sources of mass and energy entering the nodes are:

a. Bulk transport coming into the node or the storage. This includes:
   - heat flow entering the tank from the solar collector.
   - back up water from mains or supply
b. the mass flow entering node n from node n−1.
c. conductive heat transfer from an adjacent node at a higher temperature.

And the basic sources of mass and energy leaving out of the nodes are:

a. Bulk transport leaving the node or the tank. This includes:
   - heat flow leaving the storage for load delivery or heat pump storage.
   - water leaving from the tank to the collector.

b. mass flow out of node n and into node n−1

c. conductive heat transfer to an adjacent node at a lower temperature

d. heat losses from the fluid in node n to the environment.

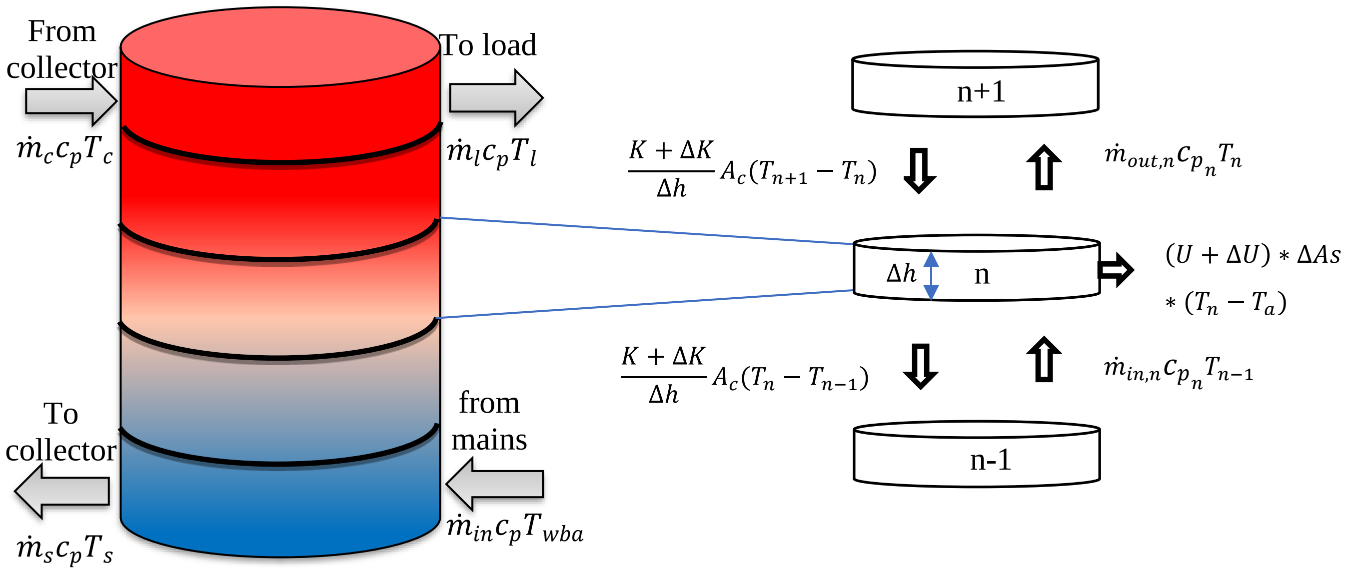


Figure 3. 3 Schematic for a stratified storage tank model and energy interactions on a PV/T Storage's single node

ii. Derivations of governing equations

Regarding the above assumptions, equations for one-dimensional multi-node model could be derived from energy and mass balances in each node. It must be noted that 1D models solve the energy equation in the axial direction only [33].

a. Energy Balance

The general energy equation obtained by combining the selected features or terms of energy sources, illustrated as on Fig. 3.3, is used to calculate nodal temperatures. This energy balance equation for the general node condition can be written as Eqn. 3.5.

$$\frac{\Delta m_n c_{p_n} T_n}{\Delta t} = \dot{m}_{in} c_{p_{in}} T_{wba} - \dot{m}_s c_{p_s} T_s + \dot{m}_c c_{p_c} T_c - \dot{m}_l c_{p_l} T_l - \dot{m}_{out,n} c_{p_n}^{\ t} T_n + \dot{m}_{in,n} * c_{p_n}^{\ t} T_{n-1} - \frac{K + \Delta K}{\Delta h} A_c (T_n - T_{n-1}) + \frac{K + \Delta K}{\Delta h} A_c (T_{n+1} - T_n) - (U_t + \Delta U_t) * \Delta A_s (T_n - T_a) \qquad (3.5)$$

Where: Δh is a node size (Height of the storage/number of nodes), ΔK= 0, It is thermal conductivity of additional conduction factors like tank wall and, ΔU_t=0, it is a heat transfer coefficient for additional losses like quilting.

By taking constant mass present in the node and material properties like density and specific heat, eliminating the terms ΔK and ΔU_t, the following equation is generated using an implicit finite difference method.

$$\Delta m c_p \frac{T_n^{t+1} - T_n^t}{\Delta t} = \dot{m}_{in} c_p T_{wba} - \dot{m}_s c_p T_s + \dot{m}_c c_p T_c - \dot{m}_l c_p T_l$$
$$-\dot{m}_{out,n} c_p T_n^{t+1} + \dot{m}_{in,n} c_p T_{n-1} - \frac{KA_c}{\Delta h}(T_n^{t+1} - T_{n-1}^{t+1})$$
$$+ \frac{KA_c}{\Delta h}(T_{n+1}^{t+1} - T_n^{t+1}) - U_t * \Delta A_s (T_n^{t+1} - T_a^{t+1}) \quad (3.6)$$

For the model has fixed inlet/outlet positions, the first four right-side terms in equation 3.6 are used in the lower and upper nodes. Rearranging and collecting like terms give the following five nodal equations of each time step which are the governing equations for the simulation of one-dimensional multi-node model.

$$T_1(\frac{\Delta m c_p}{\Delta t} + \dot{m}_s c_p + \dot{m}_{out,n} c_p + \frac{KA_c}{\Delta h} + U_t \Delta A_s) - T_2(\frac{KA_c}{\Delta h})$$
$$= \frac{\Delta m c_p}{\Delta t} T_{i1} + \dot{m}_{in} c_p T_{wba} + U_t \Delta A_s T_a \quad (3.7)$$

$$T_1\left(\frac{-KA_c}{\Delta h} - \dot{m}_{in,n} c_p\right) + T_2(\frac{\Delta m c_p}{\Delta t} + \dot{m}_{out,n} c_p + \frac{2KA_c}{\Delta h} + U_t \Delta A_s) - T_3(\frac{KA_c}{\Delta h})$$
$$= \frac{\Delta m c_p}{\Delta t} T_{i2} + U_t \Delta A_s T_a \quad (3.8)$$

$$T_2\left(\frac{-KA_c}{\Delta h} - \dot{m}_{in,n} c_p\right) + T_3(\frac{\Delta m c_p}{\Delta t} + \dot{m}_{out,n} c_p + \frac{2KA_c}{\Delta h} + U_t \Delta A_s) - T_4(\frac{KA_c}{\Delta h})$$
$$= \frac{\Delta m c_p}{\Delta t} T_{i3} + U_t \Delta A_s T_a \quad (3.9)$$

$$T_3\left(\frac{-KA_c}{\Delta h} - \dot{m}_{in,n} c_p\right) + T_4(\frac{\Delta m c_p}{\Delta t} + \dot{m}_{out,n} c_p + \frac{2KA_c}{\Delta h} + U_t \Delta A_s) - T_5(\frac{KA_c}{\Delta h})$$
$$= \frac{\Delta m c_p}{\Delta t} T_{i4} + U_t \Delta A_s T_a \quad (3.10)$$

$$T_4\left(\frac{-KA_c}{\Delta h} - \dot{m}_{in,n} c_p\right) + T_5(\frac{\Delta m c_p}{\Delta t} + \dot{m}_l c_p + \frac{KA_c}{\Delta h} + U_t(\Delta A_s + \frac{\pi d^2}{4}))$$
$$= \frac{\Delta m c_p}{\Delta t} T_{i5} + \dot{m}_C c_{p_C} T_C + U_t(\Delta A_s + \frac{\pi d^2}{4}) T_a \quad (3.11)$$

Where;$T_1, T_{2,} T_3, T_4$and T_5 are the current time step nodal temperatures.

T_{i1}, T_{i2}, T_{i3}, T_{i4} and T_{i5} are the previous time step nodal temperatures.

b. Mass Balance

For calculating the mass flow rate in each node, entering, and leaving masses balance in a single time step is considered throughout the storage [24,30]. The general mass balance equation could be derived as:

$$\frac{dm_n}{dt} = \frac{m_n^{t-1} - m_n^t}{\Delta t} = \sum \dot{m}_{in,n} - \sum \dot{m}_{out,n} = 0 \qquad (3.12)$$

Since, constant material properties and mass in each node were assumed, the two terms in the left-hand side of the above equation are omitted in which the summation of mass flowrates entering and leaving a node are equal. Rearranging and substituting proper terms would help to obtain nodal mass flowrate equations. Therefore, starting from the first lower node, the mass flow rate leaving the first node and entering the last node could be described as:

$$\dot{m}_{out,1} = \dot{m}_{in} - \dot{m}_s \qquad (3.13)$$

$$\dot{m}_{in,n} = \dot{m}_c - \dot{m}_l \qquad (3.14)$$

The mass flow rate of water leaving the upper edge of the middle three nodes is the same as the flow rate entering the bottom of the next node. Hence the mass flow rates entering and leaving in these nodes are uniform.

$$\dot{m}_{out_n} = \dot{m}_{in_{n+1}} \qquad (3.15)$$

3.2.2.4 Heat Pump System (Hot water) Storage Modelling

The heat pump system storage modelling is the same as with the existing simulation. The heat pump water heater integrated hot water storage and condenser in which the condenser coil is placed in the hot water tank for compactness. The major energy inputs of the storage are heat energy transported by the heat pump from ambient to the hot water tank and warm make-up water from the PV/T storage. Whereas the enthalpy of thermal energy of hot water supplied to the end-user and the heat lost to the ambient across the wall of the tank are the sources of energy leaving the storage. Hence the temperature of hot water in the heat pump storage is determined by the net heat gain of the storage stated in Eqn. (3.16) [4].

$$T_s^{i+1} = T_s^i + \frac{\dot{Q}_{hp} - \left(DHWC * C_p * ff(i)\right) * \left(T_s^i - T_5\right) - U_t * A_S * (T_s^i - T_a)}{\rho * \dot{V} * C_p} \qquad (3.16)$$

Where; $ff(i)$ is the fraction of daily hot water consumption and $DHWC$ is the total daily hot water consumption.

3.2.3 Two-dimensional analysis governing equations

The 2D analysis includes critical procedures such as geometric, mathematical, and physical modelling, initial and boundary conditions, meshing and time step selection [65]. This sub section only focuses on mathematical modelling which includes two-dimensional analysis governing equations.

In chapter two, computational fluid dynamics (CFD) model is selected for 2D simulation which solves the fluid flow and heat transfer problems. The mathematics that governs CFD is done through numerical discretization of the differential equations based on the laws of the conservation of mass (continuity), momentum, and energy. The following section summarizes these governing equations of unsteady two-dimensional modelling [71].

3.2.3.1 Navier–Stokes equations

Navier–Stokes equations are the non-linear partial differential equation for mass, momentum, and energy conservations. The equations are presented in two-dimensional cartesian coordinates rather than cylindrical coordinate systems.

i. Conservation of mass (Continuity equation)

The law of conservation of mass states that the mass of a system remains constant if it is closed to all transfer of mass or energy and it is usually designated by equation 3.17 having only the transient and convection term [36].

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0 \tag{3.17}$$

ii. Conservation of momentum

The equations of conservation of momentum are based on Newton's Second Law which states that the rate of change of momentum of a fluid particle equals the sum of the forces (body and surface forces) on the particle.

$$[Mass] * \begin{bmatrix} Acceleration \\ in\ i\ direction \end{bmatrix} = \begin{bmatrix} Body\ Forces\ acting \\ in\ i\ direction \end{bmatrix} + \begin{bmatrix} Surface\ Forces \\ in\ i\ direction \end{bmatrix} \tag{3.18}$$

Equations 3.19 and 3.20 showed the momentum equations in x and y-direction respectively [36].

$$\rho \frac{du}{dt} = \frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \rho f_x \tag{3.19}$$

$$\rho \frac{dv}{dt} = \frac{\partial P}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \rho f_y \tag{3.20}$$

iii. Conservation of energy

This law states that the rate of heat change for a system is equal to summation of rate of heat addition and the rate of work done on a fluid particle.

$$\begin{bmatrix} Rate\ of \\ energy \\ input\ due\ to \\ conduction \end{bmatrix} + \begin{bmatrix} Rate\ of\ energy \\ input\ due\ to \\ workdone\ by \\ conduction \end{bmatrix} + \begin{bmatrix} Rate\ of\ energy \\ input\ due\ to \\ workdone\ by \\ surface\ stress \end{bmatrix} = \begin{bmatrix} Rate\ of \\ increase\ of \\ energy\ in\ the \\ element \end{bmatrix} \qquad (3.21)$$

The equation for energy conservation derived from the first law of thermodynamics as shown in equation 3.22 [36].

$$\rho \frac{d}{dt}\left(e + \frac{U^2}{2}\right) = \rho\dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) - \frac{\partial(uP)}{\partial x} - \frac{\partial(vP)}{\partial y} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} +$$

$$+ \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \rho f.U \qquad (3.22)$$

3.2.3.2 Boussinesq Approximation

Natural-convection in buoyancy-driven flows occurred when heat is added to a fluid and the fluid density varies with temperature. This type of flow can be induced due to the force of gravity acting on the density variations and characterized in stratified storage tanks [68].

It is shown that the Navier-Stokes equations 3.17 to 3.22 are non-linear (highly coupled) and complex to solve. Consequently, simplifications must be made to reduce the non-linearity by adopting Boussinesq approximation in the equations. Faster convergence is obtained with the Boussinesq model than setting up the problem with fluid density as a function of temperature for many natural-convection flows [72].

In this water density modelling, density is treated as a constant value in all solved equations such as the temporal and convective terms, except for the buoyancy term in the momentum equation. Linear density variation is employed in the gravity or buoyancy term of y-momentum equation to show the effect of buoyancy. This model is applicable when there is temperature difference between the hot and cold fluid regions is small [66].

Abdelhak [34] presented the formula of density for Boussinesq approximation and this model is appropriate when the condition $\{[\beta(T - T_o)] \ll 1\}$ is satisfied.

$$\rho = \rho_o + \Delta\rho \approx \rho_o[1 - \beta(T - T_o)] \qquad (3.23)$$

On summary, the governing equations for the CFD two-dimensional analysis (eqns. 3.24 - 3.27) are obtained by simplifying the eqns. 3.17- 3.22 considering the conditions:

- The working fluid, water, is incompressible fluid [63].
- And the working fluid is a Newtonian fluid in which its viscosity is not affected by shear rate and the viscous stresses are proportional to the rates of deformation [66].
- Boussinesq approximations are applied in the water density modelling, in which $f = (\rho - \rho_o)g$ [72].

$$\frac{\partial(u)}{\partial x} + \frac{\partial(v)}{\partial y} = \nabla U = 0 \tag{3.24}$$

$$\frac{\partial u}{\partial t} + \nabla.(\mathrm{u}U) = -\frac{1}{\rho_o}\nabla P + \vartheta\nabla^2 u \tag{3.25}$$

$$\frac{\partial v}{\partial t} + \nabla.(vU) = -\frac{1}{\rho_o}\nabla P + \vartheta\nabla^2 v + [1 - \beta(T - T_o)]g \tag{3.26}$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla[U(\rho E + P)] = \nabla\left[k_{eff}\nabla T + \tau_{eff}U\right] + S_e + \rho g.U \tag{3.27}$$

3.3 Selection of appropriate solution packages

i. MATLAB Program

For 1D analysis MATLAB coding software is chosen because of its inherent nature of matrix manipulation in which the desired result of the simulation is a matrix showing the temperatures on the nodes. The other quality of MATLAB is its ability to solve very wide and complex equations and to handle recursive and iterative scripts or functions, which were used to calculate annual temperatures. It is also capable of working many inputs into a function and imbedding multiple functions into a single primary function. Usually, MATLAB is more applicable for modeling solar systems than traditional imperative oriented programming languages, since it provides good code scalability, faster developing time, and simpler integration with external computational tools.

ii. ANSYS Fluent

ANSYS Fluent software is an appropriate solution package for simulating 2D-CFD model because it mainly uses FEM technique to solve mathematical formulations and contains the broad physical modeling capabilities which are needed to model flow, turbulence, heat transfer and reactions of two-dimensional flow problems.

3.4 Chapter Summary

In this paper, two major simulations are presented for studying the impact of stratification on PV/T assisted heat pump system's storage tank. The annual temperature distribution and system performance are studied in one-dimensional computational modelling using implicit finite-difference scheme and program solution called MATLAB. Whereas short term simulation which includes the detailed study of the fluid flow and heat transfer in the storage is performed under two-dimensional computational finite volume modelling using ANSYS Fluent.

CHAPTER FOUR

ONE DIMENSIONAL MODELLING OF STRATIFIED STORAGE

4.1 Introduction

The one-dimensional modelling is based on the model used on the existing research [4] of hybrid photovoltaic thermal and heat pump system. The study investigated the annual performance of a glazed photovoltaic thermal system (a combination of PV module and solar flat plate collector) with a non-stratified storage tank using dynamic computational model. The model was simulated under the actual hot water demand condition of two locations in Ethiopia, Dire Dawa and Addis Ababa, for determining the co-generation of hot water (heat) and electrical energy. And the results (electrical energy, PV/T temperature and water outlet temperature) were verified with an experimental paper [67].

In this section, the computing procedures for the multi-node storage tank model is presented by adopting the necessary conditions such as site selection, data collection, electrical demand analysis, solar irradiation data analysis, and PV system sizing from the existing study. This model only used the solar irradiance data of Dire Dawa.

4.2 Geometrical Modelling

The proposed system has two vertical storage tanks in which the vertical orientation is the efficient design for a stratified storage tank since stratification efficiency of horizontal tank is considerably lower than vertical tank [34]. The so-called geometrical dimensions, diameter, and height, of the storage tank would be calculated based on the following assumptions.

i. Volume of the tank must be determined for the calculation of diameter and height. The formula for calculating volume of cylindrical storage is:

$$V_s = \pi \frac{d^2}{4} h \tag{4.1}$$

ii. The height of the storage is assumed to be twice of the diameter.

$$h = 2d \tag{4.2}$$

Therefore, equation 4.1 becomes: $V_s = \pi \frac{d^3}{2}$ (4.3)

Solving the above equation will give the exact geometrical dimensions which are used in the simulation presented in figure 4.1 (for the case of the PV/T storage). In addition, the dimeters of inlet and outlet pipes are equal (d_{in}=d_{out}).

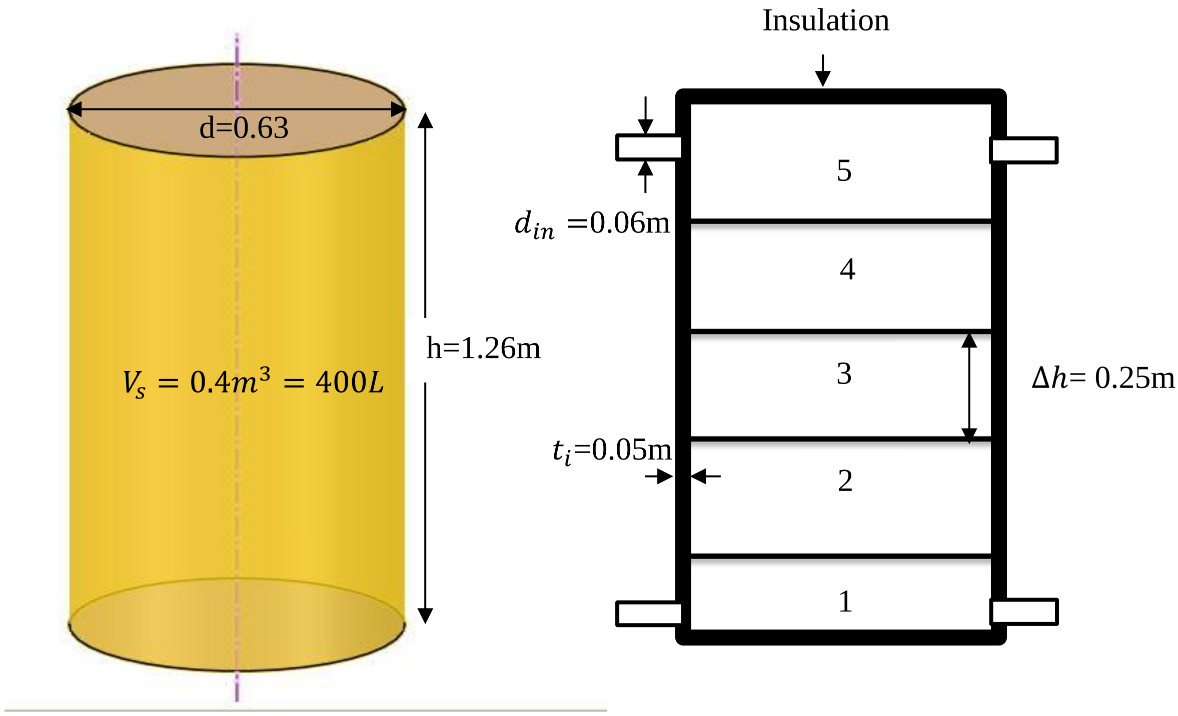


Figure 4. 1 Geometrical dimensions of the PV/T tank

4.3 Computational Modelling

Like the existing simulation, flowrate of 0.00138 kg/s, as discussed in chapter two, low-collector flow rate is used and the mass flow rates of water from and to the collector are taken as constant ($\dot{m}_s = \dot{m}_C$). On the other hand, the mass flow rate of water from the mains ($\dot{m}_{in}$) and to the load ($\dot{m}_l$) are determined by using Eqn. 4.4.

$$\dot{m}_{in} = \dot{m}_l = \frac{\rho * ff(i) * DHWC}{3600} \quad (4.4)$$

Inserting nodal mass flow rates and the above equations in the earlier nodal equations (3.7 to 3.11) would provide the exact equations used on the 1D simulation program or MATLAB.

$$T_1(\frac{\Delta m c_p}{\Delta t} + \dot{m}_c c_p + \dot{m}_{k1} c_p + \frac{KA_c}{\Delta h} + U_t \Delta A_s) - T_2(\frac{KA_c}{\Delta h}) = \frac{\Delta m c_p}{\Delta t} T_{i1} + \dot{m}_l c_p T_{wba} + U_t \Delta A_s T_a \quad (4.5)$$

$$T_1\left(\frac{-KA_c}{\Delta h} - \dot{m}_{k1} c_p\right) + T_2(\frac{\Delta m c_p}{\Delta t} + \dot{m}_{k1} c_p + \frac{2KA_c}{\Delta h} + U_t \Delta A_s) - T_3(\frac{KA_c}{\Delta h}) = \frac{\Delta m c_p}{\Delta t} T_{i2} + U_t \Delta A_s T_a \quad (4.6)$$

$$T_2\left(\frac{-KA_c}{\Delta h} - \dot{m}_{k1} c_p\right) + T_3(\frac{\Delta m c_p}{\Delta t} + \dot{m}_{k1} c_p + \frac{2KA_c}{\Delta h} + U_t \Delta A_s) - T_4(\frac{KA_c}{\Delta h}) = \frac{\Delta m c_p}{\Delta t} T_{i3} + U_t \Delta A_s T_a \quad (4.7)$$

$$T_3\left(\frac{-KA_c}{\Delta h} - \dot{m}_{k1} c_p\right) + T_4(\frac{\Delta m c_p}{\Delta t} + \dot{m}_{k1} c_p + \frac{2KA_c}{\Delta h} + U_t \Delta A_s) - T_5(\frac{KA_c}{\Delta h}) = \frac{\Delta m c_p}{\Delta t} T_{i4} + U_t \Delta A_s T_a \quad (4.8)$$

$$T_4\left(\frac{-KA_c}{\Delta h} - \dot{m}_{k2} c_p\right) + T_5(\frac{\Delta m c_p}{\Delta t} + \dot{m}_l c_p + \frac{KA_c}{\Delta h} + U_t(\Delta A_s + \frac{\pi d^2}{4})) = \frac{\Delta m c_p}{\Delta t} T_{i5} + \dot{m}_c c_p T_C + U_t(\Delta A_s + \frac{\pi d^2}{4}) T_a \quad (4.9)$$

The initial storage tank temperatures before the simulation starts (at 0 hrs) are assumed in the program code. As well-insulated storage tank is required to avoid heat losses, this thermal storage tanks are made of stainless steel and insulated with fibre and aluminium foil [4]. In general, the values of inputs and parameters used in the simulation of 1D multi-node model of the two storages are summarized in Table 4.1

4.3.1 Flow Chart of the One-dimensional Simulation

Figure 4.2 represents the general flowchart for the computational simulation assuming fixed tank inlet/outlet position with constant material properties of water in the storage of the hybrid PV/T-Heat Pump system. The specific flowchart during a single time step describes the loop in which how the simulation evaluates the energy balance equations in every sect of the tank is shown on figure 4.3.

The input data in the simulation include location and climate data, collector orientation, PV/T system parameters, storage size and hot water consumption pattern and COP manufacturer performance data, user demand and energy consumption pattern.

Table 4. 1 Input parameters used for the simulation.

Parameters	**PV/T Storage**	**Heat Pump Storage**
Storage tank volume (m^3)	0.4	0.2
Storage tank diameter (m)	0.63	0.5
Storage tank height (m)	1.26	1
Number of nodes	5	1
Storage tank thickness (m)	0.05	0.05
DHWC (m^3)	0.4	0.4
Collector flow rate of water (kg/s)	0.00138	
Constant density of water (kg/m^3)	998	998
Constant specific heat of water ($J/kg.^oC$)	4186	4186
Constant thermal conductivity of water ($W/m.^oC$)	0.625	0.625

With the implicit finite difference method described in the previous chapter, the system of equations takes the matrix form [A] $\{T_s\}$ = {C}, where [A] is an n-by-n matrix containing the coefficients of $\{T_s\}$ at time t+1, $\{T_s\}$ is an n by 1 column of the temperatures of each node at time t+1, {C} is an n by 1 column vector containing the right-hand side (constant term) of the system of equations. Inversing the matrix using $\{T_s = A\backslash C\}$ or '*linsolve'*, $\{T_s$ =linsolve (A, C)} would solve the simultaneous linear equations and obtain $\{T_s\}$.

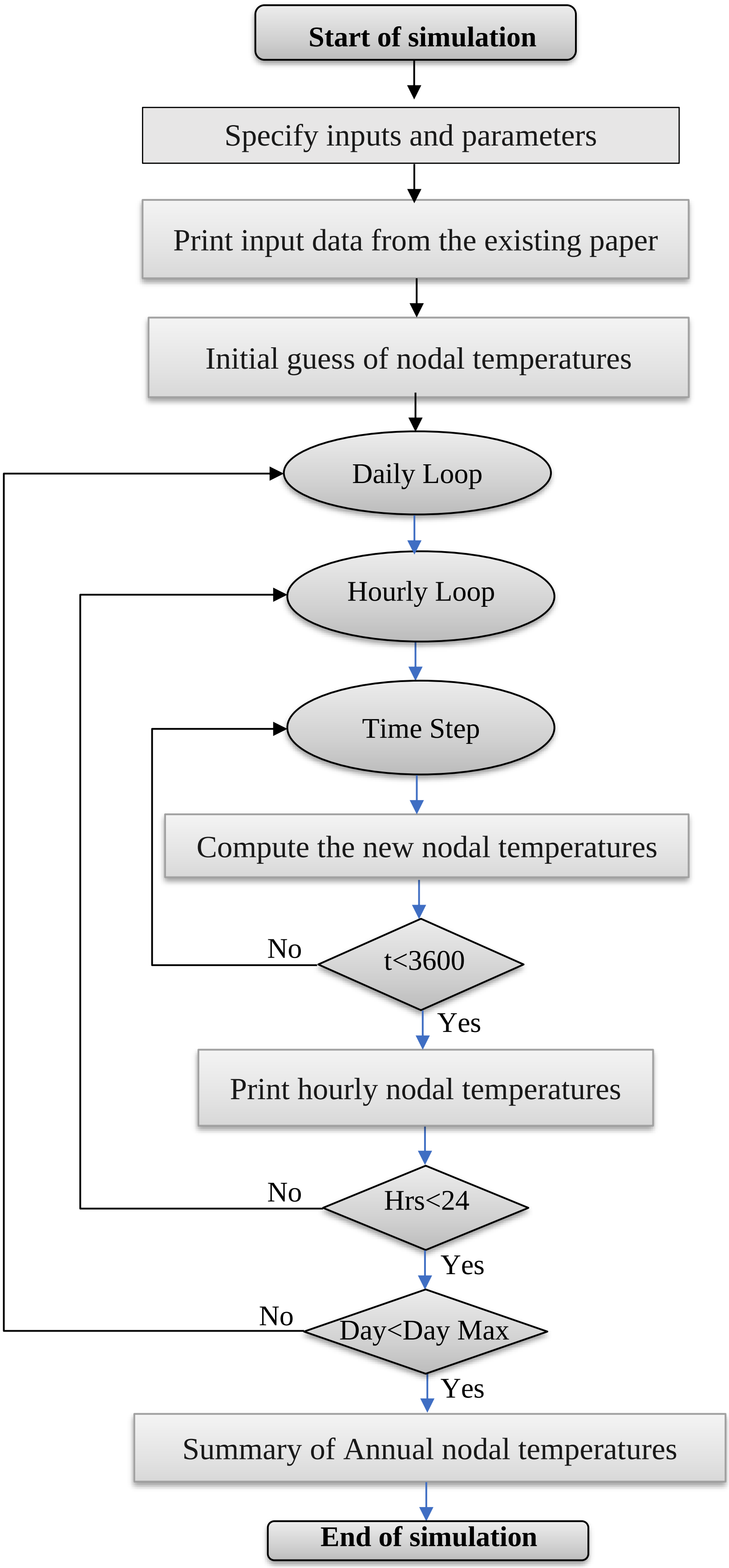


Figure 4. 2 General flow chart of numerical solution procedure for the Hybrid System

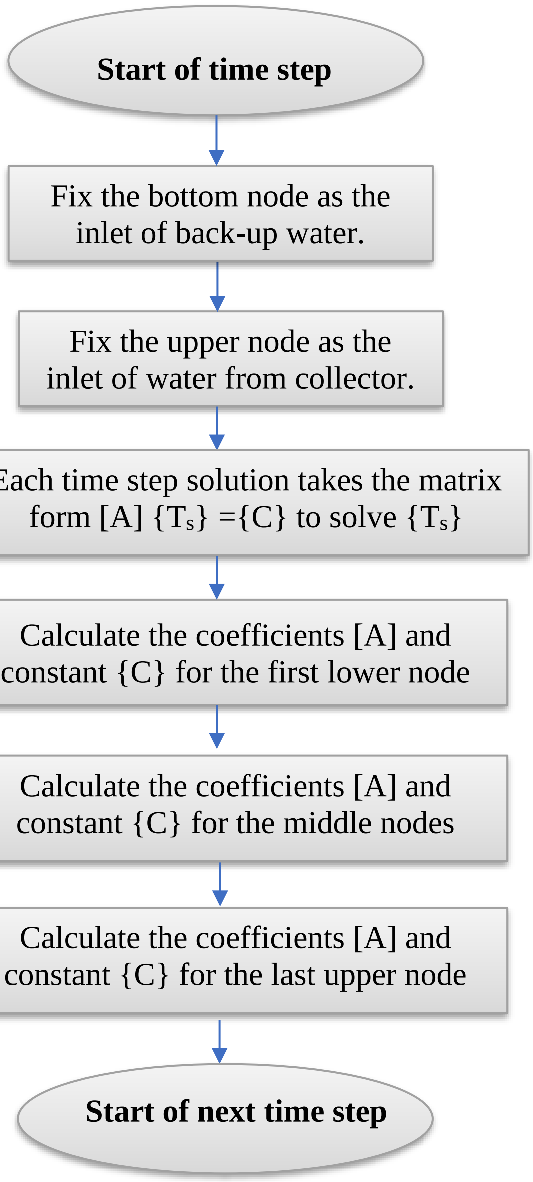


Figure 4. 3 Specific flowchart of the 1D simulation process during a single time step

4.4 Performance parameters used to compare stratified and non-stratified storage

The reference case study included the computation of monthly and annual incident solar irradiance, electrical energy generation, temperature of water at different points, thermal energy transported to storage, and thermal energy supplied as hot water to end-users, considering the hourly hot water consumption pattern and storage size effect. But this current study merely focused on temperature profile in the storages, useful heat gain, thermal energy transported to the hot water storage or supplied to end users, heat losses in the collector and storages.

Regarding the discussion on the previous chapters, studying how the thermal stratification applied in the storage tank benefits the system includes gaining high solar fraction, decreasing the heat loss, and utilizing of solar collectors efficiently. These factors are also briefly analyzed for reasonable contrasting.

4.4.1 Performance of the storage

The annual performance of a solar hot water system is mainly characterized by annual solar fraction and directly dependent on solar energy delivered to the load [6].

i. Thermal Energy in the storage

This includes the total amount of thermal energy transported or delivered to the load/ heat pump storage.

$$Q_{solar\ to\ load} = \rho * c_p * DHWC * ff(i) * (T_{n,5} - T_{wba}) \qquad (4.10)$$

Where $T_{n,5}$ is the upper nodal temperature in the storage sent to the heat pump system.

ii. Solar Fraction (f_{sol})

It is a fraction of total energy demand supplied by the solar thermal system computed by dividing the energy delivered to the load by the total energy required by the load as shown by eqn. 4.11 [3].

$$f_{sol} = \frac{Q_{solar\ to\ load}}{Q_{load}} \qquad (4.11)$$

The total energy required by the load is found to be by considering a maximum of 45–50℃ for preheating the water since tactful balance must be achieved between the low and high-temperature requirements of the water stream to serve as a coolant and satisfy the hot water need of the end-user respectively [4,73]. Hence,

$$Q_{load,PVT} = \rho * c_p * DHWC * ff(i) * (50 - T_{wba}) \qquad (4.12)$$

4.4.2 Heat losses

i. Storages heat loss

This is the amount of heat lost to the environment from the storage in which the mixed storage system heat loss is calculated by taking a uniform temperature of water in the storage, but, in the stratified storage, it is obtained using the summation of losses in each node as derived in eqn. 4.13.

$$Q_{s,loss} = U_t * [\Delta A_s * \sum_{n=1}^{n-1}(T_n - T_a) + (\Delta A_s + \frac{\pi d^2}{4}) * (T_{n,n} - T_a)] \qquad (4.13)$$

ii. Collector heat loss

The thermal heat loss through the PV/T regarding the cold water entered to the collectors are considered as collector losses.

$$Q_{c,loss} = A_C * U_L * (T_{wi} - T_a) \quad (4.14)$$

4.4.3 Performance of PV/T

i. Optical and electrical efficiencies

Based on the existing paper, thermal efficiency is the ratio of the rate of useful heat delivered by the PV module (rate of the absorbed energy minus the overall heat loss and converted electricity) to the amount absorbed heat. Here this thermal efficiency is regarded as an optical efficiency.

$$\eta_{th} = \frac{Q_{u,coll}}{GA_C} = \frac{A_C*(F*S*(\tau\alpha)_{PV}) - U_L*(T_p - T_a)}{GA_C} \quad (4.15)$$

The electrical efficiency the percentage of electrical energy generated from the absorbed solar radiation.

$$\eta_{ele} = \frac{E_{ele}}{GA_C} = \frac{A_C*S*\tau*P_f*N_{epv}*((1 - T_{fp}*(T_p - T_{rf}))}{GA_C} \quad (4.16)$$

ii. Useful heat gain, collector heat removal factor and Thermal efficiency

One of the most recent research projects on the performance evaluation of PV/T argued that there is no standard method available for evaluating the performance of PV/T collectors [75]. Following this, the thermal efficiency (i.e., hot water end-use overall efficiency) can also be described by the overall heat loss coefficient (U_L) and heat removal factor (F_R) of the collector [76]. Collector heat removal factor is a vital parameter in determining the thermal efficiency of a photovoltaic thermal (PV/T) system that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. [30,74]

$$F_R = \frac{\text{actual useful energy gain of a collector}}{\text{theoretical useful gain}} = \frac{\dot{m}C_p(T_{wo} - T_{wi})}{A_C[S - U_L(T_{wi} - T_a)]} \quad (4.17)$$

The value of collector heat removal factor is determined by collector flow factor (F'') and collector efficiency factor (F') [31].

$$F'' = \frac{F_R}{F'} = \frac{\dot{m}C_p}{A_C U_L F'}\left[1 - exp\left(-\frac{A_C U_L F'}{\dot{m}C_p}\right)\right] \quad (4.18)$$

Therefore, the respective formulas of the useful heat gain from the collector, the difference between the absorber solar radiation and thermal heat losses identified by

Hottel-Whillier equations [78], and the thermal performance using F_R and U_L are presented below with $S = (\tau\alpha)_{PV} * G$,[75,77].

$$Q_u = A_C F_R (S - U_L(T_{wi} - T_a)) \tag{4.19}$$

$$\eta_{th} = \frac{Q_u}{GA_c} = F_R(\tau\alpha)_{PV} - F_R U_L \frac{T_{wi} - T_a}{G} \tag{4.20}$$

4.4.4 Performance of the Heat Pump

i. Coefficient of performance (COP)

COP is one parameter to compare mixed and stratified tanks because it is dependent on ambient and hot water temperatures that govern heat absorption by the evaporator and heat rejection by the condenser to hot water respectively. Based on the manufacturer's tabulated value of COP, the formula derived from the existing thesis [4] is:

$$COP = (0.4641 - (0.36538 * T_{hp}) - 0.13596 * T_a - 0.01164 * T_{hp}^2 + 0.004564 * T_a * T_{hp} + 0.008122 * T_a^2 + 0.00009655 * T_{hp}^3 + 0.0003286 * T_{hp}^2 * T_a - 0.2829 * T_{hp} * T_a^2) \tag{4.21}$$

ii. Useful thermal energy

In this case, the useful thermal energy is the amount of heat transported by the heat pump system from ambient to the hot water storage tank. $\dot{Q}_{hp} = COP * P_{el}$, where P_{el} is electrical power generated by PV/T.

iii. Overall performance of the hybrid PV/T and heat pump system

The end-user overall performance of the hybrid PV/T Heat Pump system is determined by dividing total useful thermal energy from the heat pump with the solar energy incident on the PV/T surface. Eqn. 4.22 is the formula for calculating the annual efficiency of the whole system.

$$\eta_{sys} = \frac{Q_{hp}}{G} = \frac{\rho * c_p * DHWC * ff(i) * (T_{hp} - T_{wba})}{G} \tag{4.22}$$

The study also included performance analysis to examine the effect of different vital parameters on temperature contours and system performance of hybrid PV/T and heat pump system with stratified storage. The parameters are geometrical conditions such as storage volume, height to diameter ratio, inlet/exit locations and operating conditions like collector flow rate, heat removal factor, and hot water consumption patterns.

4.5 Chapter Summary

The input parameters for the geometrical and computational modelling were taken from the existing study. The flow charts for both the annual and instant simulations are also presented in this chapter. The performance parameters used to examine the difference between mixed and thermally stratified tanks subdivided into performance of storage, efficiency of PV/T, heat losses and heat pump performance.

CHAPTER FIVE

TWO-DIMENSIONAL MODELLING OF STRATIFIED STORAGE

5.1 Introduction

The 2D simulation with transient phenomena represented the most frequent state of tank thermal stratification in cylindrical hot water storage using the commercial software, ANSYS Fluent, v17.2. The program has five main steps for the CFD simulation called geometry, mesh, setup, solution, and results. The following section covers these procedures involved in the process of generating of the CFD model individually as summarized in flow chart, Fig 5.1.

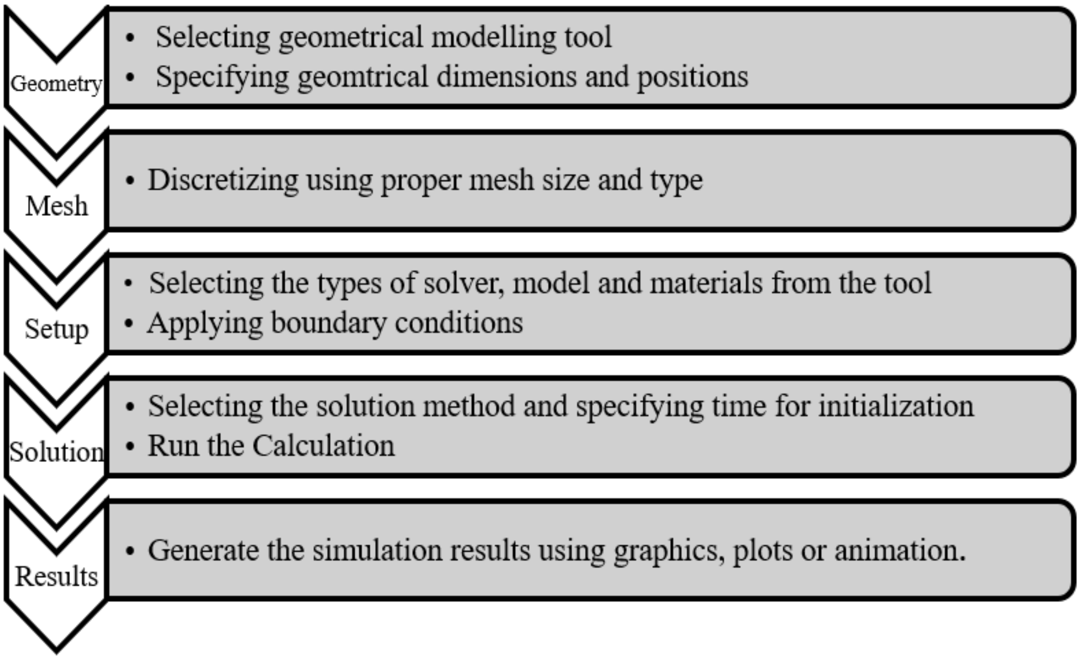


Figure 5. 1 Flow Chart of the processes in the two-dimensional CFD model

5.2 Geometrical Model

The first step in the CFD simulation is modelling the geometry of the storage tank with a suitable tool. The geometrical model assumed the hot water storage tank in the PV/T assisted heat pump water heating system with a flat design and computational domain.

- **Mode of Stratification:** The simulation considers thermal stratification, then, in the geometrical design, there is no stratifying tool, stratifier or plate, used inside the storage.

- **Geometrical Modelling Tool:** The modelling tool used for geometry is Space Claim, 17.2 ANSYS, Inc.
- **Geometrical Dimensions:** Like the one-dimensional analysis, a fixed height of the water in the tank equal to the height of the cylindrical part of the tank, i.e., 1.26m, and a fixed internal diameter of the tank equal to 0.63m are assumed.

5.3 Mesh (Discretization)

Since the accuracy of CFD calculations depends significantly on the mesh quality, this step is an integral part of the simulation.

- **Meshing Tool:** ANSYS ICEM CFD 17.2 tool was selected for computing mesh generation since it is powerful and highly manipulative software which generates high resolution grids.
- **Meshing Type:** The so-called block-structured mesh called quadrilateral mesh (cell) was used for two dimensional simulations with face meshing and sizing.

5.4 Setup (ANSYS Physics Preprocessor)

The simulation is performed in double precision using the option of serial processing in ANSYS Fluent 17.2 tool. Since there is no reason for using two-dimensional approaches in long-term simulation of solar water heating systems [32], in this 2D CFD model, short term analysis at specific time is investigated. Here, initially, perfectly stratified storage is considered and for representing a typical fully charged system, the expected maximum water temperature from collector is taken from 1D simulation. Because the heat source for the storage is the PV/T with no circulating fluid in internal heat exchanger, it is assumed that the fluid is considered as stationary after charging.

5.4.1 Solver

- **General Solving Method:** Pressure based solver is selected to solve the transient governing heat transfer equations of selected incompressible fluid, water, with absolute velocity formulation and planar two-dimensional space.
- **Gravity**: The gravitational acceleration -9.81 m/s^2 was activated in vertical direction because in stratified flows, the thermal-hydraulic dynamics in hot water storage is directly affected by gravity and buoyancy. In solar hot water tanks, the cold and hot water are separated by means of gravitational effect for load management and energy conservation applications [64].

5.5.2 Model

- **Energy Equation:** For modelling the heat transfer, natural convection, the energy equations stated in chapter three are activated. The only heat transfer mode applied is thermal energy.
- **Type of Flow:** Taking the Reynolds number from the 1D analysis, the flow through the storage tank is typically laminar.
- **Viscous Dissipation**: It is considered that viscous dissipation of energy is negligible as the heat capacity of the fluid is sufficiently large that the temperature is negligibly affected by friction.
- **Material:** The tank model includes the tank wall as a solid region and the hot-cold water volume of the tank as a fluid region with their respective properties stored in the tool.
- **Fluid Properties:** The thermo-physical properties of water taken as constant, except for the density variations with temperature, which affect the buoyancy force only, applied by selecting the Boussinesq approximation model. 998 kg/m^3 is entered for constant density input and $2.95*10^{-4}$ K^{-1} for thermal expansion coefficient of water [70].

5.3.3 Cell Zone Conditions

- **Operating Conditions:** Because Boussinesq model is used for this simulation, operating conditions were specified in cell zone. Default operating constants are set, 101.3 Kpa and 288.16 K for operating pressure and temperature respectively.

5.3.4 Boundary Conditions

- **Shear (Slip) Condition:** In all solid surface wall boundary, no slip condition is imposed, the velocity of the water at the wall is zero, $u = v = 0$ in which the water at the walls is not moving.
- **Adiabatic Wall:** As the external wall is insulated, the omission of heat losses to the surrounding ambient has no significant influence on the results [34], the boundary condition applied on the wall of the tank is adiabatic wall, $\left(\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = 0\right)$ i.e., Heat Flux=0

The boundary conditions used in the CFD simulation is summarized in the table 5.2.

Table 5. 1 Boundary conditions applied in the CFD simulation.

Zone	Phase	Type	Momentum Conditions	Thermal Conditions
Hot-Water	Fluid	Interior		$T = 50^0\text{c} = 323.15\text{k}$
Cold-Water	Fluid	Interior		$T = 20^0\text{c} = 293.15\text{k}$
Wall	Solid	Wall	Stationary Wall motion No Slip Condition	Adiabatic Condition $T_{wall} = 300\text{K}$

5.5 Solution (ANSYS Solver)

The solution is generated based on the assumptions, setup settings, boundary conditions of the mathematical and physical modelling presented in section 3.3.4. The transient CFD calculations are performed with a density of water as a function of temperature which use a constant density fluid model but applies a local gravitational body force throughout the physical domain.

5.5.1 Solution Methods

- **Scheme:** In order treat the pressure–velocity coupling, SIMPLE algorithm is used.
- **Spatial Discretization:** Second order upwind method is used for the discretization of pressure, density, momentum, and energy equations.
- **Transient Formulation:** First-order implicit formulation is applied.

5.5.2 Solution Controls:

- **Under-relaxation factors:** For most flows, the default under-relaxation factors do not usually require modification. But, in problems where density is strongly coupled with temperature, it is wise to under-relax the temperature equation and/or density [68]. Therefore, under-relaxation factor less than 1.0, 0.8 is used for density.

5.5.3 Monitors

- **Convergence criteria for residuals:** The calculation is considered convergent for the continuity, momentum, and energy equations. The convergence criterion for the scaled residual of continuity, momentum/velocity or other variables is kept 10^{-3} and 10^{-6} for the energy equation.

5.5.4 Solution Initialization:

Zero-velocity field is assumed at the start of all simulation, and it run with time step size of 0.01s.

5.6 Results (ANSYS CFD Post)

This post-processer provided reporting options for simulations. The results obtained from the CFD simulation are going to be explicitly discussed in the following chapter. For ensuring that the predicted solutions do not depend on the grid spacing during the process of simulation, independence test was applied**.** The mesh independence test was done for selecting the mesh grid by performing several simulations with different mesh sizes, starting from a coarse mesh, and refining it until numerical results were no longer dependent on the mesh size. For element sizing with 0.0015m, the generated mesh with 352800 elements and 354061 nodes was used in which the solution becomes independent before this element size.

5.7 Validation of the models

For the validation of the two models, an experimental setup with a transparent water tank was used for tracking the stratification when dye is injected into the water as presented in Fig. 5.1. Twenty T-type thermocouples were mounted halfway between the symmetry axis and the tank wall to measure the water temperature distribution along a vertical line every 10 seconds [79].

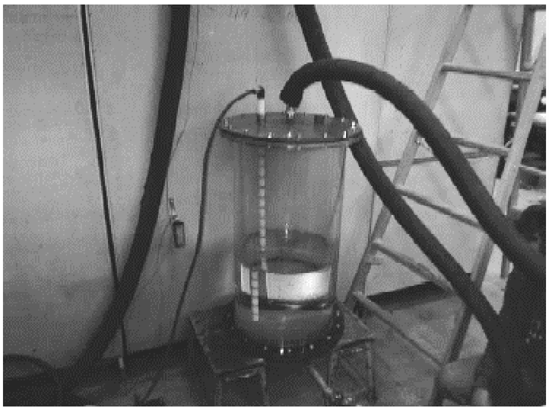


Figure 5. 2 Lay out of the experimental setup used in A. Zachar et al. [79]

Since dimensionless temperature (θ) can be used to represent the efficiency of energy storage stratification [69], comparison of the models was presented with transient temperature profile as a function of dimensionless temperature and storage height.

$$\theta = \frac{T - T_{in}}{T_{ini} - T_{in}} \qquad (5.1)$$

Where T is the instantaneous water temperature, T_{ini} is the initial temperature of water in the tank and T_{in} is the temperature of water flow into the tank.

Table 5. 2 Experimental validation input parameters

Parameters	Value
Height of the storage	0.8m
Internal diameter of the storage	0.4m
Diameter of plate	0.3m
Volume flow rate	1.6 liters/min
Time	1500s/ 25 min
Inlet water temperature	20°C
Initial temperature of water in the tank	41°C

The case of initially constant temperature field in a lower inflow arrangement was chosen for the comparison of the temperature profile between experimental findings and the computational models. The main parameters used in the experimental study are tabulated in Table 5.2.

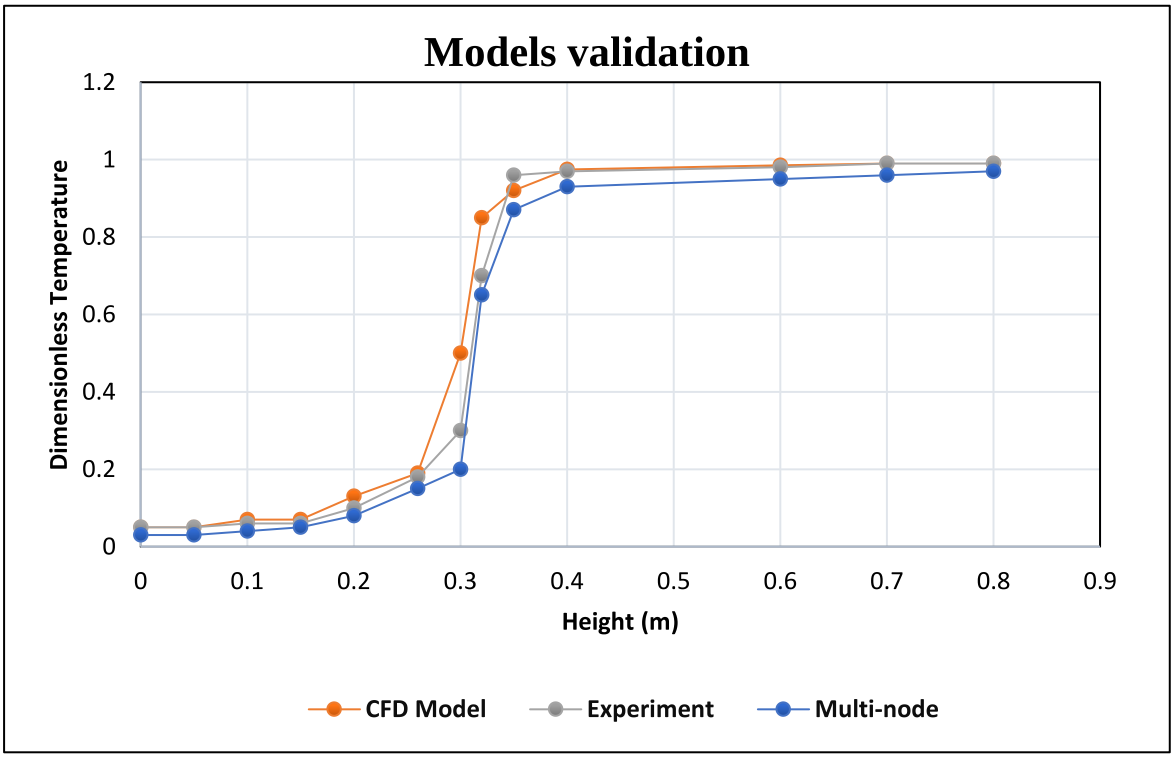


Figure 5. 3 Dimensionless temperature vs storage height curves for the 1D multi-node, CFD, and experimental models

Validation of both one-dimensional multi model and two-dimensional CFD simulations was done by comparing the temperature profiles (dimensionless temperatures vs storage height graphs on 13 vertical positions) with experimental study found on literature. Despite of both computational models have applied simplified assumptions and numerical approximations; their prediction level or accuracy is expected to be lower and different.

As shown in figure 5.3, the 1D multi-node implicit FDM simulation has underpredicted the temperature curve distribution of the storage. The possible reason might be a low node number application which led to significant discretization errors.

With the assumption of adiabatic tank wall and other reasons, the CFD model slightly overpredicted the dimensionless temperature or the stratification efficiency. The respective average errors between the multi-node, CFD modelling results and the experiment were ∼4.1% and ∼2.58%, which are nearly in the tolerable range to verify both simulations precision in modelling thermally stratified storages.

CHAPTER SIX

RESULTS AND DISCUSSION

6.1 One-dimensional modelling results

The modelling of the previous study evaluated hourly solar irradiance incident on the collector surface, electrical output, temperatures of glass, and PV/T module which were not significantly impacted with the application of thermal stratification in the storage. Though the absorber temperature is a function of water temperatures of collector inlet and outlet, based on the mathematical modelling, the results show negligible difference after stratification principle is achieved in the storage. This section focused only on the results such as temperatures of water in collector inlet/outlet, both storage tanks and performance parameters stated in section 4.4. The parametric analyses which were presented in the existing thesis such as different climatic conditions impact on the performance of the system and electrical energy storage battery effect on hot water supply temperature were not analyzed here.

6.1.1 Temperature profile in the stratified PV/T storage

Plotting a temperature versus storage height graph at different instances is the simplest technique to assess stratification. However, these methods cannot be used if the inlet temperature is changing [2,7]. Hence, instead of thermal stratification assessment, to show the temperature profile in the storage tank, the results of the first-time step are used.

Fig 6.1 shows the temperature curve by using the temperatures distribution in the walls of the PV/T storage at hours with high, low, and medium solar gain inputs. As the profile shows, the temperature of water in the storage increases with the height of the storage due to gravity effects. Therefore, the hot water from the collector is mainly stored in the upper part of the storage whereas the lower section has a lower water temperature. The profile might vary for modes (charging, discharging, and storing modes), inlet and exit locations and mass flowrate changes.

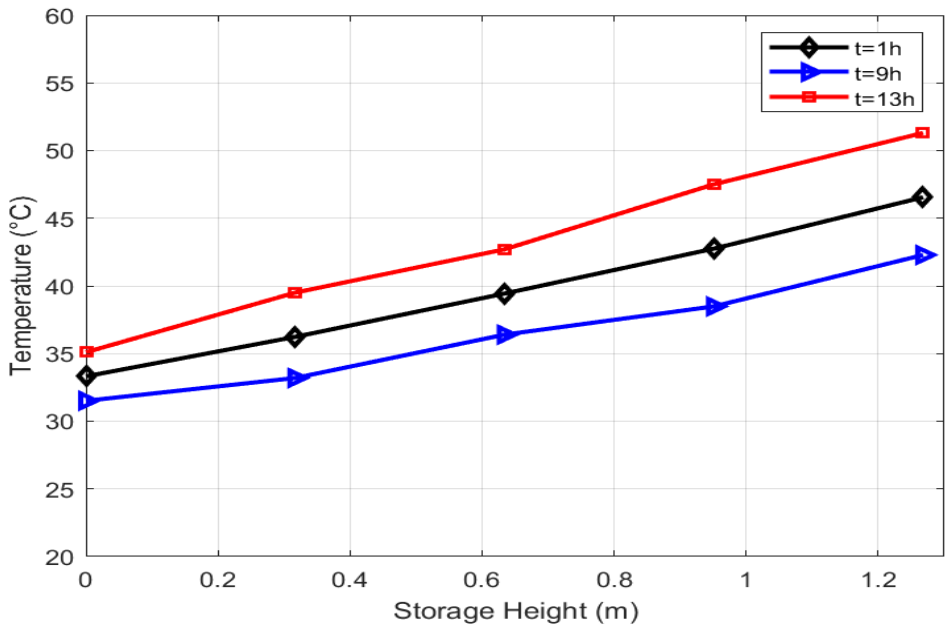


Figure 6. 1 Temperature versus storage height plot of the stratified PV/T storage during the hours at 1:00, 9:00 and 13:00 of June 11.

Furthermore, for indicating temperatures level, water temperature in five nodes of the storage versus time plot on single day of the year (June 11) is presented in figure 6.2.

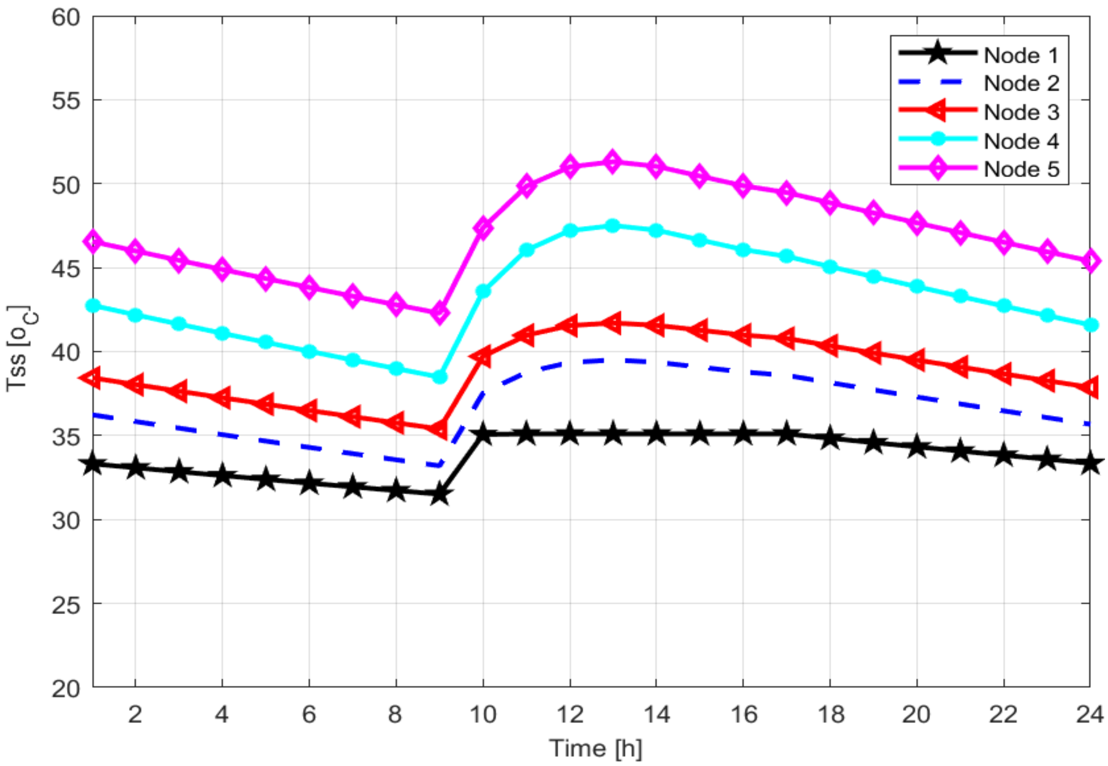


Figure 6. 2 Temperature Profile of the stratified PV/T storage on June 11

6.1.2 Temperature of water temperatures at different points

6.1.2.1 Monthly water temperatures of the collector inlet

The current program considered that the flow to the collector always leaves from the bottom. Thus, the following curves for the collector inlet water temperatures are plotted using the temperatures in lower node of the tank, node 1. It is directly depending on the backup water temperature, hot water consumption, collector flowrate and node size. The results showed that the annual temperature range is between 22.9 ^{0}C and 35.1 ^{0}C with the highest in June and the lowest in month of January.

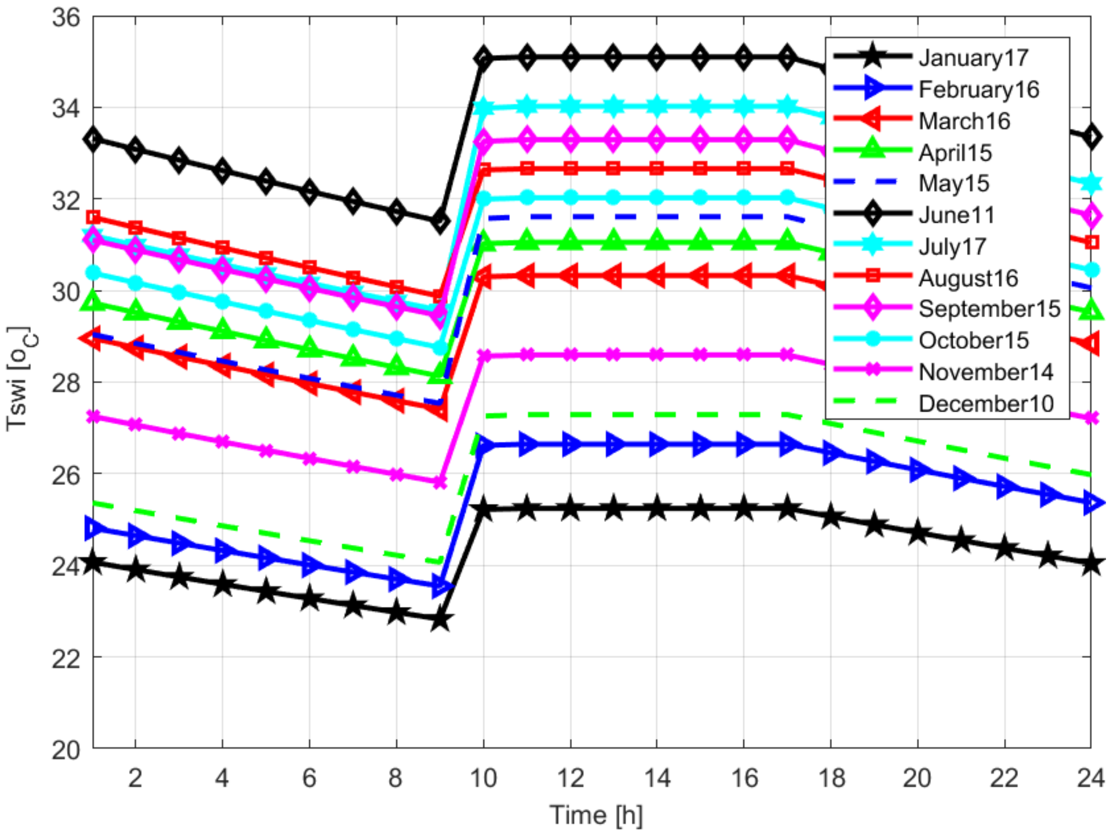


Figure 6. 3 Collector inlet water temperature of the stratified storage on the representative days of the month

6.1.2.2 Monthly water temperatures of the collector outlet

Based on the existing mathematical modelling, absorber and collector inlet temperatures, collector efficiency factor, and flowrate are the main factors that affect the temperatures of the hot water from the collector outlet. Figure 6.4 plots the monthly water temperatures of the collector outlet with the circulation mass flow rate of 0.00138 kg/s with a stratified storage in which maximum temperature, 54.4^{0}C, was attained.

Peak results are obtained during the day hours with non-zero value of constant fraction of daily hot water consumption.

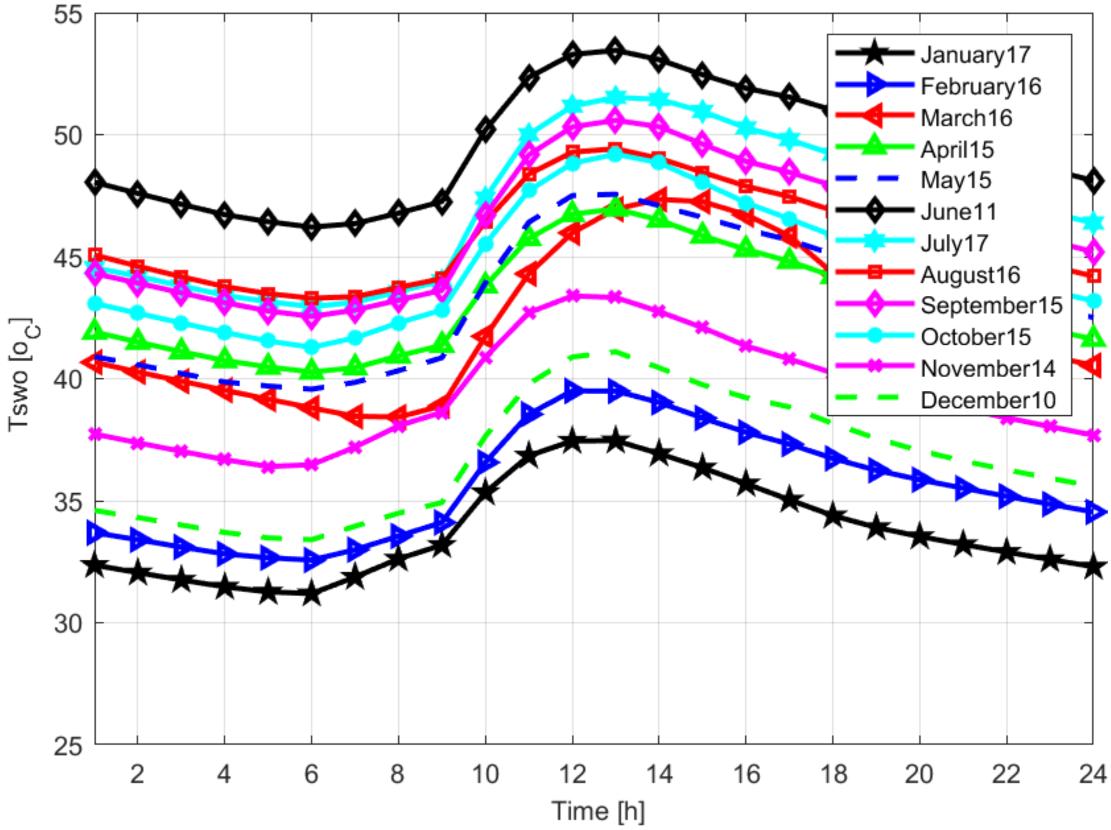


Figure 6. 4 Collector outlet water temperature of the stratified storage on the representative days of the month

6.1.2.3 Monthly hot water temperature in the upper node of the stratified tank of the PV/T system

Since the stratification multi-node modelling assumes that the flow to the load always leaves from the top, node 5, the monthly hot water temperatures in the stratified storage are the upper nodal temperatures. Inputs such as daily hot water consumption and its hourly fraction, node size, tank insulation thickness, collector outlet temperature and flowrates are the main parameters to model the hot water temperature in the stratified storage. From the plots it can be showed that the temperatures of water from the collector outlet have slightly dropped when it is compared to temperatures of water in the top node. This is due to ambient losses and conduction through nodes.

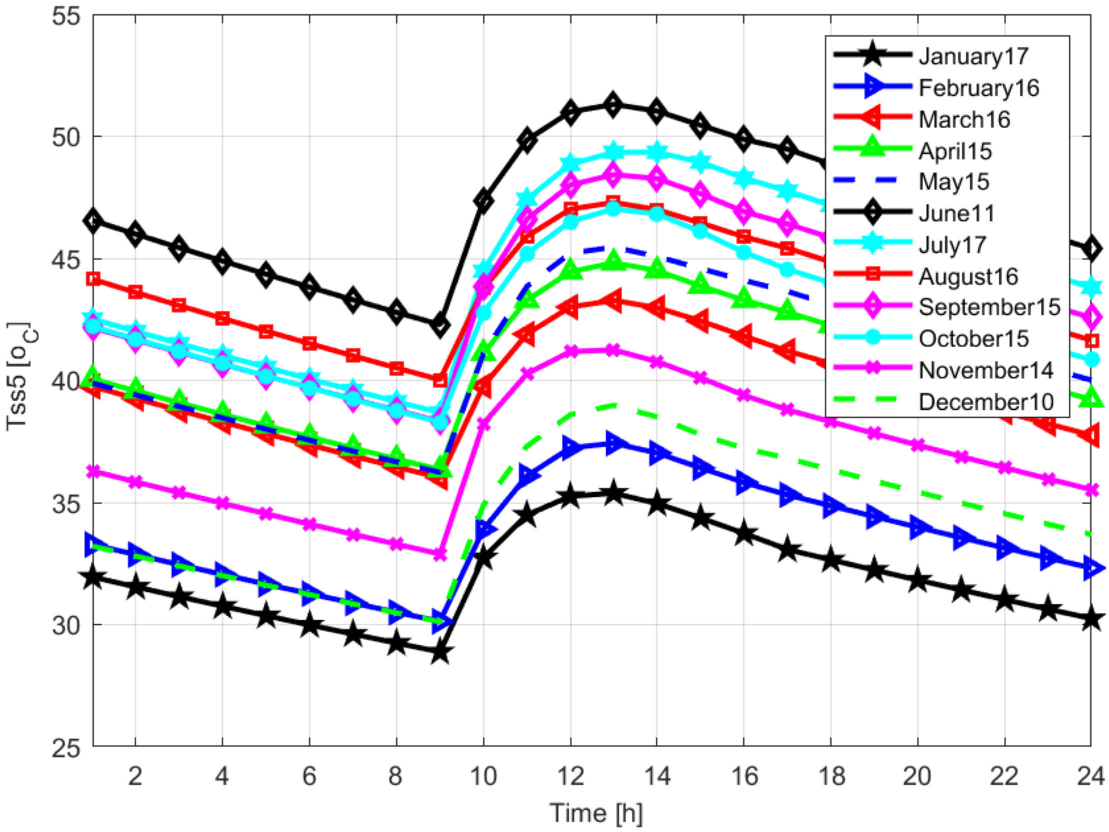


Figure 6. 5 Water temperature in the upper node of the stratified storage on the representative days of the month

6.1.2.4 Monthly hot water temperature of heat pump stratified tank

The temperature of water in the second (heat pump) storage and to the end user is a function of storage size, upper nodal of the first (pre-heated) storage and ambient temperatures. Figure 6.6 illustrated the graph of water temperature in the heat pump storage on the representative days of the month after thermal stratification is achieved in the PV/T storage.

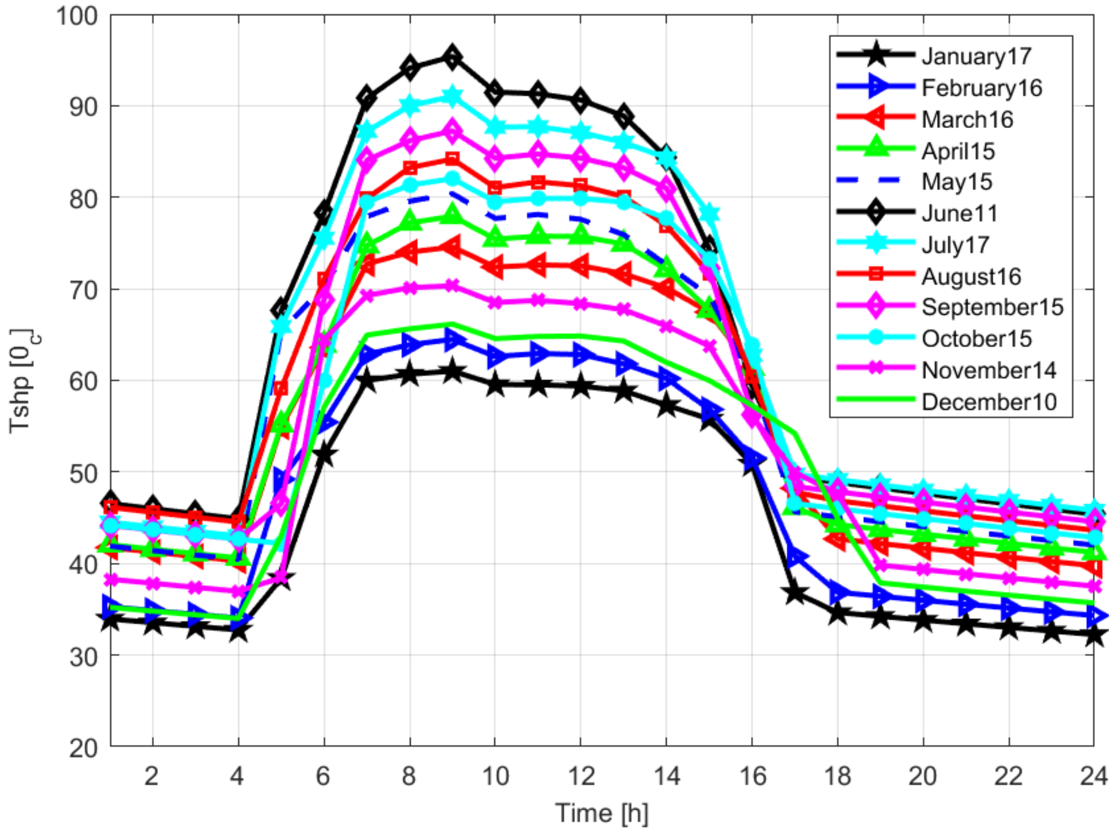


Figure 6. 6 post-stratification water temperature in the heat pump storage on the representative days of the month

6.1.3 Comparison between stratified and non-stratified (mixed) storages

6.1.3.1 Monthly water temperature of collector inlet in stratified vs mixed storage

The temperature of water inserted into the collector after stratification is lower than that of existing non-stratified system, as it is plotted in figure 6.7, in which the resultant stratification allows the cold water to circulate back to the solar collector. This lower collector inlet water temperature at the bottom of the tank increases the collected useful energy, reduce collector heat losses, and enhances collector efficiency (high utilization of the collector). The applied stratification on the simulation determined nearly 14.8 % of thermal efficiency (hot water end-use) advancement compared to the fully mixed model.

Table 6. 1 Summary of comparison between mixed and stratified storage models

Performance Parameters	Mixed Storage System	Stratified Storage System	Difference
Annual solar energy delivered to the load by PV/T (kWh)	7323.2	11598.5	4275.3
Annual solar energy required by the load (kWh)	14,844.9	14,844.9	-
Solar fraction	0.49	0.73	0.24
Annual PV/T storage heat loss (kWh)	381.07	159.58	-221.48
Annual collector heat loss (kWh)	494.95	225.75	-269.19
Optical efficiency (%)	50.55	50.55	0
Electrical efficiency (%)	15.42	15.42	0
Annual useful heat gain from PV/T (kWh)	760.8	1058.6	297.8
Thermal efficiency of the PV/T (%)	37.9	52.73	14.83
Annual thermal energy from heat pump storage (kWh)	12098.2	15918.7	3820.5
Overall Performance of the Hybrid PV/T and Heat Pump system (%)	63.69	79.29	15.6

The results of monthly hot water temperature from collector outlet in stratified compared to the fully mixed storage shows infinitesimal decrement due to lower collector inlet temperature. However, this decrement has a negligible impact on the useful heat gain from PV/T and entire performance of the system since the hot water is kept unmixed due to stratification.

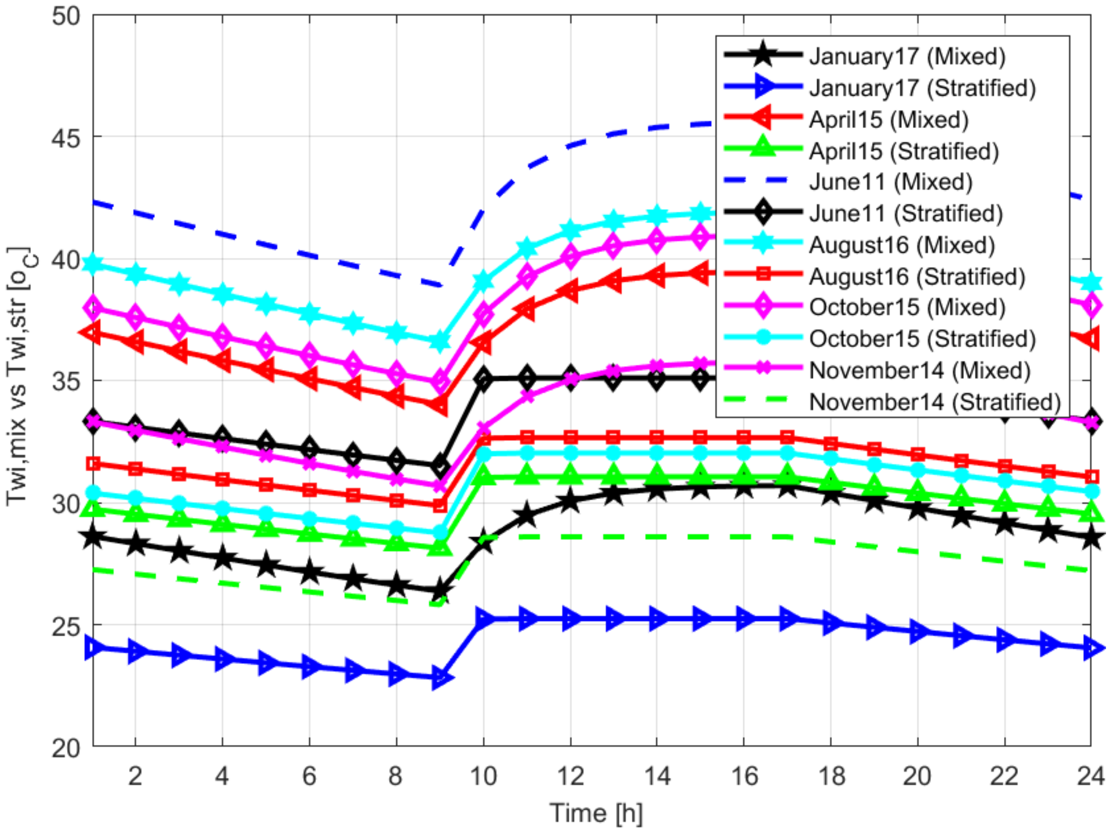


Figure 6. 7 Comparison of collector inlet water temperature between mixed and stratified storage on the representative days of the month

6.1.3.2 Monthly hot water temperature in the upper node in the stratified vs mixed tank of the PV/T system

The temperature of water in the existing model is lower than the stratified storage upper node temperatures due to the mixing of hot water from collector and back up water from loads. Consequently, the quantity of solar energy delivered to the load/end user and solar fraction of the system are higher in the stratified storage system to meet hot water temperature requirements for early morning and night consumptions.

52.2^{0}C is the maximum annual temperature of water obtained in the stratified storage whereas the non-stratified system has the highest temperature of 45.9 ^{0}C. And the solar fraction is upgraded from 0.49 to 0.73, in which larger portion (73%) of the energy required is supplied to the load by the stratified storage system. The curves below also show the significant difference of stratified and mixed storage temperatures during the peak or load hours.

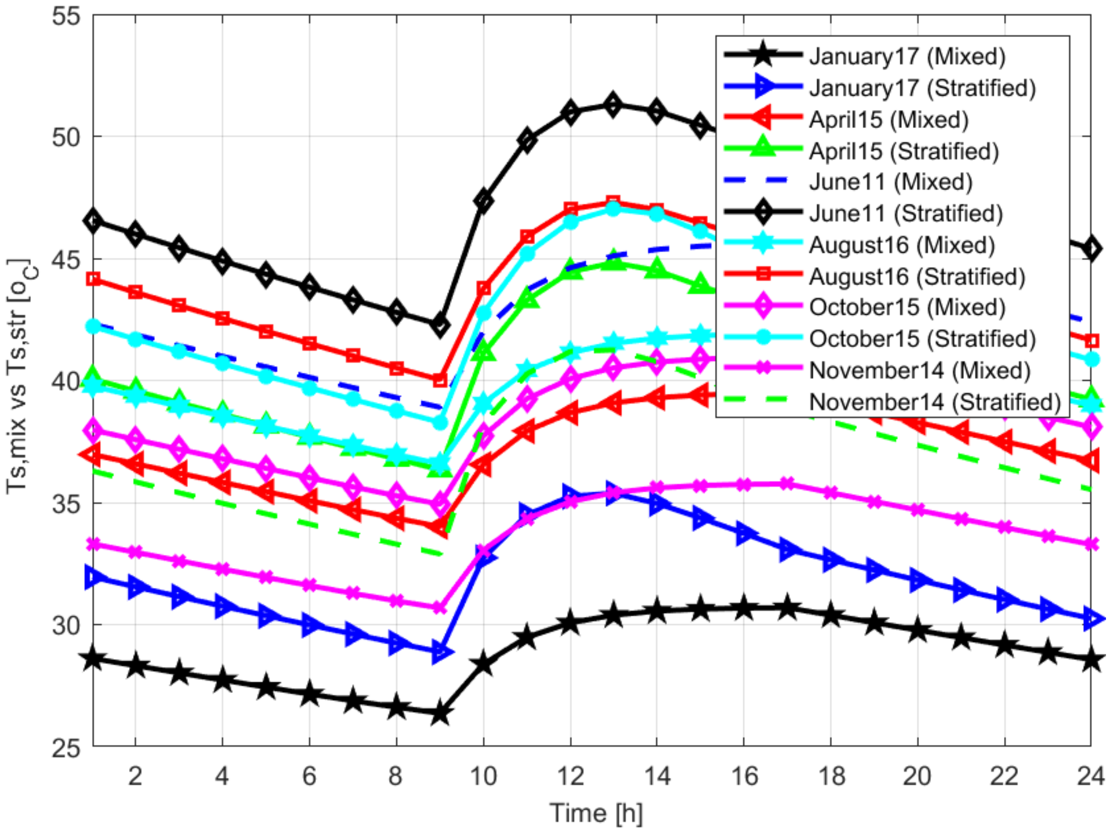


Figure 6. 8 Comparison of water temperature in mixed and stratified storages on the representative days of the month

6.1.3.3 Monthly hot water temperature of heat pump stratified vs non-stratified tank

The overall performance of the system is dependent on the thermal energy obtained from the heat pump delivered to the load/ end user. Because the temperature of hot water from the heat pump storage is highly influenced by the PV/T storage temperatures, higher second storage temperatures are obtained in the stratified system. Therefore, the entire performance of the system has increased with 15.6% after the principle of thermal stratification is applied on the existing hybrid system. Combining the PV/T with Heat Pump water heating system promotes a better performance, overall efficiency, by adopting thermally stratified storages rather than mixed tanks.

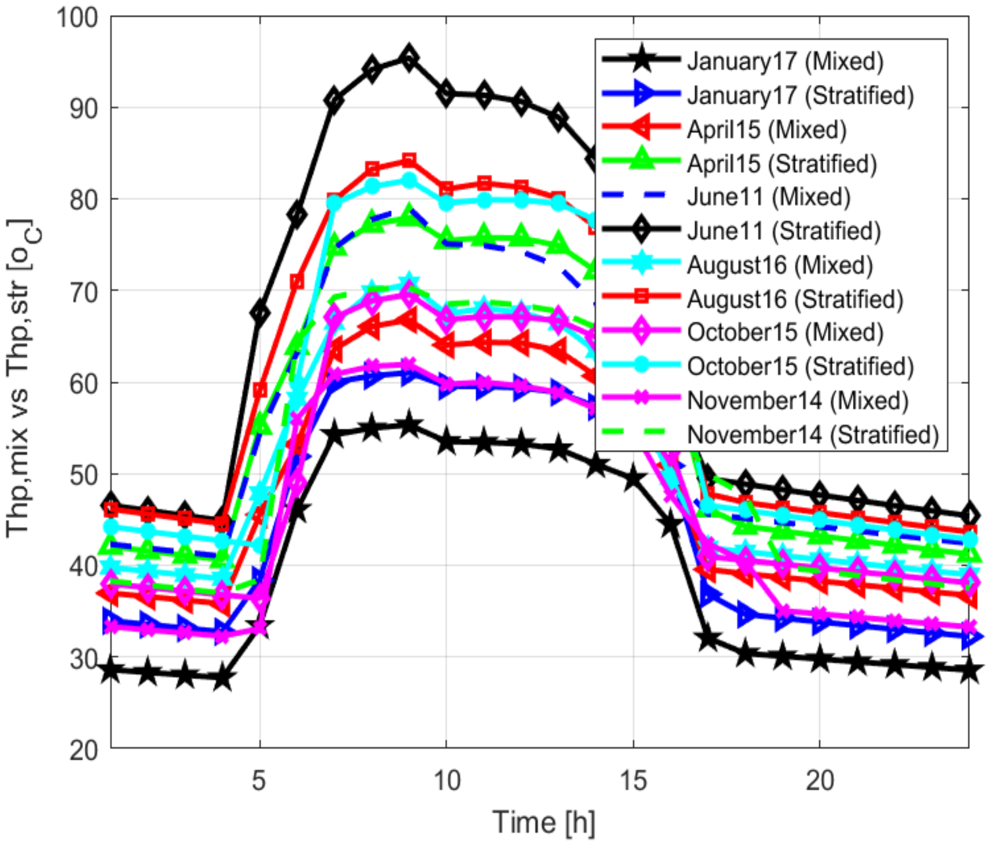


Figure 6. 9 Comparison of water temperature in the second storage for mixed and stratified systems on the representative days of the month

6.1.4 Parametric Analysis

6.1.4.1 Influence of height to diameter (H/D)/ aspect ratio and storage volume

The ratio of height to diameter of the storage in the previous results was 2. Assessing the influence of H/D on the performance of the system by increasing the ratio to 3 gives better performance index of the system since larger storage height promotes better stratification. The greater the temperature difference between the top and bottom temperatures, the better stratification is achieved, so that the efficiency is improved. On the other hand, fraction of the total load carried by solar increased from 24.4% to 24.65% when the storage volume is increased to 0.6 m^3 instead of 0.4 m^3 in which advantage due to stratification also increases with increasing tank volume.

Table 6. 2 Comparison between upper and lower temperatures of different H/D ratios

Water temperatures in the stratified storage (^{0}C)				
	H/D=2		H/D=3	
Selected day	Average temperature of the day			
	June 11	January 17	June 11	January 17
Upper node T.	49.06	33.97	49.8	34.51
Lower node T.	33.79	24.36	32.2	23.64
Difference	15.27	9.61	17.6	10.87

But the increment of H/D ratio and storage size has a negative effect on the cost of the storage and the tank with higher H/D ratio (high outer surface area) increases the annual storage heat loss from 159.58 to 207.31 kWh.

6.1.4.2 Effect of inlet and exit locations on upper node storage temperature.

Applying storage design modifications on the installation of inlet and exit locations is the other influencing factor on the efficiency of the system. It is previously stated that that thermal stratification is more affected by inlet positions than the outlet. Hence, in this parametric study, the flow to the collector and load always leaves from the bottom and top nodes respectively. Considering the quality of the energy to the load is important, the flow returning from the collector will return to the node which is closest to but less than the collector outlet temperature to avoid temperature inversions. The flow input, the back-up water which replace the flow extracted to the load, must be also at lowest possible temperature near the bottom of the tank to provide maximum stratification and maximize collector efficiency.

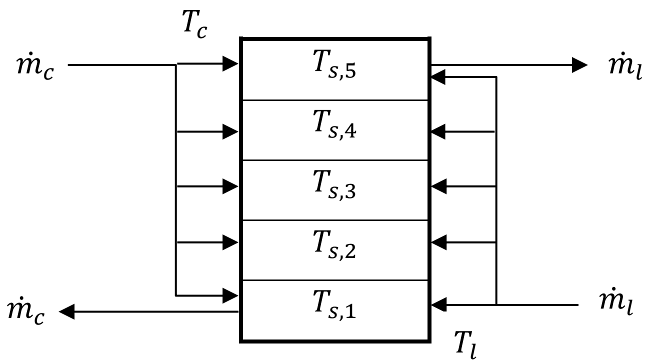


Figure 6. 10 A stratified storage with variable inlets from collector and load.

The quality of the energy to the load, solar fraction, by minimizing the destruction of available energy, has escalated to 78% with good thermodynamic availability. The collector efficiency is also upgraded with 3.67 % since lowest temperature is kept under the bottom of the storage. As shown below, the temperature curves for both fixed and variable inlet conditions have almost identical profile during the time of high solar gain because the flow from the PV/T is hotter than the upper node temperature. However, using variable inlet locations cause complexity of designing and prediction of measured energy input to the storage.

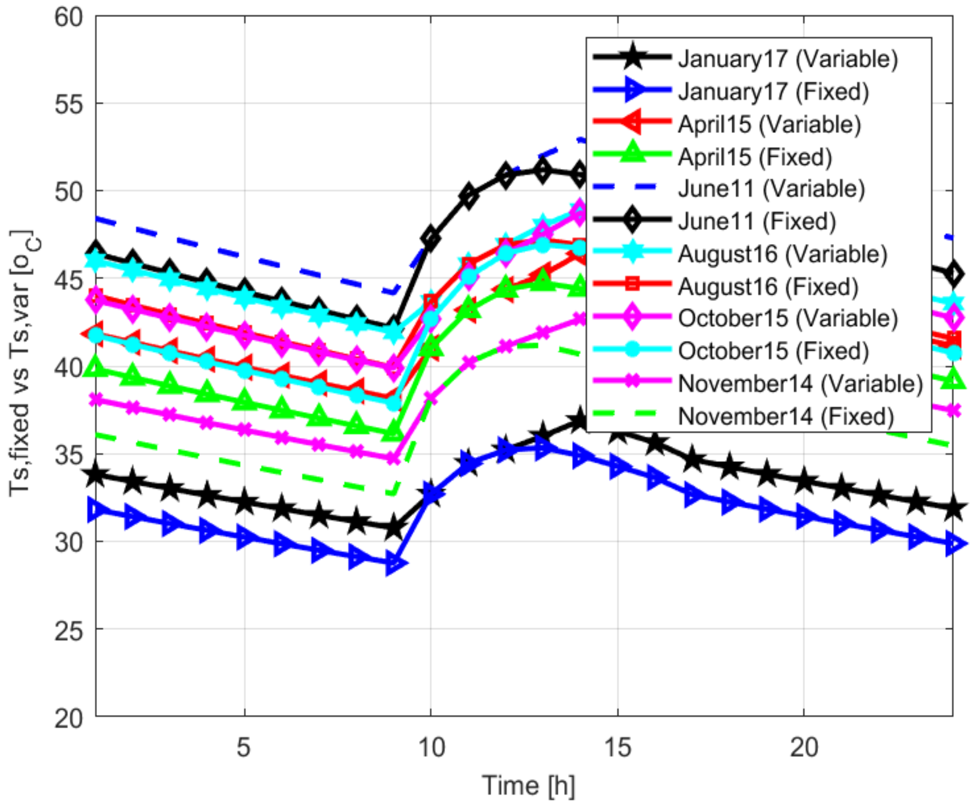


Figure 6. 11 Comparison of stratified storage upper node temperatures with fixed and variable inlet positions.

6.1.4.3 Tank insulation and wall thickness

Small thickness of the storage wall and its insulation affects the performance of the system by increasing heat losses from the side of the storage. These losses are caused by originated buoyancy driven flows which enhance larger downward flow along the storage wall and heat exchange between the nodes. Lowering the wall thickness from 0.05 to 0.03m increases storage loss, 159.58 to 181.3 kWh. Hence, optimization must be done on the storage thickness between economic conditions, insulation, and energy costs.

6.1.4.4 Effect of the collector flow rate and heat removal factor

The influence of water flow rate circulating through the collector is examined by increasing the flow rate to 0.00164 kg/s, keeping the other parameters constant, since this value is used for comparison in existing research. According to the results, the value of solar fraction dropped from 0.73 to 0.7 in which almost 3% of the annual thermal energy that must be delivered to the load is degraded due to higher collector flow rate. The entire performance of the system is also deployed to 79.08%. However, lower collector flow rate allows the hot water to enter and remain in the upper node of the tank which makes the water temperature in the stratified storage closer to the desired load temperature. Thus, lowering the collector loop fluid flow rate in low flow solar thermal systems would significantly enhance thermal stratification in the storage tank and entire performance of the system.

In addition, efficiency increment of the collector in lower collector flow rates is achieved by reducing collector heat removal factor (lower collector thermal losses). Here, the removal factor for the higher flow rate is 0.3699 and 0.3610 for the lower one (0.00138 kg/s). Figure 6.12 shows the decrement of the hot water temperature profile in PV/T upper node storage (maximum temperature has decreased to 50.1^{0}C from 52.2^{0}C) with a collector flow rate of 0.00164 kg/s. Therefore, using low collector flow rates with thermally stratified storage tanks can improve the performance of solar hot water heating, hybrid PV/T and heat pump system.

6.1.4.5 Effect of hot water consumption on system performance

Different patterns of hourly hot water consumption of the end-user for different cases such as a restaurant, motel, and health center (as shown in Figure 6.13) might also affect the efficiency of the system. For the system with mixed storage, the restaurant case has slightly the best performance.

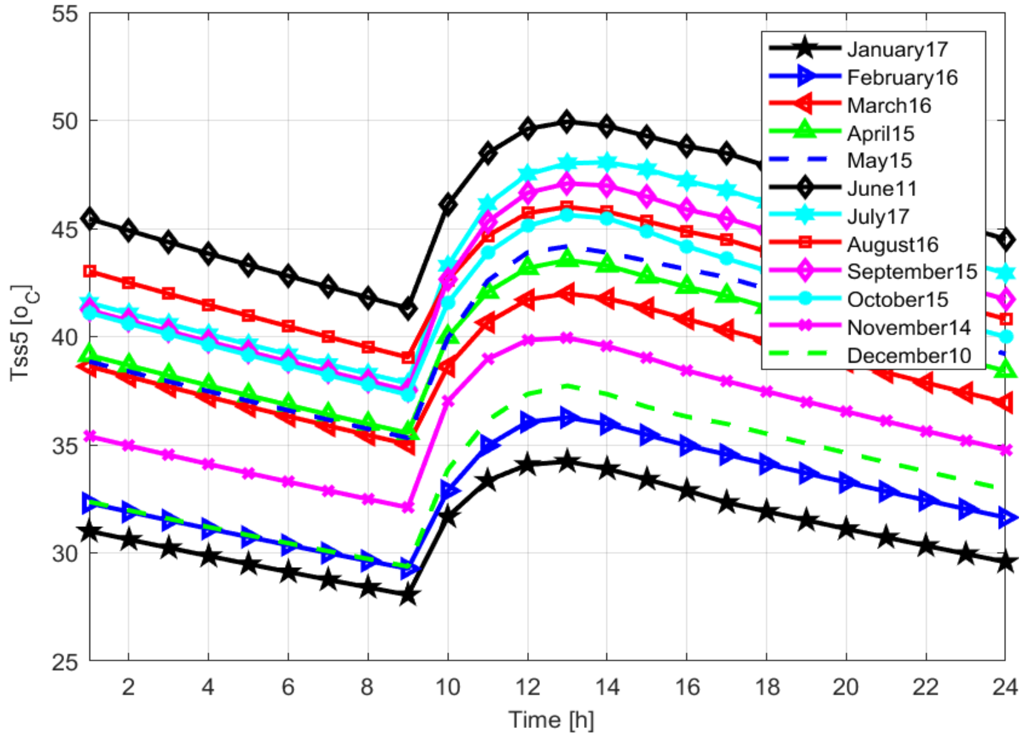


Figure 6. 12 Water temperature in the upper node of the stratified storage at mfw=0.00164 kg/s

The assessment of hourly hot water consumption fraction on a stratified storages on selected days of the year is summarized in the table below. Unlike the system with unstratified storage, the constant pattern of consumption fraction yields better efficiency than restaurant and motel cases.

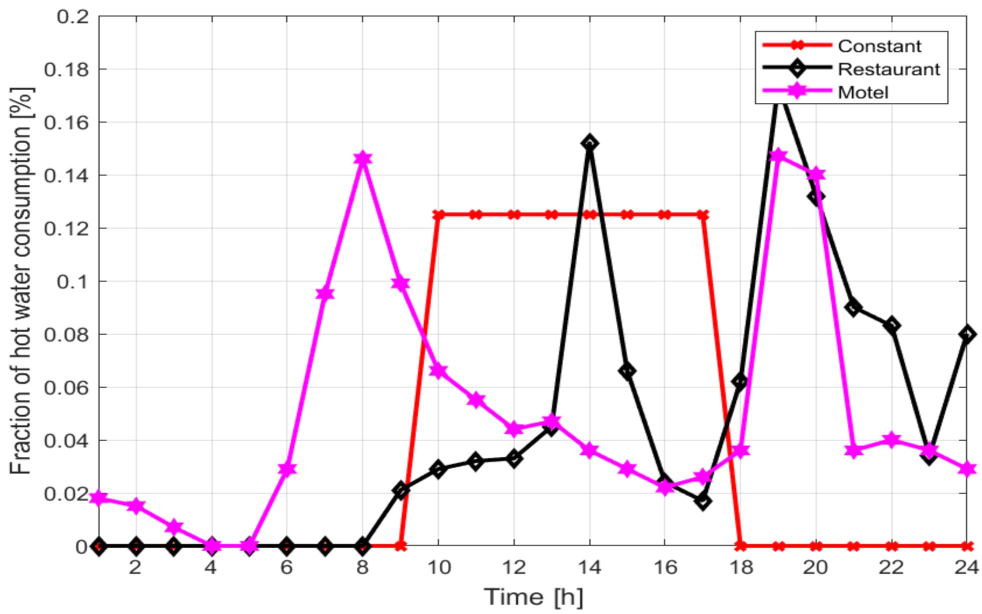


Figure 6. 13 Hot water consumption pattern for three selected cases

Table 6. 3 COP and Hot water temperature values on selected days of the year for three types of hot water consumption fraction patterns

COP of the heat pump						
Fraction	Constant		Restaurant		Motel	
Selected day	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
	June 11	January 17	June 11	January 17	June 11	January 17
Minimum	1.42	0.8	1.59	0.87	1.87	1.01
Maximum	9.33	6.96	9.21	6.94	9.22	6.95
Average	7.15	4.57	6.92	4.44	7.05	4.51
Hot water temperature from heat pump storage (^{0}C)						
Minimum	46.88	32.24	48.49	32.58	48.42	32.53
Maximum	97.37	61.01	96.75	60.82	95.7	60.45
Average	67.35	44.89	68.79	45.43	68.1	45.14

6.2 CFD modelling results

The two-dimensional modelling was done for the mixed and stratified storages separately in CFD physics preference. The non-stratified storage model temperature contour and flow field showed the mixed lower temperatures in the top elements and higher bottom temperatures after 1 hour storing time.

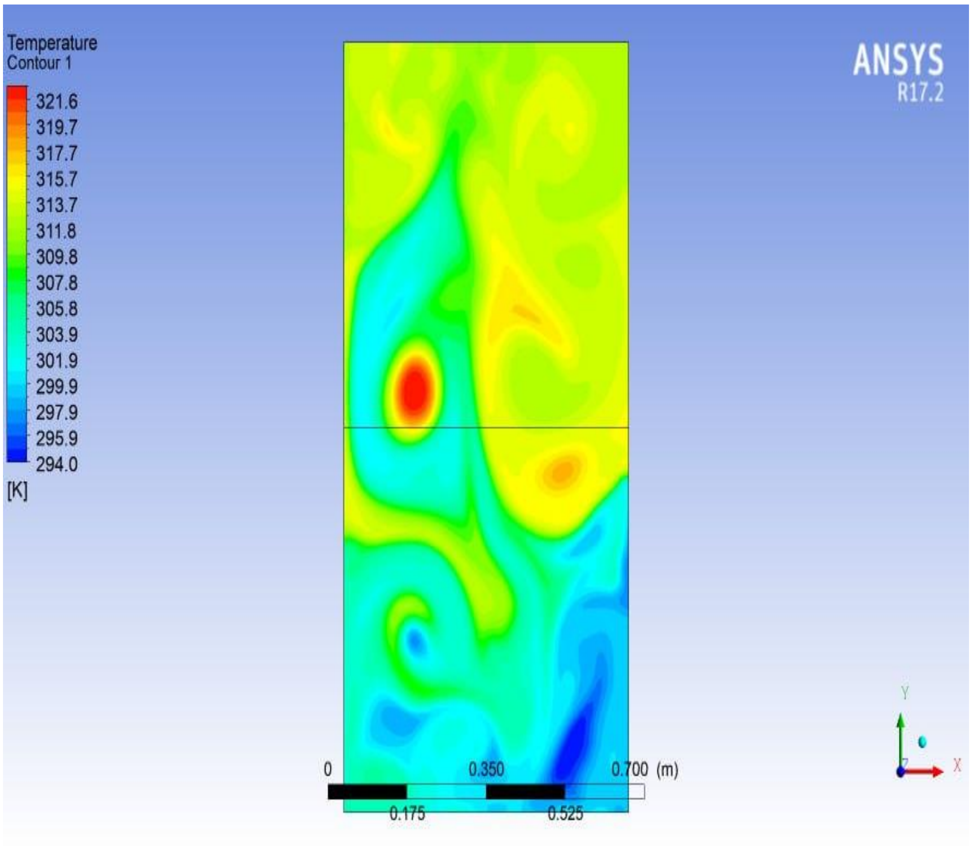


Figure 6. 14 Temperature contour of the mixed storage flow field at t=3600s

Both the temperature contour and profile showed non-determined characteristics of the temporal gradient (Figure 6.14 and 6.15). The thermodynamic quality that must be obtained from the perfectly stratified tank is significantly degraded due to the mixing of hot and cold waters. The top element temperatures are more likely uniform than the lower ones since the mixing occurred formerly in the upper part of the storage tank. In addition, the graphics show how the temperature of the upper part of the tank is disturbed by the cold water at the bottom.

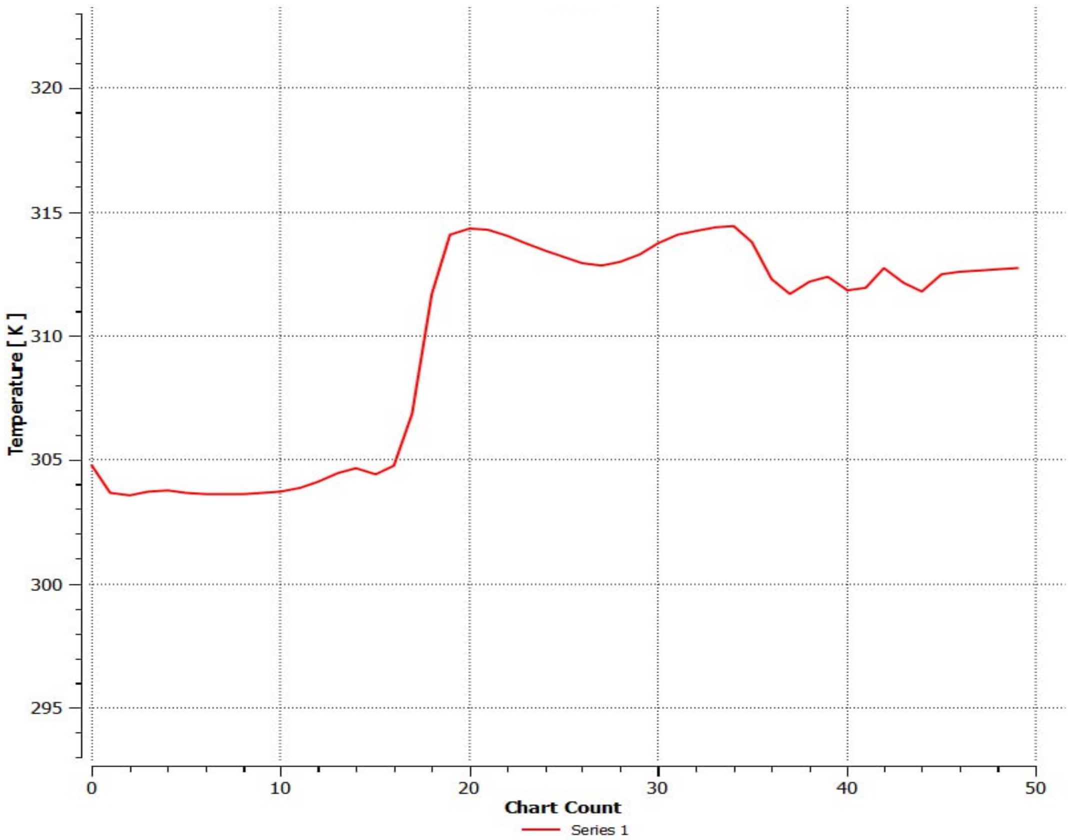


Figure 6. 15 Temperature profile of the mixed storage flow field at t=3600s

For modelling the thermal stratification created inside the storage, initially, an ideal model was created. It was assumed that the tank is perfectly stratified in the first minutes of the simulation. The index of the temperature stratification of the stored water inside the storage can be measured by the thermocline size, the intermediate temperature region.

After the system operation mode of storing continues for 1000s, the thermocline expanded and moves up and down indicating the mixing of water in the middle region. This might indicate a well stratified state of temperature stratification with a moderate level or degree of thermal stratification applied as shown in figure 6.16 and 6.17.

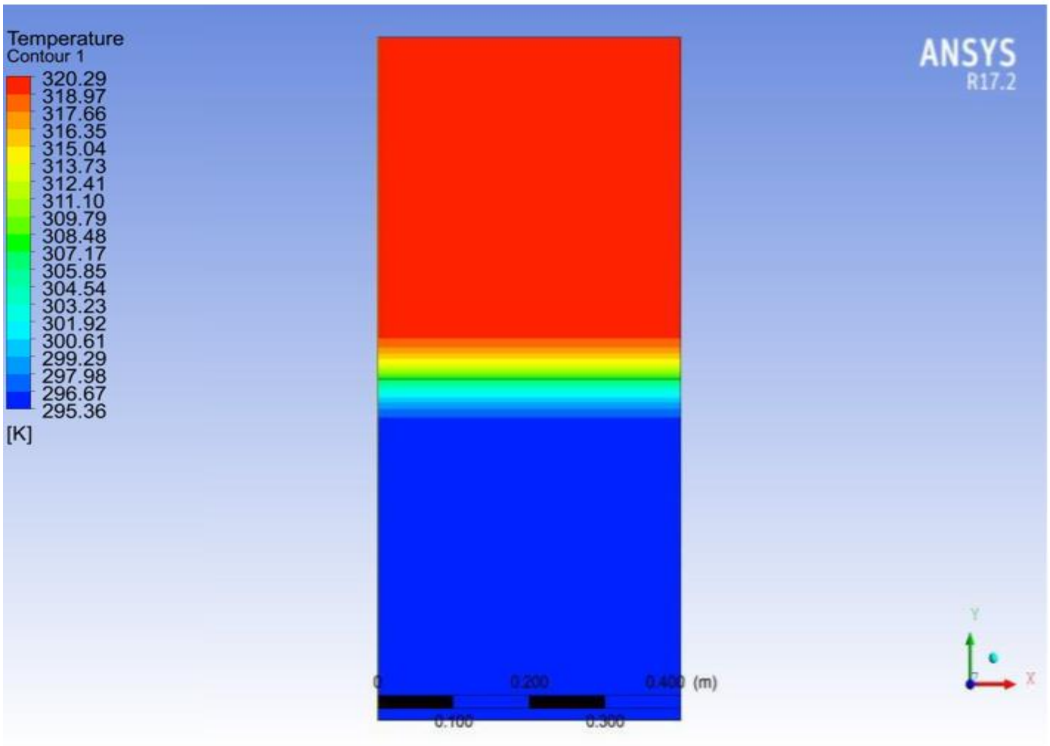


Figure 6. 16 Temperature contour of the stratified storage flow field after 1000s

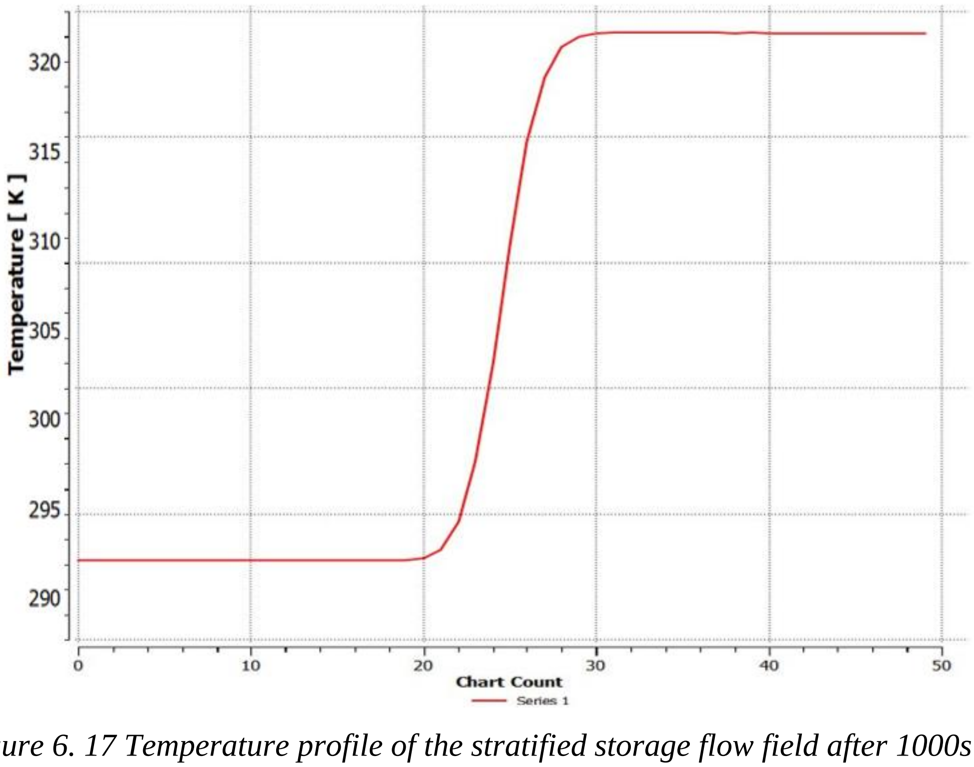


Figure 6. 17 Temperature profile of the stratified storage flow field after 1000s

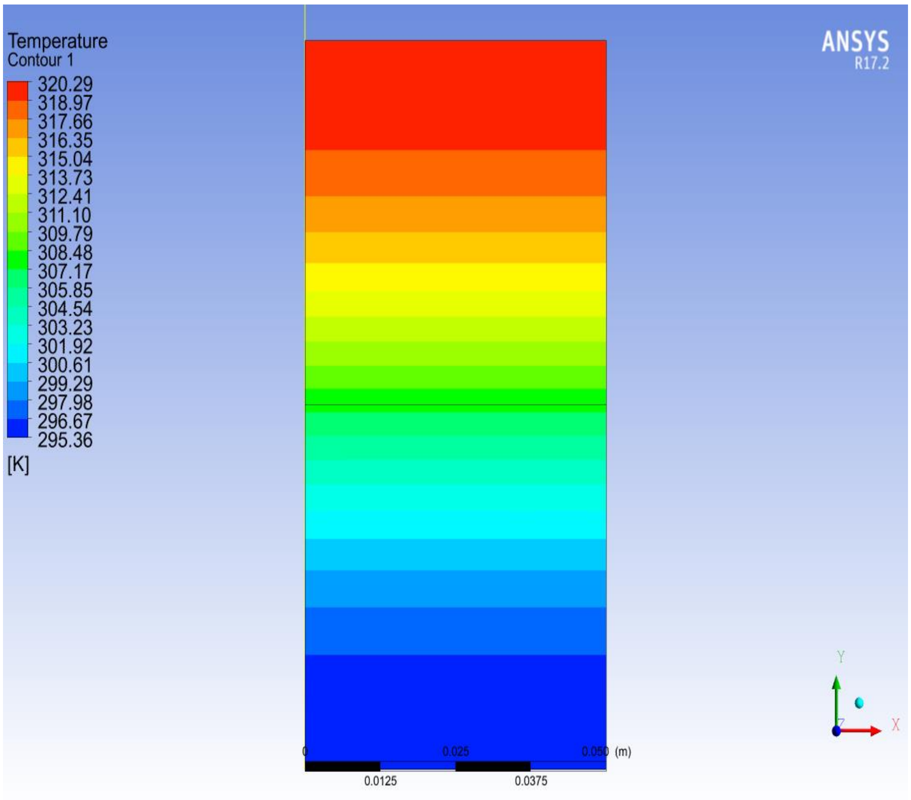


Figure 6. 18 Temperature contour of the stratified storage flow field after 1 hour

After 1 hour of simulation time, more gradient between the temperature layers has been created and the curve of the temperature profile has changed. The middle element temperature curves have been modified from exponential to linear profile.

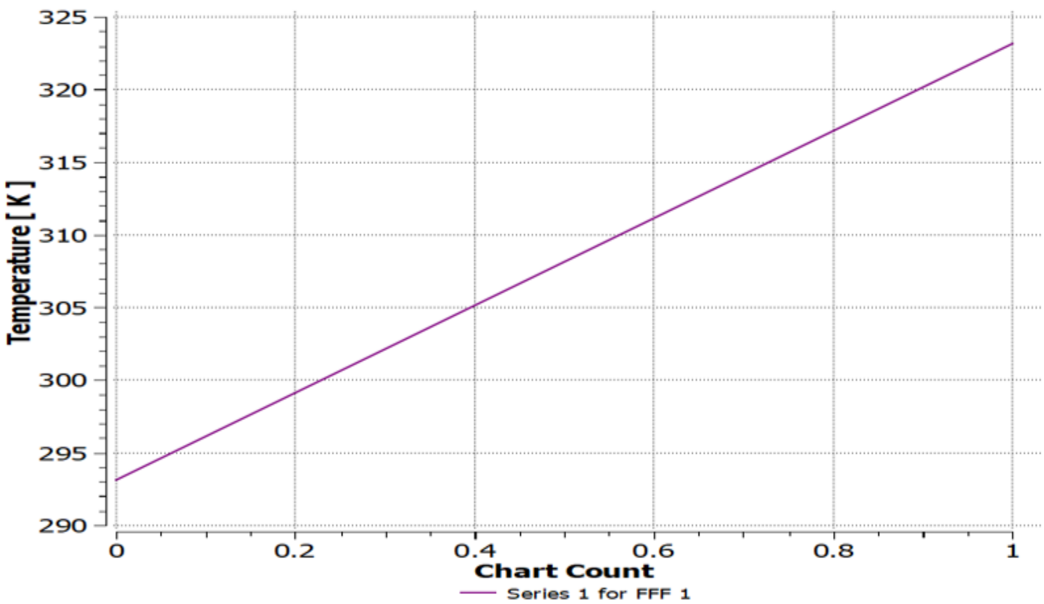


Figure 6. 19 Temperature profile of the stratified storage flow field after 1 hour

Though it requires high computational time, the CFD model was a better method for understanding the thermal phenomena of the hot water storage tank in a hybrid PV/T-heat pump domestic water heating system. In addition, selecting this modelling approach or technique of storage tank is more appropriate for short term simulations. Therefore, CFD simulations can be used as an effective tool to optimize thermal storage tank parameters, thus it may add value for the advancement of the investigation of thermal stratification impact on thermal energy storages and the whole solar thermal system performances.

6.3 Comparison of the proposed models

The major criteria to compare the modelling approaches used for this study, one-dimensional multi-node and two-dimensional CFD models, were physical phenomena applied, result accuracy and computational time.

The main advantage of the 1D model is that it had significant lower computational time than the CFD model. It has also tried to consider physical conditions and processes such as heat losses and node conduction in all days of the year. But this model was not more accurate and precise because many simplifications of the real physical system were considered for avoiding long, non-complex, and non-linear simulations. Therefore, the multi-node model with single dimension had underpredicted the thermal stratification created in the storage tank and given deficient information about the flow inside the storage.

Whereas the CFD model had illustrated more detailed information about the flow motion than the multi-node model. It has also generated more precise temperature profiles with few simplifications in applying boundary conditions like adiabatic wall and no slip conditions. But these had led to the overprediction of the characteristics of thermal stratification. The major drawback of the 2D CFD model was its computing time which increases as the size of the storage increases. It took approximately 48 hours to compete a single simulation calculation and much slower the 1D model. Hence CFD model is imaginary modelling tool for simulating systems with long term applications.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

Effective delivery of thermal energy to end users is the most emerging issue in designing and adopting solar thermal systems. Thermal energy storages (TES) are an integral part of these systems for improving the system efficiency and shifting load in demanding periods of utilization. Optimal usage of storages can be achieved by thermal stratification which inhibit the mixing between temperature layers in the tank.

This thesis investigated the impact of the application of thermally stratified in PV/T assisted heat pump system designed for one of the tropical areas of Ethiopia named Dire Dawa. The solar thermal system was designed to cogenerate both hot water (heat energy) and electrical energy for the end-users. One dimensional multi-node model was applied for the assessment of thermal stratification influence on the existing mixed storage model. The real physical flow phenomena during storing were further studied with CFD model. The two models were also verified with other related experimental study from literature. After the implementation of the thermal stratification principles in the storage, major study findings obtained are concluded in this chapter.

Both the annual and instantaneous transient temperature profiles indicated that the nodal temperatures increase along with the storage height. This helped the load to extract the maximum available heat energy from the upper part of the storage. Stratifying the PV/T storage of the existing PV/T assisted heat pump system elevated the annual solar fraction from 0.49 to 0.73. Hence, the amount of deliverable energy that out of the required load has increased and influenced the performance of the system positively. The thermal efficiency obtained with the previous mixed storage system was 37.9% but, in this study this efficiency increased to 52.73%. This is due to lower PV/T collector inlet temperatures which enhanced useful heat gain and optimized utilization of the collector. Heat gained from the heat pump and COP of the system was also elevated. Following this, the overall annual efficiency of the system was also increased from 63.69% to 79.29% compared to the existing system. The quantity of the heat lost from the storage has degraded significantly because the heat loss due to water mixing was minimized. The lower circulated water temperatures decrease collector heat losses.

On the other hand, increasing the parameters such as H/D (aspect) ratio, storage thickness storage, and insulation has a positive effect on the performance of the thermally stratified storage system. But the increment of collector flowrate degraded the expected performance outcome since the collector heat removal factor was induced. Even though additional simulations were done by differentiating the daily hot water consumption factors, the values of COP and hot water temperatures didn't show considerable change.

Therefore, we can conclude that adopting thermally stratified storage in hybrid PV/T-heat pump water heating and electric generating system improves the annual performance and utilization efficiency of the storage, the PV/T collector, and the entire system. However, thermal stratification in the storage didn't significantly affect the optical and electrical efficiencies of the PV/T.

The CFD models showed how the mixing of stored hot water from the collector and cold water from the mains affect the temperature contours inside the storage and degrade the energy extraction quality. After thermal stratification is applied the temperature gradients were created through the storage and the temporal profiles has changed with increasing storing time.

7.2 Recommendation and Future Work

In line with the above conclusions, the following recommendations are forwarded.

- In addition to the natural thermal stratification application, selecting the best actual stratifying method (diffusers, plates, stratifiers, or baffles) is highly recommended for maintaining stratification in the typical system.
- Testing the applied stratification experimentally would be better to simulate the real phenomena of the system.
- Investigation of level of the applied thermal stratification is highly recommended for optimizing the model based on the calculated index.
- In the one-dimensional multi-node model, more performance analyses such as assessing thermal stratification impact with variable thermo-physical properties, the three operational modes, plume entrainment and inlet jet mixing are recommended.
- For recommending more accurate thermally stratified tank model to the typical system, applying improved quality of CFD model is still needed.

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APPENDIX

Hybrid PV/T- Heat Pump system stratified storage1D simulation MATLAB program

```
%%% Photovoltaic Thermal assisted Heat Pump System MATLAB Program
%%% Annual simulation of one-dimensional stratified storage tank
%%% Mixed storage vs multi-node model
clc
clear all
%%% Input variables in the simulation
Ac=1.64; % Collector module area (m2)
Vs=0.4; % Volume of Storage for PV/T per one module (m3)
Vsh=0.2; % Volume of Storage for Heat pump per one module (m3)
DWC=0.4; % Daily hot water consumption per module area (m3)
d=nthroot((2*Vs/3.14),3); % Diameter of the PV/T storage (m)
dh=nthroot((2*Vsh/3.14),3);% Diameter of the Heat pump storage (m)
r=d/2;% Radius of the storage PV/T (m)
rh=dh/2;% Radius of the storage Heat pump (m)
H=2*d; % Height of PV/T storage (m)
Hh=2*dh; % Height of Heat pump storage (m)
As=(3.1416*d^2)+(3.1416*d*H); %Total Area of the PV/T storage (m2)
Ash=(3.1416*dh^2)+(3.1416*dh*Hh); %Total Area of the Heat pump storage (m2)
N=5; % No of nodes of the PV/T storage
k=1:N; % Range of node numbers of the PV/T storage
delh1=H/N; % Height of a single control volume within the PV/T tank (unit height of the
storage delAs1= 2*3.1416*r*delh1; % Unit area of PV/T storage (Area of the wall of the
control volume(Aca1= 3.1416*r^2; % Contact area between the layers of the PV/T storage
(m2)
delV1=3.1416*delh1*r^2; % Unit volume of the PV/T storage (m3)
ff=[0,0,0,0,0,0,0,0,0.125,0.125,0.125,0.125,0.125,0.125,0.125,0.125,0,0,0,0,0,0,0];
%Constant
%ff=[0,0,0,0,0,0,0,0,0.021,0.029,0.032,0.033,0.045,0.152,0.066,0.024,0.017,0.062,0.174,0.1
32,0.09,0.083,0.034,0.08];%%ff=[0.018,0.015,0.007,0,0,0.029,0.095,0.146,0.099,0.066,0.055,
0.044,0.047,0.036,0.029,0.022,0.026,0.036,0.147,0.14,0.036,0.04,0.036mfw=0.00138; % mass
flow rate of water from and to the collector
% mfw=0.00164; % mass flow rate of water from and to the collector
mdot=mfw;
Rhow=998; % Constant density of water (kg/m3)
Rhoa=1.226;% Constant density of air (kg/m3)
P=5.284; % Perimeter of the collector (m)
de=0.05; % Depth of the edge of the collector (m)
Al=P*de; % Collector side area (m2)
do=0.015; % Outer dimeter of the pipe (m)
di=0.013; % Inner dimeter of the pipe (m)
w=0.088; % Center to center distance b/n tubes (m)
Ap=0.78; % Absorbing area of the PV module from one square area (m2)
no=10; % Number of risers
Lr=16; % Length of the Pipe (m)
tpv=0.3; % Thickness of the pv module (m)
ti=0.05; % Storage thickness (m)
tei=0.025; % Edge insulation thickness (m)
tab=0.0035; % Absorber thickness (m)
eg=0.88; % Emissivity of the glass (m2.J/s)
Gtg=0.9; % Transmissivity of glass (l/m)
Trpv=0.1; % Transmissivity of the PV module (l/m)
epv=0.83; % Emissivity of the PV module (m2.J/s)
apv=0.9; % Absorptivity of PV module (l/mole.m)
tapv=0.87; % Difference b/n Absorptivity and Transmissivity of module (l/m)
eef=((1/epv)+(1/eg)-1)^-1; % Effective emissivity of PV and Glass (m2.J/s)
pf=0.88; % Packing Factor
```

```
Tfp=0.92; % Temperature coefficent of PV module
Nepv=0.163; % Nominal efficiency of PV module
Trf=25; % Reference Temperature (oC)
ka=0.026; % Thermal conductivity of air (W/mK)
kw=0.625; % Thermal conductivity of water (W/mK)
kp=0.156; % Thermal conductivity of PV (W/mK)
kab=54; % Thermal conductivity of absorber (W/mK)
kg=0.93; % Thermal Conductivity of glass (W/mK)
ki=0.045; % Thermal conductivity of insulation (W/mK)
rho=0.2; % Ground reflection
spg=0.05; % Distance between glass and PV module (m)
cg=836; % Specific heat of the glass (J/Kg.K)
Ca=1.005; % Specific heat capacity of air (J/Kg.K)
cw=4186; % Specific heat of water (J/Kg.K)
cp=677; % Specific heat of the PV (J/Kg.K)
ci=670; % Specific heat of the insulation (J/Kg.K)
ca=385; % Specific heat of the absorber plate (J/Kg.K)
mg=11.7; % Mass of glass (Kg)
mp=9.47; % Mass of PV; (Kg)
ma=10.62; % Mass of absorber and tube (Kg)
mw=1.32; % Mass of water in the collector module meter square area (Kg)
mic=1; % Mass of the collector insulation (Kg)
mis=0.2908; % Mass of the storage insulation (Kg)
mcpw=mw*cw; % Mass*Cp of water in the collector (J/K)
mcpp=mp*cp; % Mass*Cp of the PV module (J/K)
mcpc=ma*ca; % Mass*Cp of the absorber (J/K)
mcpg=mg*cg; % Mass*Cp of the glass (J/K)
ms=Rhow*Vs; % Mass of the water in the PV/T storage (Kg)
delms=ms/N; % Unit mass of water in a node of the PV/T storage (Kg)
mcps=Rhow*Vs*cw; % Mass*Cp of the water in the PV/T storage (J/K)
mcpss=Rhow*delV1*cw;
mcpi=mic*ci; % Mass*Cp of the collector insulation (J/K)
Vw=3; % Wind speed (m/s)
beta=pi/18; % Collector slope
phi=9.7*pi/180; % Latitude of the site
pr=4.772; % Prandtl number for water
pra=0.72; % Prandtl number for air
Re=733; % Reynolds number
dvi=1.81e-5; % Dynamic viscosity of air (N.s/m2)
kvis=dvi/Rhoa;% Kinematic viscocity of air (m2/s)
sigma=5.67e-8; % Boltzmann constant (m2kg/s2.K)
vis=pr*sigma; % Viscosity
deltt=7.5; % Time step for the simulation (s)
Aat=pi*do*Lr/2; % Contact area b/n pipe and absorber (m2)
Aai=Ac; % Contact area b/n absorber and insulation (m2)
Ati=pi*di*Lr; % Internal surface area of the pipe (m2)
Act=pi*di^2/4; % Cross-sectional area of the tube (m2)
Vdot=mfw/1000; % Volumetric flow rate of water (m3/s)
%%% Initialization of parameters
Tai=20; % Initial temperature of the atmosphere (oC)
TIQsolar=0; % Initialization of solar radiation (W/m2)
TQucl=0; % Initialization of collected heat gain of the mixed storage system (J)
TsQucl=0; % Initialization of collected heat gain of the stratified storage system (J)
TQstorage=0; % Initialization of heat delivered to the load from storage1 of the mixed
storage FQstorage=0; % Initialization of maximum heat that can be delivered to the load of
the mixed TsQstorage=0; % Initialization of heat delivered to the load from st.storage1 of
the stratified FsQstorage=0; % Initialization of maximum heat that can be delivered to the
load of the stratified TQuseful=0; % Initialization of useful energy of the mixed storage
system (W)
TQuseful1=0; % Initialization of useful energy of the mixed storage system (W)
TsQuseful=0; % Initialization of useful energy of the stratified storage system (W)
```

```
TsQuseful1=0; % Initialization of useful energy of the stratified storage system (W)
Qwuhp=0; % Initialization of heat delivered to the load by the heat pump
Qswuhp=0; % Initialization of heat delivered to the load by the heat pump
TElec=0;
TsElec=0; % Initialization of electrical energy gain from PV of the stratified storage
TQcloss=0; % Initialization of heat loss from collector of the mixed storage system (W)
TsQcloss=0; % Initialization of heat loss from collector of the stratified storage system
TQloss=0; % Initialization of heat loss from the PV/T storage (W)
TsQloss=0; % Initialization of heat loss from PV/T storage of the stratified system (W)
PHp=0; % Initialization of power from the heat pump of the mixed storage system (W)
PsHp=0; % Initialization of power from the heat pump of the stratified storage system(W)
Thp2=40; % Initialization of Temperature of water from the heat pump storage of the mixed
Tshp2=40; % Initialization of Temperature of water from the heat pump storage of the
Thp2i=Thp2; % Initialization of water temperature from the heat pump of the mixed storage
Tshp2i=Tshp2; % Initialization of water temperature from the heat pump of the stratified
%%% Data Analyzing and simulation
open=('FinalRN.xlsx');
Z=xlsread(open);
for j=1:365 % Days in the year
data1(:,:,j)=Z(j+(23*(j-1)):j*24,:); % Data formulation for 24 hours of each day for day
end
for n=1:365
decl(n)=(pi/180)*(23.45*sin((2*pi/365)*(284+n))); % Calculation of the declination angle
end
for ii=1:24 % Number of hours in a day
omega(ii)=(ii-12)*pi/12; % Calculation of the hour angle for each hour of the day. )))
end
for i=1
Grr=data1(:,1,i); % Global radiation data
Drr=data1(:,2,i); % Diffused radiation data
Taa=data1(:,3,i); % Ambient temperature data
for j=1
Gr=Grr(1);
Dr=Drr(1);
T=Taa(1);
Ta=T; % Initial ambient temperature
Tpi=T+3; % Initial temperature of the PV of mixed storage system
Tspi=T+3; % Initial temperature of the PV
Tgi=T+2; % Initial temperature of the glass of mixed storage system
Tsgi=T+2; % Initial temperature of the glass
Tci=T+2.5; % Initial temperature of the absorber of mixed storage system
Tsci=T+2.5; % Initial temperature of the absorber of stratified storage system
Tsky=Ta; % Initial temperature of mixed storage system
Twi=Ta+2; % Initial temperature of the water into the collector of mixed mstorage system
Tswi=Ta+2; % Initial temperature of the water into the collector of stratified storage
Two=Twi+2; % Initial temperature of the water out of the collector of mixed storage system
Tswo=Tswi+2; % Initial temperature of the water out of the collector of stratified storage
Tsi=Twi+15; % Initial temperature of the water in the storage of mixed storage system
Tssi=Tswi+15; % Initial temperature of the water in the storage of stratified storage
Twba=Ta; % Initial temperature of the backup water
Rb=((cos(phi-beta))*cos(decl(i))*cos(omega(j))+sin(decl(i))*(sin(phi-
beta)))/(cos(phi)*cos(decl(i))*cos(omega(j))+(sin(decl(i))*sin(phi)));
In=Rb*(Gr-Dr)+(Dr*0.5*(1+cos(beta)))+(0.5*rho*((1-cos(beta))*Gr));
Ic=In*apv; % Solar energy arrived in the module transmitted through the glass and absorbed
by Tf=(Tai+T)/2; % Film Temperature
Ve=2/(Tai+T); % Volume expansion coefficient
Gr=(9.81*Ve*(Tpi-Tgi)*spg^3)/kvis^2; % Grashoff number
Nu=2.5+0.0133*(90-beta); % Nusselt number based on the above Grashoff value
hc2=Nu*ka/spg; %Convection heat transfer b/n Glass and PV
Ub=ki/ti ; % Bottom heat transfer coefficient
Ue=Ub*(Al/Ac); % Edge heat Transfer coefficient
```

```
hc1=2.8+3*Vw; % Convective heat transfer coefficient at the top of the glass
hr1=eg*sigma*((Tgi^4-Tsky^4)/(Tgi-Ta)); % Radiation heat transfer b/n glass and PV module
hr2=eef*sigma*((Tpi^4-Tgi^4)/(Tpi-Tgi));% Radiation b/n PV and Glass
Ut=((1/(hc2+hr2))+(1/(hc1+hr1)))^-1; % Top heat loss
Ul=Ut+Ub+Ue; % Overall heat transfer coefficient
Uls=ki/ti; % Storage insulation loss (W/m2K)
hf=4.364*kw/di; % Heat Transfer coefficient inside the tube for natural convection
hap=kp/tpv; % Heat Transfer between PV and Absorber
hia=Ub; % Bottom heat loss
Tpm = 30 + 0.0175.*(Ic-150) + 1.14*(Ta -25); % Initial Temperature of the PV module
E=Ic*tapv.*pf.*Nepv*((1-Tfp).*(Tpm-Trf)); % Electrical energy generation
a12=hc1+hr1;
a13=hc2+hr2;
a11=a12+a13;
b11=hap;
b12=a13+b11+12;
m=(Ul/(kp*tpv))^1/2; % Constant value for fin efficiency
fe=tanh(m*((w-do)/2))/(m*((w-do)/2)); % Fin efficiency of the collector
Fw=fe*2-1;
de=0.035;
zzz=1/Ul;
zz=1/(Ul*(de+(w-de)*fe));
cb=150; % Bond conductance based on Duffie recommendation is always more than 30
zx=1/cb;
zc=1/(pi*di*hf);
Upw=zzz/(w*(zz+zx+zz)); % Collector efficiency factor
c11=Ac*b11+Upw*Ati*Fw+Aai*hia*fe;
c12=Upw*Ati/2;
c13=Aai*hia*fe;
d11=(Ati*Upw*Fw*12);
d12=(((Ati*Upw)/2)+mdot*cw);
d13=(Ati*Upw)-(mdot*cw);
e11=mdot*cw;
e12=mdot*cw+Rhow*DWC*ff(j)*cw+Uls*As;
e13=Rhow*DWC*ff(j)*cw;
e14=Uls*As;
%%% Mixed storage temperatures
Tg1=Tgi+(deltt/mcpg)*Ac*((Ic*(1-Gtg))-a11*Tgi+a12*Ta+a13*Tpi); % Glass temperature
Tp1=Tpi+((deltt/mcpp)*Ac*(Ic-E+a13*Tg1-b12*Tpi+Tci*b11)); % PV temperature
Tc1=Tci+((deltt/mcpc*fe)*((b11*Tp1)-(c11*Tci)+(c12*Two)+(c12*Twi)+(c13*Ta))); % Absorber T
Tw1=Two+(deltt/mcpw)*((d11*Tc1)-(d12*Two)-(d13*Twi)); % Water temperature
Ts1=Tsi+((deltt/mcps)*(e11*Tw1-e12*Tsi+e13*Twba-e14*Ta));
%%% Stratified storage system temperatures
Tsg1=Tsgi+((deltt/mcpg)*Ac)*((In*(1-Gtg))-(a11*Tsgi)+(a12*Ta)+(a13*Tspi)); %Glass
Tsp1=Tspi+((deltt/mcpp)*Ac*(Ic-E+a13*Tg1-b12*Tspi+Tsci*b11));
Tsc1=Tsci+((deltt/mcpc)*((b11*Tsp1)-(c11*Tsci)+(c12*Tswo)+(c12*Tswi)+(c13*Ta)));
Tsw1=Tswo+(deltt/mcpw)*((d11*Tsc1)-(d12*Tswo)-(d13*Tswi));
%%% Generating matrix coefficients for the lower node (1)
%%% Since this node is the first node, the term A(k,k-1) is omitted.
Ti5=Tssi; % Initial temperature of water in node5
Ti4=Ti5-1; % Initial temperature of water in node4
Ti3=Ti4-1; % Initial temperature of water in node3
Ti2=Ti3-1; % Initial temperature of water in node2
Ti1=Ti2-1; % Initial temperature of water in node1
ml=Rhow*ff(j)*DWC; % mass flow rate of water from the mains and to the load
mk1=ml-mfw;
mk2=mfw-ml;
f11=delms*cw/deltt;
f12=mfw*cw;
f13=mk1*cw;
f14=kw*Aca1/delh1;
```

```
f15=Uls*delAs1;
f16=ml*cw*Twba;
f17=Uls*delAs1*Ta;
f115=Uls*(delAs1+pi*(d^2)/4);
f116=mfw*cw*Tsw1;
f117=Uls*(delAs1+pi*(d^2)/4)*Ta;
f118=mk2*cw;
f119=ml*cw;
k=1;
A(k,k)= f11+f12+f13+f14+f15;
A(k,k+1)=-f14;
C(k,k)=(Ti1*f11)+f16+f17;
%%% Generating matrix coefficients for node 2 up to node 4
k=2;
A(k,k-1)=-f14-f12;
A(k,k)= f11+f12+(2*f14)+f15;
A(k,k+1)=-f14;
C(k,k)=(Ti2*f11)+f17;
k=3;
A(k,k-1)=-f14-f12;
A(k,k)= f11+f12+(2*f14)+f15;
A(k,k+1)=-f14;
C(k,k)=(Ti3*f11)+f17;
k=4;
A(k,k-1)=-f14-f12;
A(k,k)= f11+f12+(2*f14)+f15;
A(k,k+1)=-f14;
C(k,k)=(Ti4*f11)+f17;
%%% Generating matrix coefficients for the upper node
%%% Since this node is the last node, the term A(k,k+1) is omitted.
k=5;
A(k,k-1)=-f14-f118;
A(k,k)= f11+f119+f14+f115;
C(k,k)=(Ti5*f11)+f116+f117;
Tss=A\C;
Tss1=Tss(1,1); % Water temperature in node1 at initial Time
Tss2=Tss(2,2); % Water temperature in node2 at initial Time
Tss3=Tss(3,3); % Water temperature in node3 at initial Time
Tss4=Tss(4,4); % Water temperature in node4 at initial Time
Tss5=Tss(5,5); % Water temperature in node5 at initial Time
end
end
% Main Program
for i=1:365
Grr=data1(:,1,i);
Drr=data1(:,2,i);
Taa=data1(:,3,i);
T=Taa(1);
for j=1:24
Gr=Grr(j);
Dr=Drr(j);
Tamb=Taa(j);
Ta=T;
Rb=((cos(phi-beta))*cos(decl(i))*cos(omega(j))+sin(decl(i))*(sin(phi-
beta)))/(cos(phi)*cos(decl(i))*cos(omega(j))+(sin(decl(i))*sin(phi)));
if Rb<0
Rb=0.5;
end
In=Rb*(Gr-Dr)+(Dr*0.5*(1+cos(beta)))+(0.5*rho*((1-cos(beta))*Gr));
Ic=In*apv*Gtg;
if Ic<0
```

```
Ic=0;
end
TIQsolar=TIQsolar+In/1000;
for jj=1:480
Tf=(Tai+Ta)/2;
Ve=2/(Tai+Ta);
Tsky=Ta;
Twba=T+2;
Gr=(9.81*Ve*(Tp1-Tg1)*spg^3)/kvis^2;
Nu=2.5+0.0133*(90-beta);
hc2=Nu*ka/spg;
Ub=ki/ti;
Ue=Ub*(Al/Ac);
hc1=2.8+3*Vw;
hr1=eg*sigma*((Tg1^4-Tsky^4)/(Tg1-Ta));
hr2=eef*sigma*((Tp1^4-Tgi^4)/(Tp1-Tg1));
Ut=((1/(hc2+hr2))+(1/(hc1+hr1)))^-1; %
Ul=Ut+Ub+Ue;
Uls=ki/ti;
hf=4.364*kw/di;
hia=Ub;
Tpm = 30 + 0.0175.*(Ic-150) + 1.14*(Ta -25); %Initial Temperature of the PV module
a12=(hc1+hr1);
a13=(hc2+hr2);
a11=(a12+a13);
b11=hap;
b12=a13+b11+10;
m=(Ul/(kp*tpv))^1/2; %Constant value for fin efficiency
fe=tanh(m*((w-do)/2))/(m*((w-do)/2)); %fin efficiency of the collector
Fw=fe*2-1;
de=0.035;
zzz=1/Ul;
zz=1/(Ul*(de+(w-de)*fe));
cb=150;
zx=1/cb;
zc=1/(pi*di*hf);
Upw=zzz/(w*(zz+zx+zz));
c11=(Ac*b11*0.01+Upw*Ati*Fw+Ac*hia*fe);
c12=Upw*Ati/2;
c13=Aai*hia*fe;
d11=(Ati*Upw*Fw*9);
d12=((Ati*Upw)/2)+(mdot*cw);
d13=((Ati*Upw)/2)-(mdot*cw);
%%% Mixed Storage
e11=mdot*cw;
e12=mdot*cw+(Rhow*DWC*ff(j)*0.65*(deltt/3600)*cw)+Uls*As;
e13=Rhow*DWC*ff(j)*(deltt/3600)*cw;
e14=Uls*As;
e15=Ac*Ul*Upw;
yy1=e11/e15;
yy2=e15/e11;
Cff=yy1*(1-exp(-yy2)); %Collector flow factor
Fr=Cff*Upw; %Collector heat removal factor
%%% Non-stratified (mixed storage) system temperatures
Tg1=Tgi+((deltt/mcpg)*Ac)*((In*(1-Gtg))-(a11*Tgi)+(a12*Ta)+(a13*Tpi));
Tp1=Tpi+((deltt/mcpp)*Ac*(Ic-E+a13*Tg1-b12*Tpi+Tci*b11));
Tc1=Tci+((deltt/mcpc)*((b11*Tp1)-(c11*Tci)+(c12*Two)+(c12*Twi)+(c13*Ta)));
Tw1=Two+(deltt/mcpw)*((d11*Tc1)-(d12*Two)-(d13*Twi));
E=Ac*Ic*tapv*pf*Nepv*((1-0.0045*(Tp1-Trf)));
if E<0
E=0;
```

```
end
Eff=tapv.*pf.*Nepv.*((1-0.0045.*(Tpm-25)));
TElec=TElec+E*deltt/3600000;
Qu=Ac*(Upw*(Ic*(apv*Gtg)-Ul*(Tp1-Ta)));
if Qu<0.1
Qu=0;
mdot=0;
else
mdot=mfw;
end
if jj>18
mdot=0;
else if jj<6;
mdot=0;
end
end
TQucl=TQucl+Qu*deltt/3600000;
Aload=(Rhow*cw*DWC*ff(j)*(Tsi-Twba))*deltt; %water to the end user
TQstorage=TQstorage+Aload/3600000;
Fload=(Rhow*cw*DWC*ff(j)*(50-Twba))*deltt; %water required by the load
FQstorage=FQstorage+Fload/3600000;
A12=Uls*As*(Tsi-Ta)*deltt; %Heat loss in the PV/T storage
TQloss=TQloss+A12/3600000;
A13=Ac*Ul*(Twi-Ta)*deltt; %Heat loss from the collector
TQcloss=TQcloss+A13/3600000;
if Qu<0.0
Qu=0;
mdot=0;
else
mdot=mfw;
end
A11=(Ac*mdot*cw*(Tw1-Twi)); %Useful heat gain from the collector
if A11<0
A11=0;
end
Ath=Ac*(Ic-(Ul*(Twi-Ta))); %Theoretical useful heat gain
AHW= Ac*Fr*(Ic-(Ul*(Twi-Ta))); %Useful heat gain using Hottel-Whillier equations
if AHW<0
AHW=0;
end
TQuseful=TQuseful+A11*deltt/3600000;
TQuseful1=TQuseful1+AHW*deltt/3600000;
%%% Non-stratified storage temperature
Ts1=Tsi+((deltt/mcps)*(e11*Tw1-e12*Tsi+e13*Twba-e14*Ta));
%%% Stratified storage system temperatures
Tsg1=Tsgi+((deltt/mcpg)*Ac)*((In*(1-Gtg))-(a11*Tsgi)+(a12*Ta)+(a13*Tspi));
Tsp1=Tspi+((deltt/mcpp)*Ac*(Ic-E+a13*Tsg1-b12*Tspi+Tsci*b11));
Tsc1=Tsci+((deltt/mcpc)*((b11*Tsp1)-(c11*Tsci)+(c12*Tswo)+(c12*Tswi)+(c13*Ta)));
Tsw1=Tswo+(deltt/mcpw)*((d11*Tsc1)-(d12*Tswo)-(d13*Tswi));
Es=Ac*Ic*tapv*pf*Nepv*((1-0.0045*(Tsp1-Trf)));
if Es<0
Es=0;
end
Eff=tapv.*pf.*Nepv.*((1-0.0045.*(Tpm-25)));
TsElec=TsElec+Es*deltt/3600000;
Qsu=Ac*(Upw*(Ic*(apv*Gtg)-Ul*(Tsp1-Ta)));
if Qsu<0.1
Qsu=0;
mdot=0;
else
mdot=mfw;
```

```
end
if jj>18
mdot=0;
else if jj<6;
mdot=0;
end
end
%%% Amount of heat to the load and heat loss from stratified storage tank
TsQucl=TsQucl+Qsu*deltt/3600000;
Asload=(Rhow*cw*DWC*ff(j)*(Tssi-Twba))*deltt;
TsQstorage=TsQstorage+Asload/3600000;
Fsload=(Rhow*cw*DWC*ff(j)*(50-Twba))*deltt;
FsQstorage=FsQstorage+Fsload/3600000;
As12=Uls*delAs1*((Ti1-Ta)+(Ti2-Ta)+(Ti3-Ta)+(Ti4-Ta)+(Ti5-Ta))*deltt; %Heat loss in each
node
TsQloss=TsQloss+As12/3600000;
As13=Ac*Ul*(Tswi-Ta)*deltt;
TsQcloss=TsQcloss+As13/3600000;
if Qsu<0.0
Qsu=0;
mdot=0;
else
mdot=mfw;
end
As11=(Ac*mdot*cw*(Tsw1-Tswi));
if As11<0
As11=0;
end
Asth=Ac*(Ic-(Ul*(Tswi-Ta)));
AsHW= Ac*Fr*(Ic-Ul*(Tswi-Ta));
if AsHW<0
AsHW=0;
end
TsQuseful=TsQuseful+As11*deltt/3600000;
TsQuseful1=TsQuseful1+AsHW*deltt/3600000;
ml=Rhow*ff(j)*DWC*(deltt/3600);
mk1=ml-mfw;
mk2=mfw-ml;
f11=delms*cw/deltt;
f12=mfw*cw;
f13=mk1*cw;
f14=kw*Aca1/delh1;
f15=Uls*delAs1;
f16=ml*cw*Twba;
f17=Uls*delAs1*Ta;
f115=Uls*(delAs1+pi*(d^2)/4);
f117=Uls*(delAs1+pi*(d^2)/4)*Ta;
f116=mfw*cw*Tsw1;
f118=mk2*cw;
f119=ml*cw;
fi1=Ti1*f11;
fi2=Ti2*f11;
fi3=Ti3*f11;
fi4=Ti4*f11;
fi5=Ti5*f11;
k=1;
A(k,k)= f11+f12+f13+f14+f15;
A(k,k+1)=-f14;
C(k,k)=fi1+f16+f17;
k=2;
A(k,k-1)=-f14-f12;
```

```
A(k,k)= f11+f12+(2*f14)+f15;
A(k,k+1)=-f14;
C(k,k)=fi2+f16+f17;
k=3;
A(k,k-1)=-f14-f12;
A(k,k)= f11+f12+(2*f14)+f15;
A(k,k+1)=-f14;
C(k,k)=fi3+f17;
k=4;
A(k,k-1)=-f14-f12;
A(k,k)= f11+f12+(2*f14)+f15;
A(k,k+1)=-f14;
C(k,k)=fi4+f17;
k=5;
A(k,k-1)=-f14-f118;
A(k,k)= f11+f119+f14+f115;
C(k,k)=fi5+f116+f117;
Tss=A\C;
Tss1=Tss(1,1);
Tss2=Tss(2,2);
Tss3=Tss(3,3);
Tss4=Tss(4,4);
Tss5=Tss(5,5);
Tgi=Tg1;
Tpi=Tp1;
Tci=Tc1;
Two=Tw1;
Twi=Ts1;
Tsi=Ts1;
Tsgi=Tsg1;
Tspi=Tsp1;
Tsci=Tsc1;
Tswo=Tsw1;
Tswi=Tss1;
Tssi=Tss5;
Ti1=Tss1;
Ti2=Tss2;
Ti3=Tss3;
Ti4=Tss4;
Ti5=Tss5;
% Simulation of heat pump with mixed storage system
COP=(0.4641+((0.36538*Thp2i)-(0.13596*Ta)-
(0.01164*Thp2i.^2)+(0.004564*Ta*Thp2i)+(0.009122*Ta.^2)+(0.00009655*Thp2i.^3*(deltt/480))+
(0.0003286.*Thp2i.^2*Ta)-(0.02829*Thp2i*Ta.^2*(deltt/480))));
Pcomp=Ph;
PHp=PHp+Pcomp/1000;
Qhp= COP*Ph;
Thp2=Thp2i+((Qhp-(DWC*cw*ff(j)*(Thp2-Ts1))*(deltt/480)-Uls*Ash*(Thp2-
Ta))*(deltt/480)/(Rhow*Vdot*cw));
if Thp2<Ts1
Thp2=Ts1;
else
end
Thp2i=Thp2;
Qwu=(Rhow*cw*DWC*ff(j)*(Thp2-Twba))/360000;
Qwuhp=Qwuhp+Qwu/240;
%%% The effect of the stratified storage on the second storage
Tshp2=Tshp2i+((Qshp-(DWC*cw*ff(j)*(Tshp2-Tss5))*(deltt/480)-Uls*Ash*(Tshp2-
Ta))*(deltt/480)/(Rhow*Vdot*cw));
Phs=E;
Pscomp=Phs;
```

```
PsHp=PsHp+Pscomp/1000;
Qshp= COPs*Phs;
COPs=(0.4641+((0.36538*Tshp2i)-(0.13596*Ta)-
(0.01164*Tshp2i.^2)+(0.004564*Ta*Tshp2i)+(0.01522*Ta.^2)+(0.00009655*Tshp2i.^3*(deltt/480)
)+(0.0003286.*Tshp2i.^2*Ta)-(0.02829*Tshp2i*Ta.^2*(deltt/480))));
if Tshp2<Tss5
Tshp2=Tss5;
else
end
Tshp2i=Tshp2;
Qswu=(Rhow*cw*DWC*ff(j)*(Tshp2-Twba))/360000;
Qswuhp=Qswuhp+Qswu/240;
%%% Annual results of the systems
use(i,j)=A11;
Ict(i,j)=Ic;
Eff111(i,j)=E;
Qu111(i,j)=Qu;
Tam(i,j)=Tamb;
Twba1(i,j)=Twba;
Tgt(i,j)=Tg1;
Tpt(i,j)=Tp1;
Tc111(i,j)=Tc1;
Tw111(i,j)=Tw1;
Twi111(i,j)=Twi;
Ts111(i,j)=Ts1;
Tsgt(i,j)=Tsg1;
Tspt(i,j)=Tsp1;
Tsc111(i,j)=Tsc1;
Tsw111(i,j)=Tsw1;
Tswi111(i,j)=Tswi;
Tss111(i,j)=Tss1;
Tss222(i,j)=Tss2;
Tss333(i,j)=Tss3;
Tss444(i,j)=Tss4;
Tss555(i,j)=Tss5;
COP_1(i,j)=COP;
COP_2(i,j)=COPs;
Pcomp_1(i,j)=Pcomp;
Thp_2(i,j)=Thp2;
Tshp (i,j)=Tshp2;
QHP_1(i,j)=Qhp;
end
end
end
%%% Simulation Results
Tqsolar=sum(sum(TIQsolar))
Tqucoll=sum(sum(TQucl))
Tsqucoll=sum(sum(TsQucl))
Tqstored=sum(sum(TQstorage))
Tsqstored=sum(sum(TsQstorage))
Tqusefull=sum(sum(TQuseful))
Tsqusefull=sum(sum(TsQuseful))
Telec=sum(sum(TElec))
Tselec=sum(sum(TsElec))
Tqloss=sum(sum(TQloss))
Tsqloss=sum(sum(TsQloss))
Tqcloss=sum(sum(TQcloss))
Tsqcloss=sum(sum(TsQcloss))
Fqload=sum(sum(FQstorage))
Tqwuhp=sum(sum(Qwuhp))
Tsqwuhp=sum(sum(Qswuhp))
```

```
Eef=Telec/Tqsolar
Esef=Tselec/Tqsolar
Tef=Tqucoll/Tqsolar
Tsef=Tsqucoll/Tqsolar
solf=Tqstored/Fqload
ssolf=Tsqstored/Fqload
Thotwater=Tqusefull/Tqsolar
Tshotwater=Tsqusefull/Tqsolar
PtHp=sum(sum(PHp))
Tseff=Tqwuhp/Tqsolar
Tsseff=Tsqwuhp/Tqsolar
% Comparison of results between the mixed storage and stratifed storage
Tdstored = Tsqstored-Tqstored
Tdqusefull=Tsqusefull-Tqusefull
Tdqloss= Tqloss-Tsqloss
Tdcqloss= Tqcloss-Tsqcloss
Tdqwuhp= Tsqwuhp-Tqwuhp
sdsolf=ssolf-solf
Tdhotwater=Tshotwater-Thotwater
Tdseff=Tsseff-Tseff
rr=1:24;
% Plots Temperature profile of the stratified storage on June 11
% hh = linspace(0, H, N);
% Tssh1=[Tss111(162,1) Tss222(162,1) Tss333(162,1) Tss444(162,1) Tss555(162,1)];
% Tssh9=[Tss111(162,9) Tss222(162,9) Tss333(162,9) Tss444(162,9) Tss555(162,9)];
% Tssh13=[Tss111(162,13) Tss222(162,13) Tss333(162,13) Tss444(162,13) Tss555(162,13)];
% plot(hh, Tssh1, 'k-d',hh, Tssh9, 'b->',hh, Tssh13, 'r-s','linewidth',2,'MarkerSize',6);
% xlabel('Storage Height (m)');
% ylabel('Temperature (°C)');
% % title('Monthly Average Water Temperature of the Nodes in the Stratified Storage')
% legend('t=1:00','t=9:00','t=13:00')
% grid on
% xlim([0 1.3])
% ylim([20 60])
% pause
% clf
% Plots nodal temperatures of the stratified storage on June 11
% Tss111J11=Tss111(162,:);Tss222J11=Tss222(162,:);Tss333J11=Tss333(162,:);
% Tss444J11=Tss444(162,:);Tss555J11=Tss555(162,:);
% plot(rr,Tss111J11,'k-p',rr,Tss222J11,'b--',rr,Tss333J11,'r-<',rr,Tss444J11,'c-*',...
% rr,Tss555J11,'m-d','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Tss [o_C]','FontSize',10)
% % title('Monthly Average Water Temperature of the Nodes in the Stratified Storage')
% legend('Node 1','Node 2','Node 3','Node 4','Node 5')
% grid on
% xlim([1 24])
% ylim([20 60])
% pause
% clf
% Plots Mean Monthly Water Temperature to the Collector
% TswilJ17=Tswi111(17,:);TswilF16=Tswi111(47,:);TswilM16=Tswi111(78,:);
% TswilA15=Tswi111(105,:);....
% TswilM15=Tswi111(135,:);TswilJ11=Tswi111(162,:);
% TswilJu17=Tswi111(198,:);TswilA16=Tswi111(228,:);....
%
TswilS15=Tswi111(258,:);TswilOct15=Tswi111(288,:);TswilN14=Tswi111(318,:);TswilD10=Tswi111
(
% plot(rr,TswilJ17,'k-p',rr,TswilF16,'b->',rr,TswilM16,'r-<',rr,TswilA15,'g-%
%^',rr,TswilM15,'b--',...
```

```
% rr,TswilJ11,'k-d',rr,TswilJu17,'c-h',rr,TswilA16,'r-s',rr,TswilS15,'m-
d',rr,TswilOct15,'c-*',...
% rr,TswilN14,'m-x',rr,TswilD10,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Tswi [o_C]','FontSize',10)
% % title('Monthly Average Water Temperature to the Collector of the Stratified Storage')
% legend('January17','February16','March16','April15','May15','June11','July17',.....
% 'August16','September15','October15','November14','December10')
% grid on
% xlim([1 24])
% ylim([20 40])
% pause
% clf
% Plots Mean Monthly Water Temperature From the Collector
% TswlJ17=Tsw111(17,:);TswlF16=Tsw111(47,:);TswlM16=Tsw111(78,:);
% TswlA15=Tsw111(105,:);....
% TswlM15=Tsw111(135,:);TswlJ11=Tsw111(162,:);
% TswlJu17=Tsw111(198,:);TswlA16=Tsw111(228,:);....
TswlS15=Tsw111(258,:);TswlOct15=Tsw111(288,:);TswlN14=Tsw111(318,:);TswlD10=Tsw111(344,:);
% plot(rr,TswlJ17,'k-p',rr,TswlF16,'b->',rr,TswlM16,'r-<',rr,TswlA15,'g-^',rr,TswlM15,'b--
',...
% rr,TswlJ11,'k-d',rr,TswlJu17,'c-h',rr,TswlA16,'r-s',rr,TswlS15,'m-d',rr,TswlOct15,'c-
*',...
% rr,TswlN14,'m-x',rr,TswlD10,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Tswo [o_C]','FontSize',10)
% % title('Monthly Average Water Temperature from the Collector of the Stratified
Storage')
% legend('January17','February16','March16','April15','May15','June11','July17',.....
% 'August16','September15','October15','November14','December10')
% grid on
% xlim([1 24])
% ylim([20 60])
% pause
% clf
% % Plots Average Monthly Hot Water Temperatures of the Stratified Storage Tank
Tss1J17=Tss555(17,:);Tss1F16=Tss555(47,:);Tss1M16=Tss555(75,:);Tss1A15=Tss555(105,:);....
% Tss1M15=Tss555(135,:);Tss1J11=Tss555(162,:);
% Tss1Ju17=Tss555(198,:);Tss1A16=Tss555(228,:);....
%
Tss1S15=Tss555(258,:);Tss1Oct15=Tss555(288,:);Tss1N14=Tss555(318,:);Tss1D10=Tss555(344,:);
% plot(rr,Tss1J17,'k-p',rr,Tss1F16,'b->',rr,Tss1M16,'r-<',rr,Tss1A15,'g-^',rr,Tss1M15,'b--
',...
% rr,Tss1J11,'k-d',rr,Tss1Ju17,'c-h',rr,Tss1A16,'r-s',rr,Tss1S15,'m-d',rr,Tss1Oct15,'c-
*',...
% rr,Tss1N14,'m-x',rr,Tss1D10,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Tss5 [o_C]','FontSize',10)
% % title('Monthly Average Stratified Hot Water Storage Temperature ')
% legend('January17','February16','March16','April15','May15','June11','July17',.....
% 'August16','September15','October15','November14','December10')
% grid on
% xlim([1 24])
% ylim([20 60])
% pause
% clf
% Plots Heat Pump Storage Hot Water Temperatures of the Stratified Stoarge System
% TSS2J17=Tshp(17,:);TSS2F16=Tshp(47,:);TSS2M16=Tshp(75,:);TSS2A15=Tshp(105,:);....
% TSS2M15=Tshp(135,:);TSS2J11=Tshp(162,:); TSS2Ju17=Tshp(198,:);TSS2A16=Tshp(228,:);....
% TSS2S15=Tshp(258,:);TSS2O15=Tshp(288,:);TSS2N14=Tshp(318,:);TSS2D10=Tshp(344,:);
```

```
% plot(rr,TSS2J17,'k-p',rr,TSS2F16,'b->',rr,TSS2M16,'r-<',rr,TSS2A15,'g-^',rr,TSS2M15,'b--
',...
% rr,TSS2J11,'k-d',rr,TSS2Ju17,'c-h',rr,TSS2A16,'r-s',rr,TSS2S15,'m-d',rr,TSS2O15,'c-
*',...
% rr,TSS2N14,'m-x',rr,TSS2D10,'g-','linewidth',2,'MarkerSize',6);
% xlabel('Time [h]','FontSize',10)
% ylabel('Tshp [0_c]','FontSize',10)
% % title('Monthly Average Hot Water Storage Two Temperature of the Stratified System')
% legend('January17','February16','March16','April15','May15','June11','July17',.....
% 'August16','September15','October15','November14','December10')
% grid on
% xlim([1 24])
% ylim([20 100])
% pause
% clf
% Plots Average Monthly Hot Water Temperatures to collector of the Mixed and Stratified
Storages
% TwiJ17=Ts111(17,:);TswilJ17=Tswi111(17,:);TwiA15=Ts111(105,:);Tswi1A15=Tswi111(105,:);
....
% TwiJ11=Ts111(162,:);Tswi1J11=Tswi111(162,:);
% TwiA16=Ts111(228,:);Tswi1A16=Tswi111(228,:);....
% TwiO15=Ts111(288,:);Tswi1O15=Tswi111(288,:);TwiN14=Ts111(318,:);Tswi1N14=Tswi111(318,:);
% plot(rr,TwiJ17,'k-p',rr,TswilJ17,'b->',rr,TwiA15,'r-<',rr,Tswi1A15,'g-^',rr,TwiJ11,'b--
',...
% rr,Tswi1J11,'k-d',rr,TwiA16,'c-h',rr,Tswi1A16,'r-s',rr,TwiO15,'m-d',rr,Tswi1O15,'c-
*',...
% rr,TswiN14,'m-x',rr,Tswi1N14,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Twi,mix vs Twi,str [o_C]','FontSize',10)
% % title('Monthly Average Collector Inlet Water Temperature of Mixed vs Stratified System
')
% legend('January17 (Mixed)','January17 (Stratified)','April15 (Mixed)','April15
(Stratified)
% 'August16 (Stratified)','October15 (Mixed)','October15 (Stratified)','November14 (Mixed)
','
% grid on
% xlim([1 24])
% ylim([10 50])
% % pause
% % clf
% Plots Average Monthly Hot Water Temperatures from collector of the Mixed and Stratified
Storages
% Tw1J17=Tw111(17,:);TswlJ17=Tsw111(17,:);Tw1A15=Tw111(105,:);Tsw1A15=Tsw111(105,:); ....
% Tw1J11=Tw111(162,:);Tsw1J11=Tsw111(162,:);
% Tw1A16=Tw111(228,:);Tsw1A16=Tsw111(228,:);....
% Tw1O15=Tw111(288,:);Tsw1O15=Tsw111(288,:);Tw1N14=Tw111(318,:);Tsw1N14=Tsw111(318,:);
% plot(rr,Tw1J17,'k-p',rr,TswlJ17,'b->',rr,Tw1A15,'r-<',rr,Tsw1A15,'g-^',rr,Tw1J11,'b--
',...
% rr,Tsw1J11,'k-d',rr,Tw1A16,'c-h',rr,Tsw1A16,'r-s',rr,Tw1O15,'m-d',rr,Tsw1O15,'c-*',...
% rr,Tw1N14,'m-x',rr,Tsw1N14,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Two,mix vs Two,str [o_C]','FontSize',10)
% % title('Monthly Average Collector Outlet Water Temperature of Mixed vs Stratified
System
% legend('January17 (Mixed)','January17 (Stratified)','April15 (Mixed)','April15
(Stratified)
% 'August16 (Stratified)','October15 (Mixed)','October15 (Stratified)','November14 (Mixed)
','
% grid on
% xlim([1 24])
% ylim([20 60])
```

```
% pause
% clf
% Plots Average Monthly Hot Water Temperatures in the Mixed and Stratified Storages
% Ts1J17=Ts111(17,:);Tss1J17=Tss555(17,:);Ts1A15=Ts111(105,:);Tss1A15=Tss555(105,:); ....
% Ts1J11=Ts111(162,:);Tss1J11=Tss555(162,:);
% Ts1A16=Ts111(228,:);Tss1A16=Tss555(228,:);....
% Ts1O15=Ts111(288,:);Tss1O15=Tss555(288,:);Ts1N14=Ts111(318,:);Tss1N14=Tss555(318,:);
% plot(rr,Ts1J17,'k-p',rr,Tss1J17,'b->',rr,Ts1A15,'r-<',rr,Tss1A15,'g-^',rr,Ts1J11,'b--
',...
% rr,Tss1J11,'k-d',rr,Ts1A16,'c-h',rr,Tss1A16,'r-s',rr,Ts1O15,'m-d',rr,Tss1O15,'c-*',...
% rr,Ts1N14,'m-x',rr,Tss1N14,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Ts,mix vs Ts,str [o_C]','FontSize',10)
% % title('Monthly Average Mixed vs Stratified Storage Water Temperature')
% legend('January17 (Mixed)','January17 (Stratified)','April15 (Mixed)','April15
(Stratified)
% 'August16 (Stratified)','October15 (Mixed)','October15 (Stratified)','November14 (Mixed)
','
% grid on
% xlim([1 24])
% ylim([20 60])
% pause
% clf
% Plots Monthly Average Water Temperatures of Heat Pump Storage for Mixed vs Stratified
Systems
% ThpJ17=Thp_2(17,:);TshpJ17=Tshp(17,:);ThpA15=Thp_2(105,:);TshpA15=Tshp(105,:); ....
% ThpJ11=Thp_2(162,:);TshpJ11=Tshp(162,:);
% ThpA16=Thp_2(228,:);TshpA16=Tshp(228,:);....
% ThpO15=Thp_2(288,:);TshpO15=Tshp(288,:);ThpN14=Thp_2(318,:);TshpN14=Tshp(318,:);
% plot(rr,ThpJ17,'k-p',rr,TshpJ17,'b->',rr,ThpA15,'r-<',rr,TshpA15,'g-^',rr,ThpJ11,'b--
',...
% rr,TshpJ11,'k-d',rr,ThpA16,'c-h',rr,TshpA16,'r-s',rr,ThpO15,'m-d',rr,TshpO15,'c-*',...
% rr,ThpN14,'m-x',rr,TshpN14,'g--','linewidth',2,'MarkerSize',6);
% xlabel(' Time [h]','FontSize',10)
% ylabel(' Thp,mix vs Thp,str [o_C]','FontSize',10)
% % title('Monthly Average Water Temperatures of Heat Pump Storage for Mixed vs Stratified
Systems % legend('January17 (Mixed)','January17 (Stratified)','April15 (Mixed)','April15
(Stratified)
% 'August16 (Stratified)','October15 (Mixed)','October15 (Stratified)','November14 (Mixed)
','
% grid on
% xlim([1 24])
% ylim([20 100])
% Plots Water Load by the User
% plot(rr,ff1,'-xr',rr,ff2,'k-d',rr,ff3,'m-h','linewidth', 2,'MarkerSize',6);
% xlabel('Time [h]','FontSize',12);
% ylabel('Fraction of Hot Water Consumption [%]','FontSize',12);
% % title('water load fracton in one day');
% legend ('Constant', 'Restaurant', 'Motel')
% grid on
% xlim([1 24])
% ylim([0 0.2])
```