TRANSIENT OPERATION AND SIMULATION OF A FLAT PLATE SOLAR COLLECTOR WITH TANK AND THERMAL STORAGE

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To my parents, "Venkata Rami Reddy Kurri" and "Padmavathi Kurri", for your unconditional love and support which cannot be described using 26 alphabets and 10000 words in English

To my sister, The Late "Manideepika Kurri", for your love and grief by leaving me alone in this world

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NOMENCLATURE

A	area of the collector (m^2)
c	specific heat (J/kg-K)
d	diameter of the collector tube (m)
G	solar irradiance (W/m^2)
h	heat transfer coefficient (W/m^2-K)
k	thermal conductivity (W/m-K)
l	length of the collector(m)
$\dot{m}$	mass flow rate (kg/s)
M	number of nodes perpendicular to the flow direction
n	number of solar collector tubes
N	number of cross-sections (nodes in flow direction)
p	pitch of the tube (m)
r	radius of the collector tube (m)
T	temperature (K or °C)
V	volume(m^3)
v	flow velocity (m/s)
z	spatial coordinate (m)
α	absorption coefficient
β	collector inclination angle (rad)
δ	thickness (m)
$\Delta\tau$	time step (sec)
Δz	spatial size of control volume (m)
ε	emissivity
ρ	density(kg/m^3)

σ	Stefan-Boltzmann constant(W/m^2-K^4)
t	time (sec or min)
$\tau\alpha$	effective transmittance-absorption coefficient
L	latent heat of fusion (kJ/kg)

ABSTRACT

Manikanta Reddy Kurri, Master of Science in Engineering, Purdue University, December 2018. Transient Operation and Simulation of a Flat Plate Solar Collector with Tank and Thermal Storage. Major Professor: Donald W. Mueller, Jr., Ph.D., P.E..

Global warming due to over usage of fossil fuels is leading to different kinds of pollutions. Global warming can be controlled by switching non-renewable fossil fuels with renewable alternative power sources like wind, solar, geothermal, biomass, and ocean. Solar power is the most prominent alternative source around the world. Solar power is being used as alternative power source in almost all countries around the globe. Solar power uses radiation from sun to produce heat and the heat used for different heating and cooling applications whereas electricity being one of them. Solar power is being used in domestic applications as water heaters.

A solar collector is used to transfer energy from sun to heat water. A flat plate solar collector is commonly used for water heating systems. Solar radiation is not available entire day as other alternative energy sources so there may be a need to store the collected radiation using a thermal storage system. This study considers a solar collector system with a storage tank and phase change material (PCM). The simulation of a transient process using one-dimensional mathematical model for the collector and storage system with phase change materials (PCMs) is presented. The collector used in this study is a flat plate model and paraffin wax encapsulated in aluminum cylinders as phase change material (PCM). The thermal energy gained by solar radiation can be stored for longer period in a system which has phase change materials (PCMs) due to latent heat storage or enthalpy of fusion.

This study builds on previous work [Saleh, 2015]. A mathematical model is developed using differential equations with an implicit finite difference method for both flat plate collector and thermal storage system with PCMs. The mathematical model and computer code developed in this study allow for measured time-varying ambient temperature and irradiance as inputs. The model and computer code also allow for PCM to be included in the thermal storage system.

The core experiment used in the study was initially built by a Purdue University Fort Wayne capstone senior design team. The modifications to the original experiment include new piping, a new pump, and a new data acquisition system along with reconfiguration of the cart for improved access and maneuverability.

Two different experiments, with and without phase change materials in the reservoir, are performed. The simulations and measurements show reasonable agreement.

1. INTRODUCTION

1.1 General

Global warming and reduction in amount of fossil fuels has lead the world to concentrate on alternative power sources. Many of these sources are renewable and produces zero pollution, e.g. wind power, solar power, geothermal power, biomass power etc. Solar power is an important renewable power source. Extensive research and development is being conducted to improve the efficiency of the devices which collect energy from the sun.

The power produced radiation from the sun is called solar power. Solar power can be converted to electricity, using photovoltaic cells or through solar thermal power plants. Photovoltaic cells directly convert solar radiation into electricity. The solar thermal power plants use generators to heat a fluid which drives turbines to produce electricity.

Solar radiation can also be used in devices to provide heating. Passive solar heating of structures seeks to maximize heat gain, while minimizing heat loss, by choosing appropriate materials, structure orientation, and architectural features. Solar radiation is also used to heat fluids, such as water and air, for industrial and residential applications.

Solar radiation, as an energy source, costs nothing, is renewable, and abundant. The conversion of solar radiation into other forms of energy is essentially pollution free and does not produce greenhouse gases. A drawback to solar power usage is that solar power is not continuously available throughout the day. Other drawbacks are typically low conversion efficiencies, relatively high-initial costs, and weather dependence.

Figure 1.1 shows that only small percentage (0.5%) of United States energy consumption is from solar. Research and development is ongoing to improve the con-

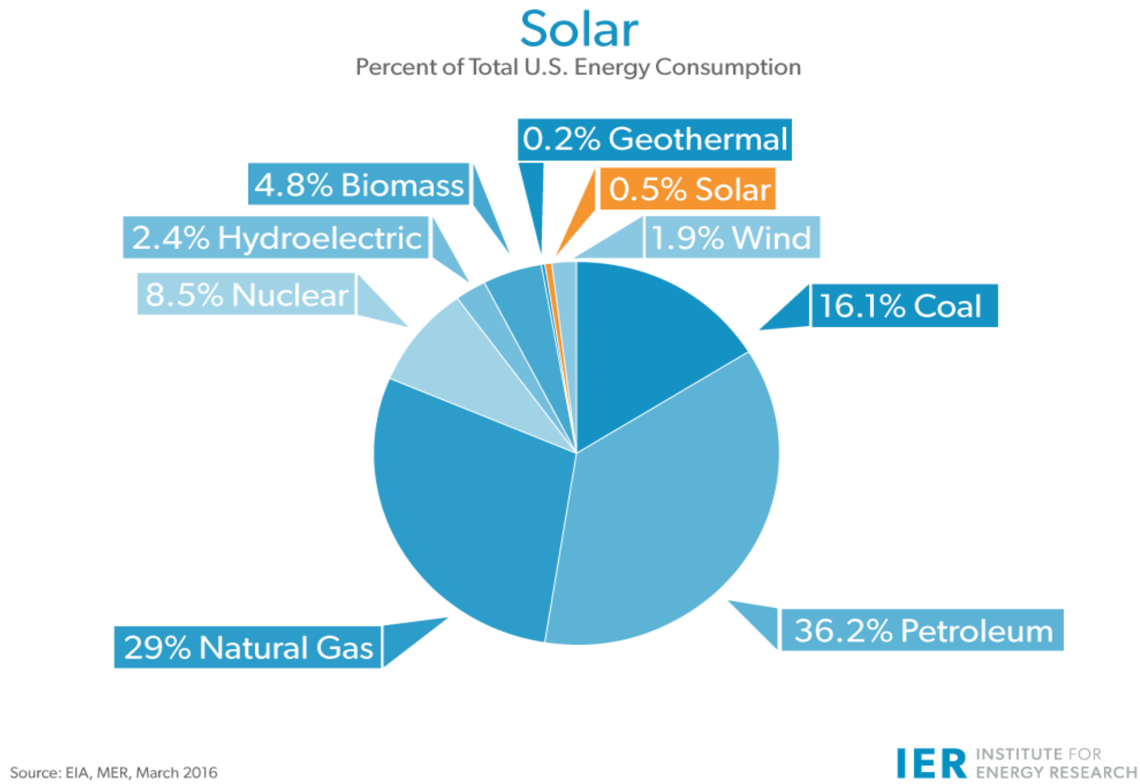

Fig. 1.1. U.S. power utilization percentage in the year 2016.

[http://instituteforenergyresearch.org]

version efficiency and reduce the cost of solar collection devices. Efforts to overcome intermittancy problems are being investigated with energy storage devices. Figure 1.2 shows that amount of solar energy consumption is rapidly increasing.

Solar power involves the transformation of insolation (solar radiation) into potentially more useful forms of energy, e.g. electricity or heat. A solar collector is device used for collecting solar radiation. The focus of this study is on solar collectors used to heat a fluid. The classification of different solar collectors used to heat fluids are shown in figure 1.3.

The most common type of solar collectors is the flat plate collector shown in figure 1.4. Flat plate collectors are metal boxes covered with a transparent glazing with a

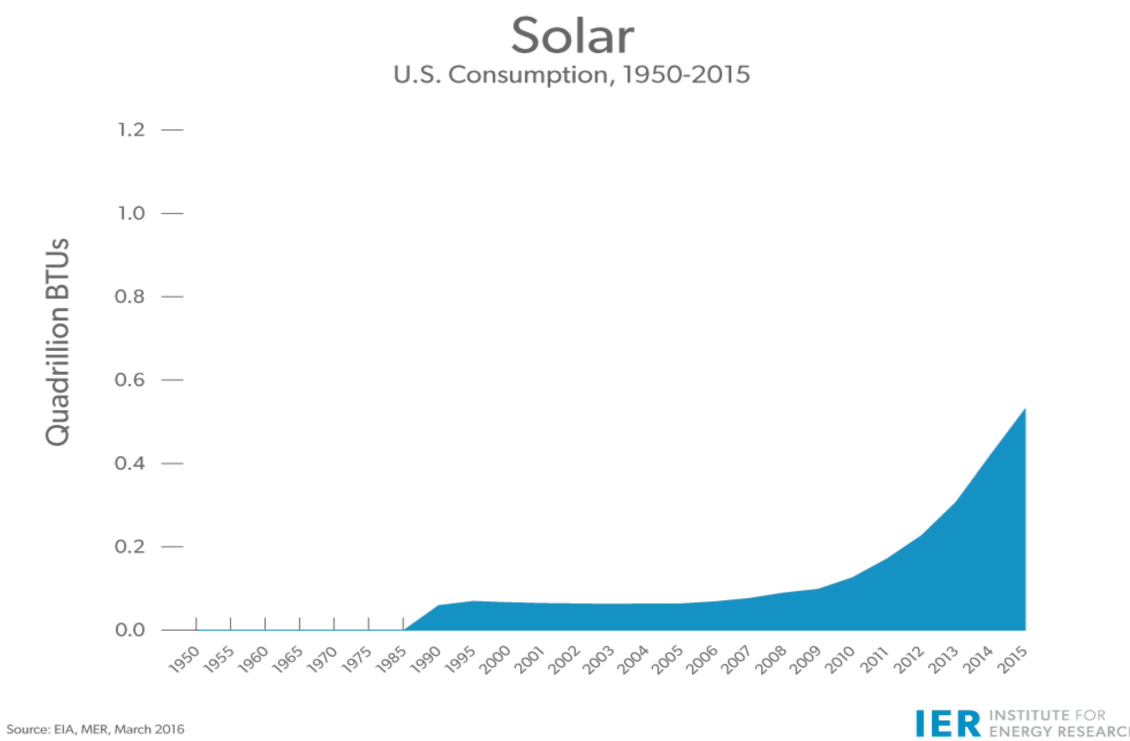

Fig. 1.2. Total U.S. power consumption from 1950 to 2015.

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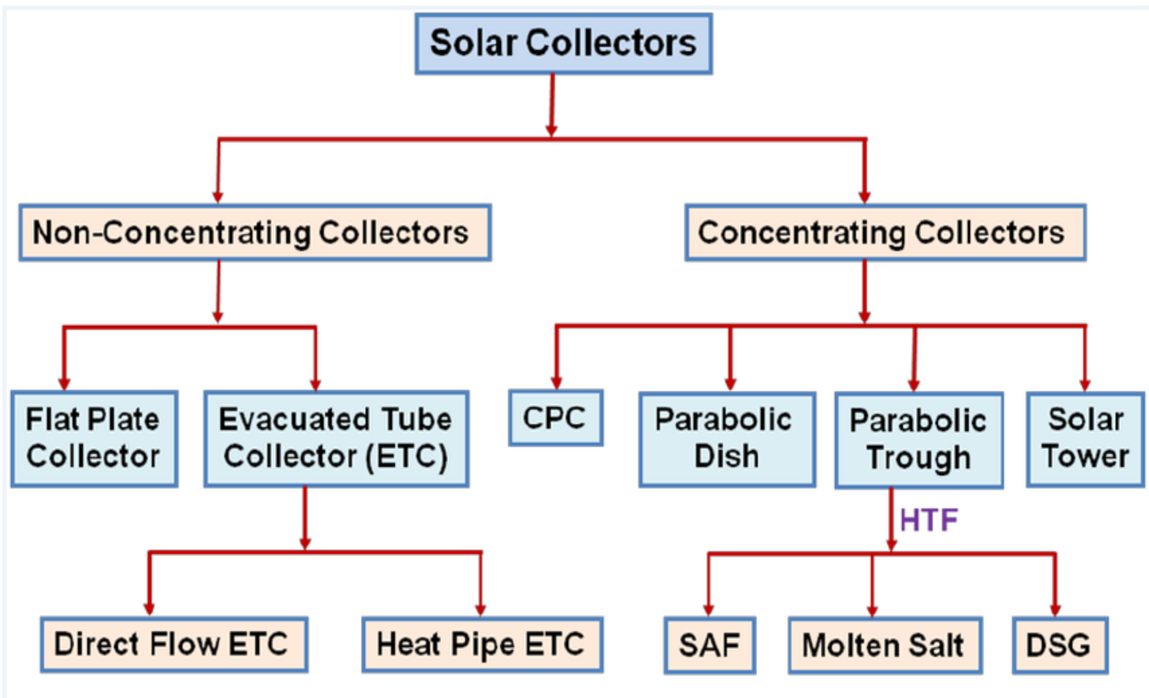

Fig. 1.3. Types of solar collectors.

[https://www.researchgate.net/]

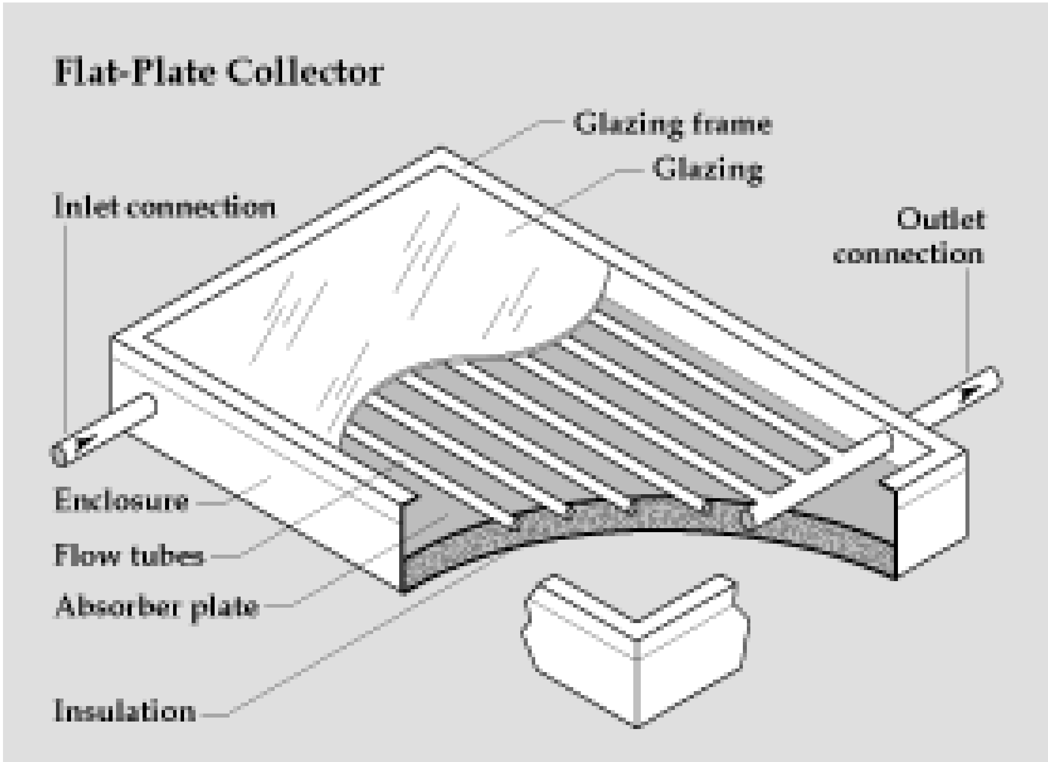

Fig. 1.4. Schematic of a flat plate solar collector.

[http://energyeducation.ca]

dark-colored absorber plate inside. The metal box is insulated to reduce the thermal loss through collector. The incident solar radiation passes through the glazing and passes through the absorber plate which heats the fluid passing through the tubes. The absorber connected to tubes painted with dark colors in order to absorb more heat. The absorber plates are generally made of copper or aluminum due to high thermal conductivity.

Solar collectors with evacuated tube are shown in figure 1.5. Evacuated tube solar collectors have tubes which are connected in series to absorb the heat from insolation to heat the fluid. The evacuated tubes with metal strip at the center acts as absorber. The pipes carry the solar radiation to fluid which has a particular pressure. The pipe has hot end has a boiling liquid while the cold end the condensing vapor at a particular pressure. This makes the thermal movement very easy from one end to the other and

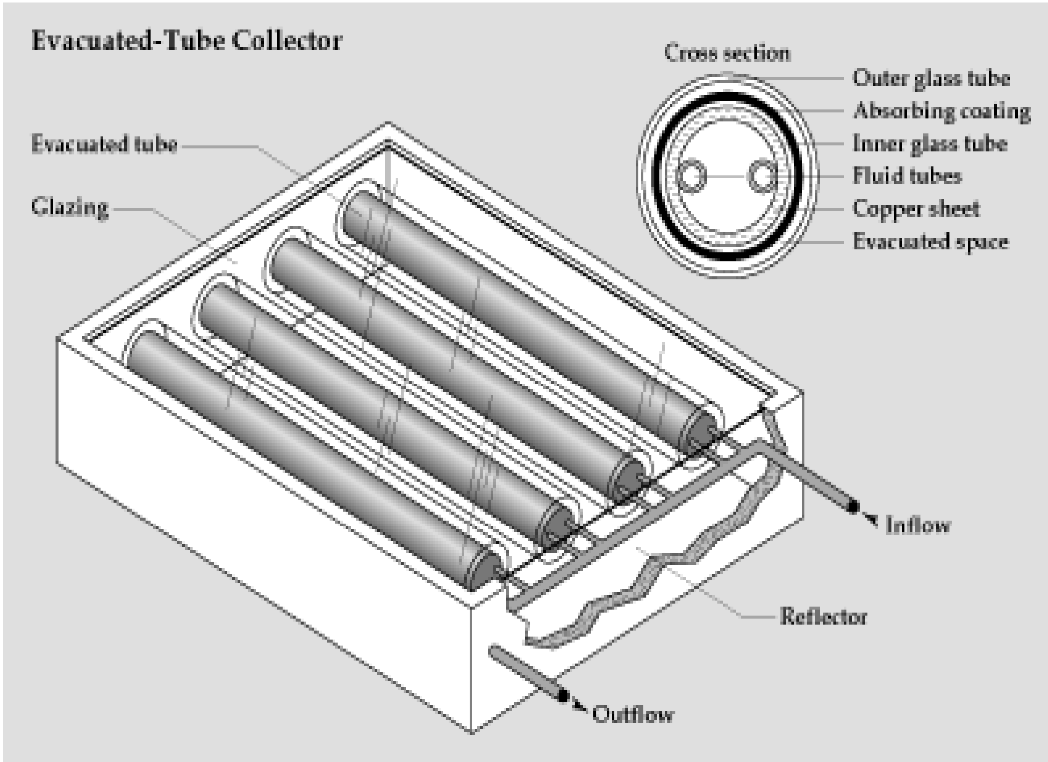

Fig. 1.5. Schematic of an evacuated tube solar collector.

[http://energyeducation.ca]

helps to transport thermal energy from hot end to condensing end to heat water for domestic or any other use.

Line focus solar collectors are parabolic shape toughs as shown in figure 1.6. The line focus solar collectors are also called as parabolic troughs due to the shape. Reflective materials are used to concentrate thermal energy from the sun. The reflective materials are connected to a parabolic trough and made to reflect the collected radiation on a pipe which is located at the center with coolant. The reflected radiation heats the coolant.

Parabolic solar collectors, shown in figure 1.7, are most powerful solar collectors. Parabolic solar collectors are similar to line focus solar collectors but are used for generating steam which can rotate turbines to generate electricity. The parabolic solar collectors contains parabolic dishes with highly reflective materials to capture

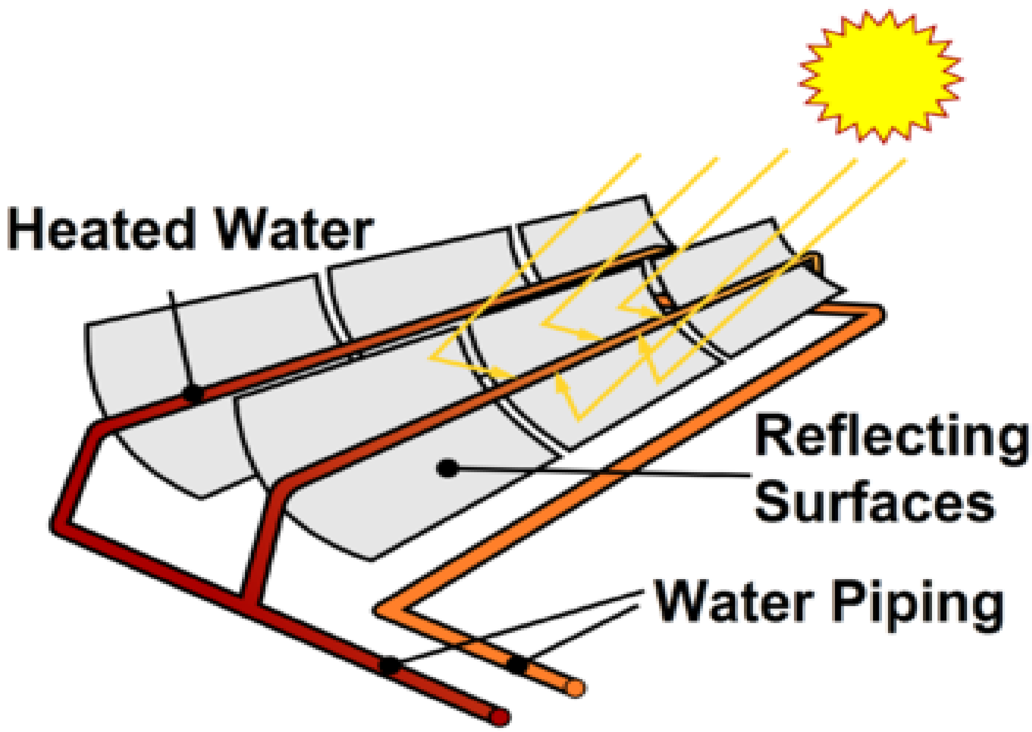

Fig. 1.6. Schematic of a line focus solar collector.

[http://energyeducation.ca]

Fig. 1.7. Schematic of a parabolic solar collector.

[http://energyeducation.ca]

higher thermal energy from insolation. The radiation is concentrated on pipes with a circulating fluid. Parabolic solar collectors can have a single large dish or an array of dishes. [http://energyeducation.ca]

This study considers flat plate collectors. The processes involved in a flat plate collector are shown in figure 1.8. Flat plate collectors receive radiation from the sun which is also known as insolation. As shown in the figure, radiation from the sun strikes the glass cover. The radiation is transmitted through the glass and passes across the air gap, striking the absorber plate. The absorber plate transfers the energy to a fluid circulating via a pump through tubes. The tubes are designed to absorb heat from incident radiation. The glass cover helps to protect the copper tubes from wind, rain, snow, and dust, and is designed to maximize radiation passing into the

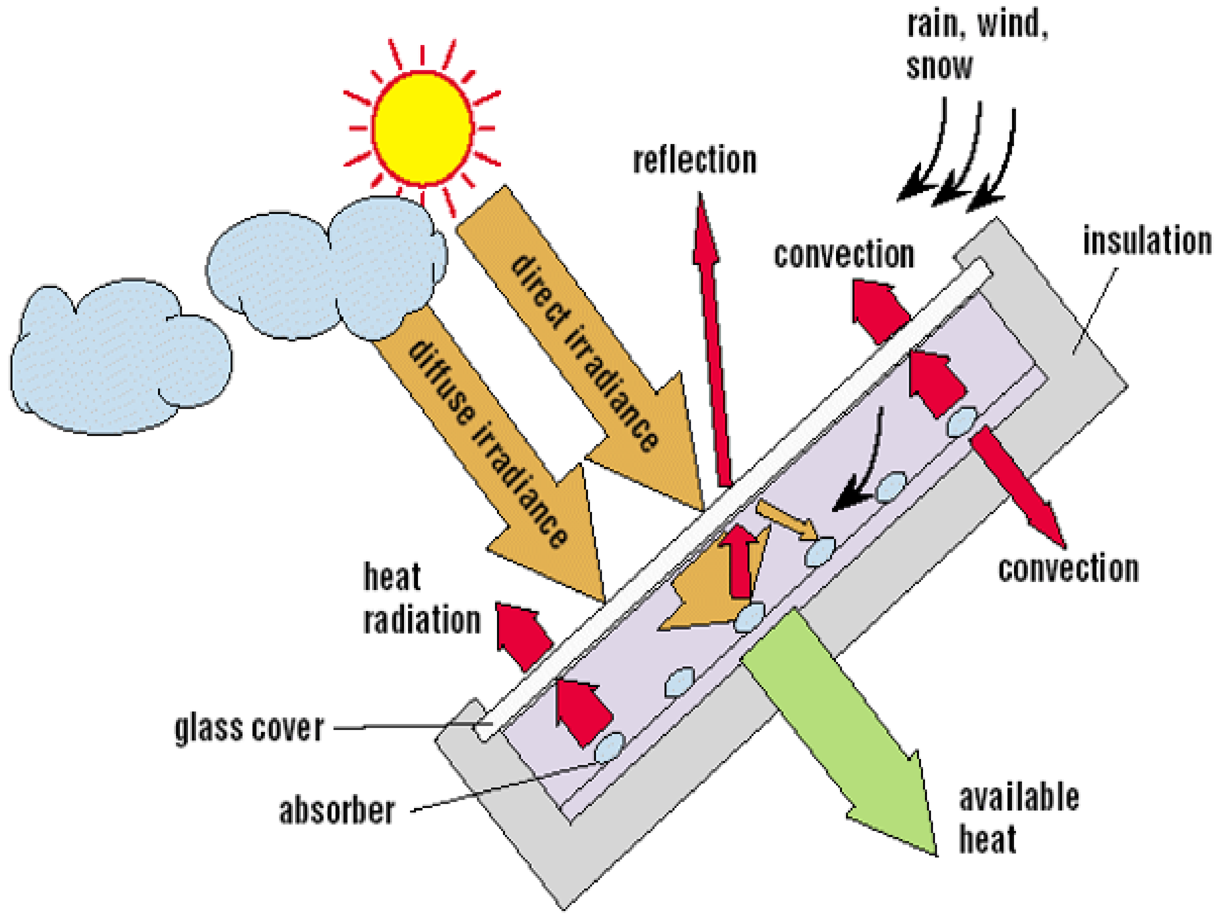

Fig. 1.8. Schematic of processes in flat plate collectors.

[https://www.volker-quaschning.de]

collector and minimize radiation passing out. Flat plate collectors are covered with insulation to minimize the thermal loss from the collectors to the surroundings.

Solar collectors have ability to collect the insolation, but in many applications, systems to store the energy are needed to overcome the absence of insolation during night times and during cloudy days. Thermal energy can be stored in three forms as sensible heat, latent heat and thermo-chemical heat. Thermal energy stored in the form of latent heat is most efficient form of thermal energy storage. Thermal energy stored in latent heat form uses phase-change materials or PCMs. PCMs transform phases to absorb and discharge thermal energy. PCM transform phase from solid-liquid most frequently as liquid-gas transformation not possible whereas solid-solid transformation has very minor useful energy density. Initially, PCM heated which acts as sensible heat that enhances the materials temperature and the materials began to absorb thermal energy at constant temperature after reaching the phase change temperature with change in phase. Thermal energy ingested during the constant temperature is known as the latent heat of the transition. Thermal energy can be recaptured by switching the phases of the PCM from liquid to solid in the form of latent heat.

Pielichowska [2014] studied a wide variety of phase change materials (PCMs). PCMs can be used to conserve the thermal loss and enhance performance of the solar power device. The unique property of latent heat storage can absorb and discharge the large amounts heat energy. Studies of different groups of PCMs is ongoing.

Thermal storage with phase change materials (PCM) can play a significant role in solar collectors. PCM absorb large amounts of energy and are also able to discharge absorbed energy by switching phase, i.e. latent heat. In latent heat storage there is no change in temperature. Certain combination of pressure and temperature can helps to undergo phase changes. The change in phases helps to release or store the latent heat energy over a smaller difference in temperature. Various forms of PCM exist. The main types are organics which are paraffins and fatty acids and inorganics

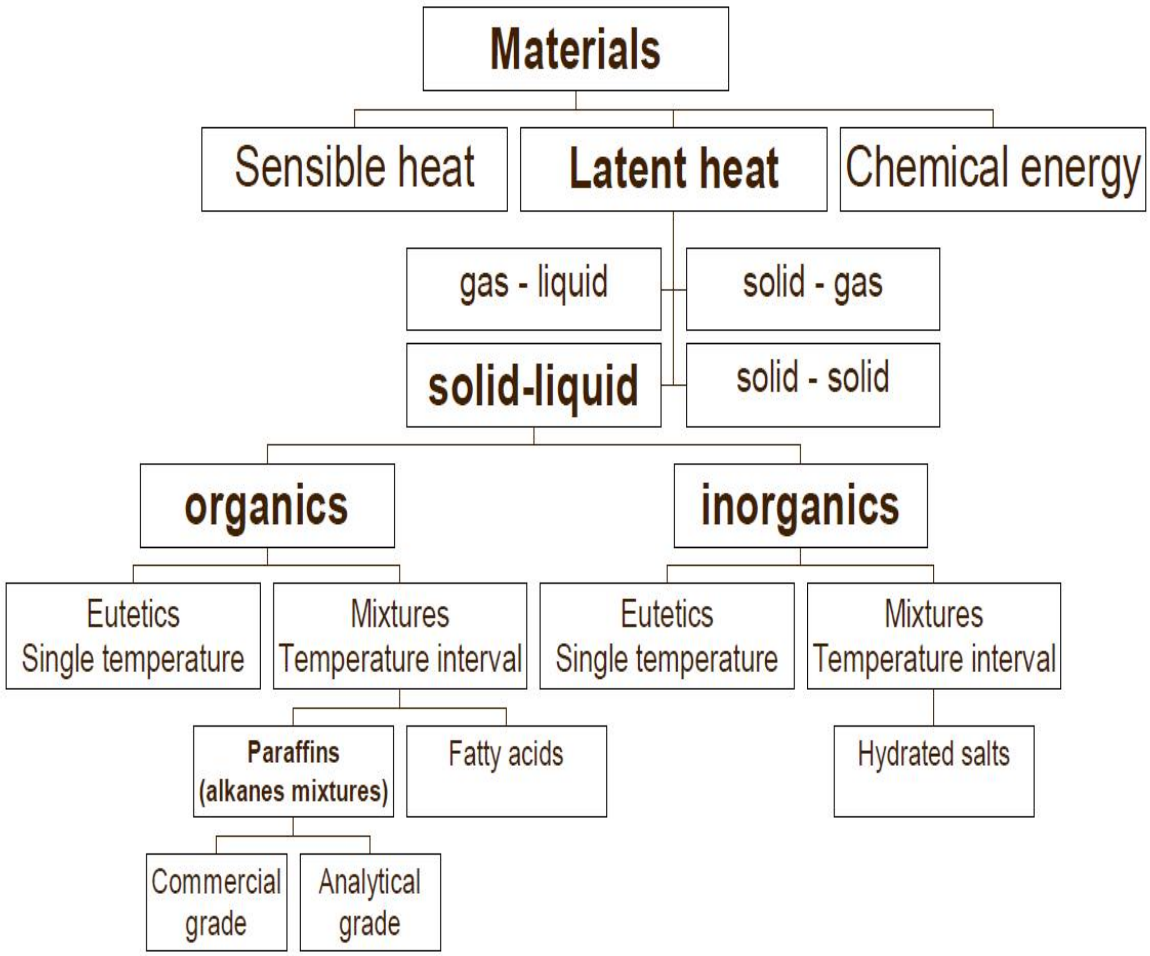

Fig. 1.9. Classification of phase change materials.

[http://www.climatetechwiki.org]

such as salt hydrates. The classification of PCM are given in figure 1.9. A brief explanation on organic and inorganic PCMs is given.

Salt hydrates are the most common inorganic PCM. Inorganic are the earliest PCM used for thermal storage applications. The advantages of the inorganics are high latent values, incombustible, inexpensive and easily available. Inorganic phase change materials have disadvantages such as corrosiveness, volatility, inaccurate re-solidification, and a tendency to super cool. The high storage density of salt hydrates decreases with cycling. The low hydrated salt tends to melt making the process irreversible which results in decrease in efficiency.

Paraffins and fatty acids are organic phase change materials which are chemically more stable than inorganic phase change materials. Organic phase change materials melt congruently but never prone to super cooling. The disadvantages with organic phase materials are high initial cost, flammable, hydration in concrete, thermal oxidative ageing, odor and the size change. However the organic phase materials are mostly preferred.

1.2 Purpose

The objective of this study is to investigate the performance of a flat plate solar collector with a storage tank that contains paraffin wax as a thermal storage material. This study builds upon two previous studies, viz. Saleh [2012] and Gaskill et. al [2014].

Saleh [2012] studied flat plate collectors systems, as shown in figure 1.10, working under transient conditions. The flat plate collector system used for the study contains the collector and storage reservoir. The collector gains heat from insolation and heats the fluid which is flowing though the pipes. The insolation received by the collector is shown by Q_i, while the heat loss rate is given by by Q_o. The fluid with heat gained goes into the storage tank. Active systems, like that shown in figure 1.10, use a pump to circulate the fluid. Saleh [2012] developed a mathematical model and computer code. His solar collector model includes cover, air gap, absorber, working fluid, insulation, and storage tank. His computer code was verified and validated, and a comparison between the numerical simulation and measurements was made [Saleh et. al, 2015].

The core of the experiment used in this study was built by a Purdue University Fort Wayne senior design team (Gaskill et. al [2014]). Experiments performed in this present study were made by making some modifications to the core experiment.

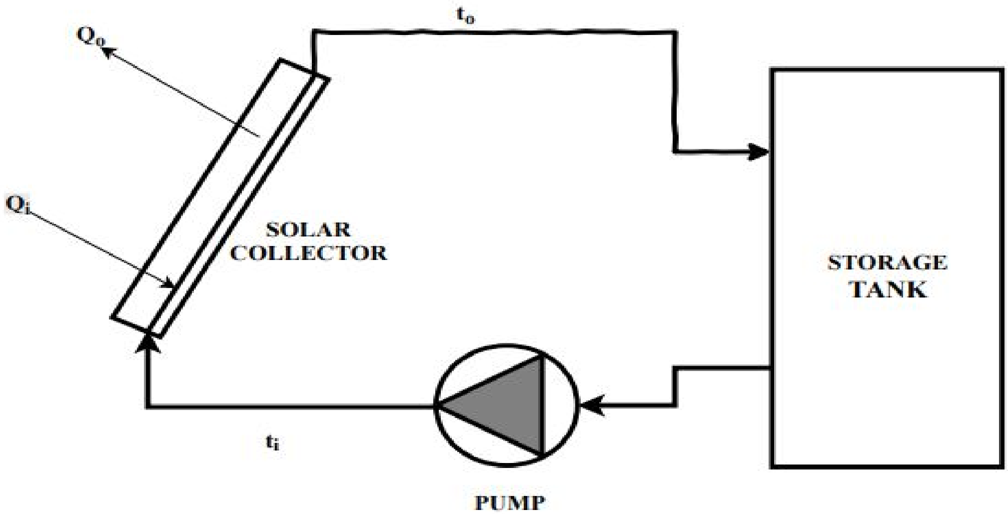

Fig. 1.10. Schematic of an active solar energy collection system.

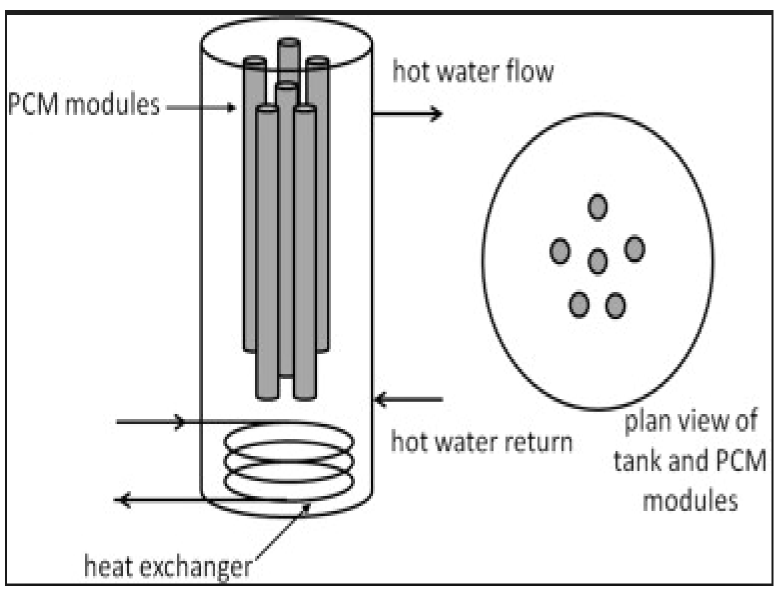

Fig. 1.11. Schematic of phase change material in storage tank.

[https://www.researchgate.net]

The modifications include new piping, new pump, new data acquisition system with reconfiguration of the cart for better access and maneuverability.

The significant outcomes of this research is to:

- Generalize the previous numerical simulation to allow for time-varying ambient temperature and solar irradiation measurements as inputs.
- Extend the mathematical model for an active flat plate collector to include thermal storage by phase change material.
- Obtain validation of mathematical model and numerical simulation by comparison between measurement and simulation.

1.3 Thesis Organization

A total of seven chapters comprise the thesis with first chapter being introduction about solar power, solar collectors and phase change materials (PCMs)

Chapter two gives the literature review of the previous studies and scope of the present study.

Chapter three gives the derivation of the mathematical model for solar collector and thermal storage system.

Chapter four gives the detailed experimental procedure used to obtain the measured results.

Chapter five gives the details about steps involving in numerical solution using MATLAB code with inputs to obtain numerical results.

Chapter six gives measured and numerical results along with the comparison between both results i.e., measured and numerical simualtion.

Chapter seven gives concluding remarks.

2. LITERATURE REVIEW

Solar power is a renewable power considered to be the best alternative source to replace the fossil fuels. Solar power is collected by the solar collectors of different types i.e., flat plate collectors, concentrated collectors etc. A flat plate model collector being used in this study that heats coolant with insolation from the sun. The study is also concentrating on thermal storage of the captured solar energy using phase change materials. Phase change materials enhance the thermal storage capacity of the flat plate collector as phase change materials store thermal energy during the presence of solar radiation by melting and emits stored thermal energy in the absence of insolation from the sun by solidification. The study presents basic fundamentals of the flat plate solar collectors with thermal storage using phase change materials and predicts the performance using MATLAB code.

The stationary models of the solar collectors by Hottel and Woertz [1942], Hottel and Whillier [1985] and Bliss [1959] considered zero capacitance in those models due to negligible effect of capacitance. The optical efficiency and thermal loss coefficient are determined for the collectors. The inertia in stationery models is not considered.Thermal capacity not affects the collector performance under steady state conditions. It is difficult to obtain steady state conditions in outdoor measurements, this makes the stationery test more expensive and complicated. The stationary test is done in indoor conditions or should wait until steady-state conditions are obtained.

Close [1967] developed a model to include the capacitance effects on the performance of the collector. The transient conditions of the collector performance can be illustrated by a set of energy balance around each component. He assumed that collector can be regarded as a lumped system at mean temperature water passing through the collector and simplified model used for experiments. The model helped to estimate the transient nature of the collector and measure collector performance under transient and unsteady conditions by using the differential equations. Assuming linear temperature distribution in the direction of flow considered as drawback. Similar temperatures for the fluid and base are maintained .The model helped in predicting the collector performance including the thermal storage due thermal capacitance of the collector. The transient conditions of thermal capacitance can be measured with the more complicated model.The performance of the solar collector can be measured by considering transient and unsteady conditions. The performance of the solar collector with transient conditions can be found out by using more complicated multi-dimensional model. The equations involved in these models are difficult to solve. However, this model helped to the development of the new model with more assumptions that can predict the performance of the collector under transient conditions.

Klein [1974] developed a two-node model. The nodes in this model are arranged in between the collector plate and single glass cover. An assumption is made that the mean temperature is the average algebraic sum of inlet and outlet temperatures. First order and second order derivatives are used in this model for the calculation of the solar collector performance. Partial differential equations are used as the collector is distributed to give a complete description of the performance of the solar collector. Since the models responded to sudden changes of the meteorological variables within a fraction of an hour, there is a conclusion that it is not necessary to take any collector dynamics into account at all if hourly meteorological data are used. The model concluded that all collector dynamics are not considered as it reacts to rapid variations in climatic fluctuations within a fraction of an hour considering hourly data.

De Ron [1980] developed a dynamic single cover flat-plate model that can extended to numerous covers with some assumptions to the model developed by Duffie and Beckman [1974]. The assumptions made by De Ron [1980] are given:

- All the thermal transmission process are taken independent of Y-direction.
- Thermal transmission by fluid flow is the only heat in x-direction.

- Thermal transmission through z-direction is negligible as the very small amount of heat flow back through insulation.
- Insulation at the edges of the collector is perfect i.e., no heat is lost.
- Thermal capacities between the air layers and between the air layer and covers are neglected as compared to the other heat capacities.

None of the above assumptions used in the model is necessary for the mathematical reasons.

De Ron[1980] divided the collector into a definite array of identical divisions. For each division, energy balance is established. The energy balance equations for the glass cover and absorber plate is represented by ordinary differential equations. Partial differential equations used to illustrate the fluid temperature. The equations for the model are non-linear. Although model derived is non-linear, the linear model with the equations gives more information. Linearization provides approximate responses of the non-linear models.The model works well only for simple second and higher order derivatives. The model is not useful when there are large changes in wind and flow speed.

Kamminga [1985] developed transient analytical similarities of the temperatures inside the collector at a moment, t=0 by using the property that a part of thermal resistance in collector is lower than others. In this method, the approximation of temperature measurements is taken from a four node model which is represented by the cover plate, the absorber, the fluid and the insulation. The temperature of the collector depends on the coordinate in the direction of the fluid flow. The heat balances are derived by using the partial differential equations. The model includes several approximations which includes neglecting thermal losses by cover and edges. Thermal resistance and thermal capacities are neglected with flow rate of fluid being constant. The model suits well for calculating single flow rate but not for multiple ones.

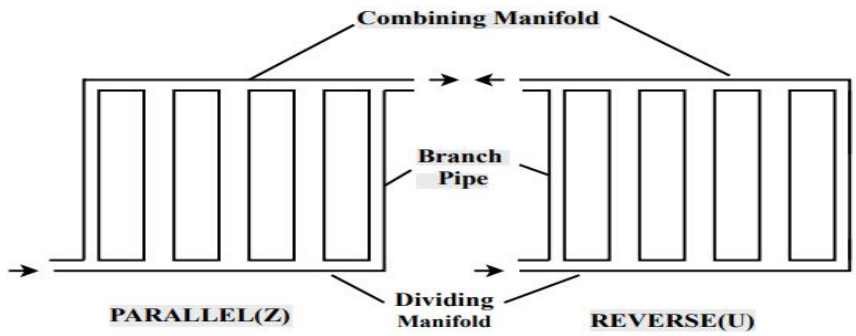

Fig. 2.1. Schematic of collector arrays Z-type and U-type.

Wang and Wu [1990] developed a distinct analytical model and made analysis to measure the flow and distribution by considering the flow non-uniformity, the longitudinal heat conduction, and the buoyancy effect. The non-uniformity in flow of fluid effects the thermal performance of the solar collector array. The collector array is formed by assembling M collectors in parallel and with N branch pipes. The whole collector has two manifolds i.e., dividing manifold, a combining manifold, with $M \times N$ branch pipes.

According to the flow, there are two types of collector arrays are shown in figures. Figure 2.1 shows the Z-type array and U-type array in which the flow are paralle and revesre in two manifolds respectively. The performance is obatined by making some assumptions which are differnt from the asssmptions made by H-W-B models such as irregular distribution of flow in branch pipes, buoyancy effect considered due to independence of fluid properties on temperature, longitudinal heat conduction in absorber plate and pipe wall considered, and thermal Transmission in the manifolds considered. The model needs a steady inlet temperature and flow rate during the test which is difficult to obtain. Since the inconsistency in flow would result in adverse affects on the collector output the model may result in a large error with large collector array.

Olivia [1991] presented an analytical model to study the thermal behavior considering multidimensional and transient conditions which define the phenomena of thermal transmission in the collector. The model analyses the aspects such as flow non-uniformity distribution, shadow areas, variation in dimensions and properties of various components. The model takes transient and multidimensional medialization of various components of a collector such as cover, ducts, fluid flow, insulation etc. and their combination in a global algorithm. Rectangular ducts of air collector are used for the analysis. The model used in this test is physically built in a right way but the results are not as practical as expected.

Duffie and Beckman [1991] a flat plate solar collector is a different kind of heat exchanger that transmits insolation fron the sun into thermal power. A solar collector is far different from conventional heat exchangers in many aspects. The investigation of solar collectors demonstrates different issues of energy fluctuations due to insolation from the sun. The equations developed in this model is simpler which can give detailed explanation of the functions by components along with the output by the collector. The methods used for collection of insolation from the sun which tells the performance of the solar collector is of two types: the stationary test and dynamic solar collector model. The dynamic model presents the performance in a simple way by using the effect of thermal capacitance. The dynamic model is developed as a simple model first and later developed to multi-node model. The multi-node model is maintained at single temperature and capacitance.

Muschaweck [1993] Dynamic models are made to avoid the difficulty caused by stationery models. The test method involved in dynamic model gives extra data on the collector besides making the model easier to perform experiments under unsteady conditions. This method guarantees to make testing conditions in stationary outdoor climatic conditions, fluctuating inlet temperature and volume flow rate. The testing of the dynamic model is less expensive while model and computations are complex. The model and calculation process is established once and the experimental expense is made for each test.

Onyegegbu [1993] presented a study of an unsteady two-dimensional investigation of a flat plate solar collector exposed to transient insulation by a considerable distributed segments. The study considers the thermal masses of the absorber, tube, glazing and the functioning fluid in the system along with optical and thermal behavior of the beam and distributed insolation from the sun. Two sets of insulation data, one for the clear day and other for clouded day is used. The energetic optimization done and the flow rates which improve the total energy output were figured out for the flow update periods of 30 minutes, 1 hour and entire sunlight period. The spontaneous maximum flow rates were found to follow the insulation arrangement. The study finally concluded that the system performance was good during the clear day than on a clouded day.

Muschaweck and Spirkl [1993] developed a model which is dynamic that can predict output and can identify dynamic limitations. The solar collector (loop) under unstationary exterior climatic conditions like fluctuating inlet temperature and volume flow rate is tested. Three tests sequence measurements such as collector limitations are determined in one sequence and the collector output is predicted in other two sequences with determined parameters are taken. The presented model is the extension of the one model presented by H-W-B model with multi-nodes. The presented model is used to predict the results accurately in short-term (less than two days). The model is failed to produce accurate results with variable flow rates.

Schnieders [1997] presented the analysis of one node and five distinct dynamic models of a solar collector in distinct styles. The energy yield prediction made by comparing a set of measured data and the results obtained by the collector. Divisions in the collector is made to create several nodes which convert several partial differential equations to an ordinary differential equations. The 3n-node model is the most complicated model which does not suits for fluctuating flow rates whereas, the 2n-node-model is exposed to powerful fluctuating inputs with an ideal single fluid channel with a minimum of one thermal capacity known foremost. The study stated that the dynamic models give same results with longer interval inputs where as stationary models gives over exaggerate with shorter intervals.

Hilmer [1999] developed a method to compute the short-term changing conditions of non glossy solar collectors working with fluctuating fluid flow rate and based on the first-order partial differential equations. The assumption of constant thermal transmission between the fluid and the absorber is used. The method yielded accurate results with non glossy solar collectors presented by a 2-node model. The steady-state model developed yielded good results under constant flow rate but failed under variable flow rates.

Zueva and Magiera [2000] a mathematical model for thermal transmission in a system with a solar collector and a heat exchanger is proposed. The combined system of collector and heat exchanger are treated as lumped structure. Solar energy flux gives an analytical solution for heat conduction through the collector wall under the Cauchy boundary conditions with regard to internal heat sources. The model produced decent results with steady conditions but failed to produce decent results with unsteady conditions.

Weitbrecht [2002] presented a study on flat plate collector with laminar flow to investigate flow conditions by performing experiments with the collector. Laser Doppler anemometry (LDA)-measurements were carried to understand the link between losses through junction and the local Reynolds number. A sensitivity analysis to describe different flow distributions in collectors and a simple parametric approach to predict the flow distribution without performing a pipe network calculation. The two main objectives flow distribution related to overall discharge through the actual collector and the loss coefficients for the pipe intersections related to Reynolds-number were analyzed. velocity and pressure measurements in every junction and riser. Higher efficiency is achieved with a highly uniform flow rate which is not always possible in case of solar collectors.

Farkas and Geczy-Vig [2003] presented a study on artificial neural networks (ANN) which describes modeling the temperature layers located inside a tank of solar thermal storage system. The model gives calculations for temperature for 8 different layers considering average time interval of insolation from sun, consumed water, the ambient temperature, the mass flux of collector loop along with previous time-step temperature of the layers. The proposed ANN models produce satisfying results within training interval. Training and validation done by using Hottel-Vhillier model for the proposed model.

Kalogirou [2005] used ANN for the prediction of output limitations of the flat-plate solar collector. In this model, six ANN models with both wind and no wind conditions proposed to predict the basic output of collector equation coefficients. The models include incidence angle modifier coefficients at longitudinal and transverse directions, the collector time constant, the collector stagnation temperature and the collector thermal capacity. The analysis is done under steady-state conditions. The results obtained with unknown data were satisfactory and closely related to the thermal output of the flat plate collectors.

Fan [2007] investigated both theoretical and experimental effects of flow and temperature distribution in a solar collector with horizontally inclined strips in an absorber. The fluid flow and thermal transmission were calculated by using the computational fluid dynamics (CFD) calculations. The temperature on the backside of the absorber tubes calculates the flow distribution. A comparison is made between measured data and the data obtained from CFD model, both the data appeared to be similar for high flow rates. Due to over simplification of the model, the results for low flow rates, shows a large difference between CFD calculations and experimental results.

Augustus and Kumar [2006] presented a mathematical model for unglazed transpired collectors (UTC) using thermal equations for the collector components and experimental relations for predicting different thermal transmission coefficients.The model predicts the UTC over an extensive area of design and working conditions and used to analyze the crucial limitations effects on the outputs of the UTC. The parameters such as varying porosity, airflow rate, solar radiation and solar absorptivity or thermal emissivity and finding their influence on collector efficiency, heat exchange effectiveness, air temperature rise and useful heat delivered. The results proved that the solar absorptivity, collector pitch, and airflow rate have strong influence on collector heat exchange effectiveness as well as efficiency.

Molero [2009] developed a transient 3-D mathematical model for solar flat plate collectors based on setting mass and energy balances in finite volumes. The model considers the multidimensional character and the issue of the uneven flow on the collector. The efficiency was evaluated with a defined degree of decline in collector efficiency. The investigation showed that this decline directly proportional to the unsteady flow, although for very limited. Verification of the proposed model done under steady-state conditions. Results show that the collector efficiency of the collector at 1.5 times faster flow at outer risers compare to central rises with the outlet temperatures for each tube being different.

Cadafalch [2009] developed a 1-D time dependent analytical model for flat-plate solar thermal devices. Investigation of variable set ups and elements were done. Thermal transmission is 1-D but some 2-D and 3-D occurs due to the impact of edges due to non-uniform elements due to temperature inclinations in different directions but the central thermal flow remains 1-D. Thermal flow from one element to another in the form of convection, solar and thermal radiation, conduction. The results obtained from the model verified with the data obtained from the experiments done under steady-state conditions.

Anderson [2010] made an investigation on the output of solar collectors in series with variable colors(ranging from white to black) were studied theoretically and experimentally. The theoretical performances of these collectors were determined depending on the transmittance-absorptance results of variable colored collectors utilizing the Hottel-Whillier-Bliss 1-D steady-state models by Duffie and Beckmann [2006]. The results showed that colored solar collector absorbers can take more thermal loads but thermal efficiency was less than absorbers with extremely advanced selective coating.

Singh [2010] proposed that better efficiency of the solar collector obtained with minimum heat loss from absorber. Collectors with a set of 8 trapezoidal absorbers concentrated in linear fashion investigated under steady flow rate and temperatures. The overall thermal loss coefficient of the absorbers directly proportional to absorber temperature in all cases. Switching to selective surface coating on the absorbers to ordinary black paint resulted a significant reduction in overall thermal loss coefficient by 20-30%.The investigation found that the absorber temperature increases the thermal loss coefficient and the use of double glass cover to single glass cover resulted in reduction of overall heat loss coefficient by 10-15% .

Martinopoulos [2010] model which gives an analysis experimentally and with computational fluid dynamics (CFD) considering insolation from the sun, as well as convection and thermal transmission between the elements of the collector. Black color working fluid to absorb energy directly. Validation of the CFD is done by the distribution of temperature and velocity over its area and the collector efficiency at the normal flow rate. Similarities found between data from experiment and data from CFD. Steady conditions for the collector were used for the CFD calculations to get the output.

Zima and Dziewa [2011] developed a 1-D model for performing the simulation for time dependent processes occur in the liquid flat-plate solar collector tubes by considering the collector tube as a distributed parameters. All thermo-physical properties of the fluid, absorber and air gap are calculated in actual time and the time-spatial distributions of thermal transmission coefficients are also calculated in the on-line mode with a time-varying boundary conditions.The results are verified by comparing experimental results and merging of both measured and calculated fluid temperatures at the collector outlet made a good agreement.

Amrutkar [2012] presented a study to calculate the output of the flat plate collector with different geometrical configuration. The absorber coated with a selective color in order to receive more solar radiation.Heat collection surface transfer area of the absorber obtained with change in geometry of the same space conventional flat plate collector which results in higher thermal efficiency or higher water temperature. The reduction in collector area and number of tubes can increase the efficiency and reduce the cost of the flat plate collector.

Hamed [2014] developed a numerical investigation to determine optical performance and design limitations of flat plate solar collectors. The model has a transient simulation method to describe the dynamic behavior established with energy balance analysis. The model helps to study the effects of various limitations on the output of the flat plate collector using a set of equations.The results show that fluid flow rates inversely proportional to outlet water temperature and the overall heat loss coefficient, the output temperature increase with input temperature. Maximum tubes in the collector leads maximum output water temperature depending on water flow rates.

Saleh [2012]and Saleh et. al [2015] and presented a simulation for a time dependent process liquid flat-plate solar collector with a storage tank with a mathematical model. A 5-node model with differential equations is used for the study. Inputs to the model include the constant liquid flow rate, insolation from the sun, and the ambient air temperature, as well as the volume of coolant in the storage tank and initial temperature of the system. An implicit iterative method using MATLAB software gives solution to differential equations. The results obtained for the MATLAB software are compared with experimental results which are obtained under variable flow rates and ambient conditions. Good agreement is found between the calculated results and results from experiments. The developed model can predict the output of the flat plate collector without conducting any physical experiment.

Genc [2018] proposed a time dependent thermal transmission model to determine thermal inertia of the glass, trapped air, absorber and working fluid in a flat plate solar collector using Nano fluids instead of water as coolant. Al_2O_3 preferred as Nanofluid for the study. The experiment is carried out with water and Nano-fluids.Nanofluids Al_2O_3 with variable concentrations as 1%, 2% and 3% and variable mass flux of coolant ranging between 0.04 and 0.06 kg/s, is used to determine the effect of thermos physical properties at different flow Reynolds numbers. the optimum increase of the outlet temperature is obtained by Nano-fluids is observed from results. Nano-fluids particles has more thermal efficiency than water.In this study Nano-fluids gives high outlet temperature with a critical mass flux of 0.016 kg/s.

Flat plate solar collectors became an important part in many places especially domestic purposes and are used for heating purposes like solar water heaters. To mitigate the thermal requirements during the absence of insolation from the sun, a thermal storage unit is been introduced to the flat plate collectors. Different varieties of thermal storage units helped to keep the heat in the collector for longer periods and also used helped to avoid heat loss from the unit. The thermal storage units consists of nanofluids and phase change materials. Studies proved that thermal storage units with phase change materials are found to be more efficient than the thermal storage units with Nano fluids. Different studies on flat plate collector with thermal storage unit are given.

Close [1966] developed a study on the storage of the solar flat plate collector to study thermal output of the collector under transient conditions. The model has a storage tank with water is used as a coolant running through tank. Differential equations have been used to analyze the thermal storage. A three section storage tank is used. Three differential equations have been used to analyze. However, the model is more concentrated on the output of the solar collector could not give adequate information regarding thermal storage.

Buzas [1998] developed a mathematical model to simulate a solar hot water system to describe the thermal performance of solar collectors and hot water storage tanks.The Dynamic model is analyzed using block-oriented technique with MATLAB-SIMULINK software. In this study three kinds of storage tanks used: divided hot water storage tank, storage tank with heat exchanger, and mixed storage tank model. In divided model, the storage tank divided into three sections and the thermal transmission studied through the wall. A heat exchanger provided inside a storage tank. Mixed storage tank model is fully mixed thermally and high thermal efficiency than other two models. Differential equations are used to analyze the storage of the tanks. The results obtained show the great agreement with calculated results.

Farkas [2003] presented the analysis of the flat plate collector with artificial neural networks (ANN) by using the heat network model and Hottel-Villiers (H-V) models which includes a heat storage collector. The storage of air collector was due to latent heat storage matrix of $CaCl_2.6H_2O$. Thermal energy absorbed by the surface of the storage which serves as an absorber. Critical phase change temperature was 29°C and a range of T = +/-1°C was used in the analysis of phase change process. However, the whole process is to be carried out under steady-state conditions and it is not so applicable under unsteady conditions.

Zalba [2003] made a review on thermal storage with phase change i.e., solid - liquid. The review mainly focused on three aspects: materials, thermal transmission and functions. The study contains 150 materials which are used in research. Phase change materials(PCMs) major part in thermal storage, especially in solar collectors. Thermal storage tanks with PCMs storage more heat and keeps the fluid warm even in the absence of insolation from the sun. Enthalpy of fusion(Latent heat) storage is used in solar collectors.

Trelles [2003] presented a study on permeable enthalpy of fusion storage for thermoelectric cooling in a 3-D domain with a system made of two aluminum vessel in which the inner vessel has the cooling objective and the outer vessel has the phase change material (PCM) in a permeable aluminum matrix. The system is charged and discharged using different porosities of the aluminum matrix. Simulation carried-out for constant thermoelectric module (TEM) cold side temperature. The analysis simplified using mathematical model while the metal matrix in the PCM greatly enhances output. The method used for this study can be used for any study as it is more robust and results can be obtained in a small number of iterations.

Nallusamy [2006] presented a study on solar thermal systems and thermal loss recovery systems. The study concentrates on evaluation of thermal output of a packed bed enthalpy of fusion thermal energy storage (TES) unit integrated with solar flat plate collector. Paraffin filled in spherical capsules used as a phase change material (PCM) packed in a storage tank of cylindrical shape protected with proper insulation and water being used as a coolant to transfer heat from the solar collector to the storage tank and acts as sensible heat storage material. Charging experiments were carried out to analyze storage capacity while discharging experiments to analyze the thermal loss recovery of the system. The results concluded that enthalpy of fusion storage system with phase change materials are far efficient than regular conventional storage systems without PCM.

Vikram [2006] presented a study on solar thermal storage using Phase Change Materials (PCMs) and the energy stored using PCMs to keep water warm during night time. Solar water heater used during day time whereas phase change material encapsulated inside aluminum cylinders are used as heat storage system during night time. PCM absorb heat during day time by changing their phase form solid to liquid and during night time again phase change materials change their phase to liquid to solid by transferring the heat gained to the water passing through the cylinders. PCMs stores excess heat as sensible heat and proper insulation used in the system. The results show that phase change materials keeps water warm for longer periods compared to normal storage system. Enthalpy of fusion energy storage with phase change materials can be used commercially.

Shukla [2009] investigated thermal energy storage with and without phase change materials which uses latent heat storage property to store thermal energy in solar water heaters.The study differentiated by type of collector used and type of storage i.e., sensible or latent. The study finally concluded that the solar water heater with phase change material of high melting temperature and large surface area of the collector are required for better results.

Sharma [2009] presented a study on the thermal energy storage using phase change materials(PCMs). The study concentrates on the thermal energy required to keep water warm in a solar water heater. (PCMs) are installed in storage tank by encapsulating them in a cylinders made of aluminum or copper. The main theme is to meet thermal energy requirements by providing warm water in residential houses even during absence of insolation from the sun i.e., mornings, evenings and night. Thermal storage reservoir with phase change material used to keep water warm entire day. Results concluded that unique property called latent heat or enthalpy of fusion storage of a PCM plays a significant role in solar thermal storage.

Zhao and Tian [2010] investigated solar collector and thermal storage applications. The study investigated various thermal storage systems including latent heat storage, sensible heat storage, chemical storage and cascaded storage. Analysis done by using various design criteria, material selection, and different transfer technologies. Finally, molten salts with exceptional properties are regarded as best suitable for high-temperature thermal storage applications. To overcome poor thermal transmission graphite components and metal foams are considered as the ideal materials.

Saw [2011] developed an experimental approach using 37 fins attaching below absorber with phase change material integrated in flat plate solar collector. Phase change material(PCM) integrated to improve the output of the flat plate collector. Fins are installed for thermal transmission from the absorber plate to any phase change material below the absorber plate. Experiments performed without considering the effect of phase change materials and correlated with reference model using three variables sets of flow rates and tilt angles. The results show that for low tilt angle and flow rate the high temperatures are obtained with insulation playing a big role to reduce heat losses, water temperature on the top and bottom of the tank remained constant from night till morning as no external heat to develop the temperature difference.

Tian [2013] reviewed different solar energy systems. Every solar energy system consists of two different components i.e., solar collector and Solar thermal storage unit. Studies have been made on concentrating solar collectors and non-concentrating collectors. PVT solar collectors among the non-concentrating collectors are considered as the best. Molten salts are considered as the best materials for thermal energy storage.

Reddy [2014] investigated discharging and charging processes of the thermal energy storage systems which are effected by encapsulated phase change materials (PCMs). Paraffin and water are used as PCM and coolant. capsules made of three different materials which are high-density polyethylene (HDPE), aluminum (Al), and mild steel (MS) are used for the study to analyze the output of each material. Results show that high-density polyethylene (HDPE) and mild steel (MS) are high efficient than aluminum (Al) which has very immense internal thermal resistance of PCM material encapsulated in spherical capsules.

Archibold [2014] presented a study to obtain analytical solution of thermal transmission and change of phase that occurs during the solidification process of a phase change material (PCM) enclosed in a spherical vessel. A time dependent 2-D axisymmetric mathematical model was solved using control volume discretization approach along with the enthalpy-porosity method to track the melting point. A comprehensive analysis provides the access to study the role of the capsule size, buoyancy-driven flow in the liquid phase, and shell outer surface temperature on the thermal output of the system. 39.25% reduction in solidification time predicted when the Stefan number changed from 0.095 to 0.143. The model based on the predicted thermal transmission results states that the natural convection heat transfer mode was found to be negligible during the solidification of $NaNO_3$, under calculated limitations. The model also found that the conduction heat transfer mode controls the energy transport with the isotherms in the solid portion coincident with the solution of the Laplace equation and also overall energy transferred by natural convection is less in solidification of solidification of $NaNO_3$ than conduction.

Kanimozhi [2014] presented a study on thermal transmission applications in domestic as well as industrial domains based on experimental and analytical results. Various types of heat transfer system had been discussed in this study. The thermal energy storage system with phase change material (PCMs) due to latent heat storage property gaining prominence these days. The energy conservative methods which are useful to conserve energy are discussed. Thermal energy storage with PCMs in solar applications is very much attractive and useful.

Jaffal [2014] presented a theoretical analysis to enhance the output of solar Organic Rankine cycle power generation system with packed bed thermal energy storage using phase change material (PCM). A finite difference technique used to study the numerical behavior of the storage system with paraffin as a PCM during charging and discharging process. Study show that effective thermal efficiency of the solar Organic Rankine cycle effected by various limitations such as inlet temperature, mass flux, and bed porosity, the diameter of capsule and turbine inlet temperature.Theoretical results and experimental results of the previous study has been compared. Results show that turbine inlet temperature plays a key role in the geometrical limitations of the packed bed. High inlet coolant temperature decreases the total charging time of PCM by increasing the thermal storage whereas lower porosity increases discharging time for PCM.

Khot [2014] studied the effect of HS-58 phase change material (PCM) on the thermal storage system for domestic solar water heater. HS-58 encapsulated in spherical capsules. An experimental study done with and without phase change material with water giving same thermal input for both cases. The model proves that the performance of solar water with 26% of phase change material increased 22% thermal capacity. Study states that thermal storage system with phase change material utilized with higher size solar collector or storage system reduced to the same size of the collector. Higher size of the storage tank with phase change materials will bring larger and cheaper thermal storage capacity compared to conventional system.

Bellan [2014] presented a 2-D two-phase model to investigate the dynamic nature of a packed bed thermal energy storage system with phase change material (PCM-sodium nitrate) encapsulated in spherical capsules. High-temperature synthetic oil (Therminol 66) is used as coolant. Inner thermal transmission coefficient and inner flow of the capsules are calculated by enthalpy formulation model and the extended Brinkman equation. The effect of capsule size, fluid temperature (Stefan number), tank size (length and diameter), fluid flow rate and the insulation layer thickness of tank wall on the output of the system investigated using developed model after validation. Analysis on the dynamic behavior of the system during partial charging and discharging cycles are directly proportional to the capsule size, fluid flow rate, or inversely proportional to the Stefan number, results in an inflation in the thermocline region which finally decline the effective discharge time and the total energy utilization.

Bellan [2015] presented a study on a concentrating solar power plants with latent thermal energy storage system with sodium nitrate encapsulated in spherical capsules as phase change material (PCM) and a high-temperature synthetic oil, Therminol 66, as coolant. The behavior of the system is investigated with a numerical model and validated using data obtained from experiments and analytical solution.The natural convection effect calculated by effective thermal conductivity and calculated by enthalpy formulation method. Experimental results show that increase in thermal transmission rate eventually decrease the charging/discharging time with decrease in capsule size, or with increase in coolant flow rate . Numerical results show the thermal transmission rate inversely proportional to the capsule size due to the surface to volume ratio, and the complete melting time is shorter than the solidification time due to the convection effects during the melting process. This model provides more accurate results than continuous phase model along with more details of the fluid flow and thermal transmission aspects of the system.

Chaichan [2015] presented a study on thermal energy storage from the concentrated solar water heater for distillation of water. Paraffin wax used as phase change material which stores energy in the form of enthalpy of fusion energy used for the study. Energy stored during the daytime used later during the night time. Addition of the phase change material helped to keep the water warm even due to lack of insolation from the sun. In this study concentrated solar collector is used but in my study flat plate solar collector with paraffin inserted into aluminum cylinders.

Naghavi [2015] developed a theoretical model of a solar water heater consisting of an series of evacuated tube heat pipe solar collectors connected to a common manifold filled with phase change material(PCM) which acts as a enthalpy of fusion storage tank. The analysis was conducted using the actual data collected in Malaysia, for both charging and discharging processes of PCMs. The results show that the output of the proposed system was more than the baseline system for supply of water flow more than 55 mph. Developments to collector area and fin design needed for the study to obtain better results. Experiment need to be carried out to compare the results with the theoretical results.

Hamed [2015] made an analysis on the dynamic thermal nature of a flat plate solar collector with a phase change material (PCM) using theoretical model. Energy balance equations were developed and executed using MATLAB program for the various components of the collector along with (PCM). The effect of inlet water temperature, water mass flux, and PCM thickness on the outlet water temperature and the melt fraction during charging and discharging modes in investigated using the developed model. A correlation with and without PCM was made which shows that addition of PCM caused a decline in temperature during charge and an increment during discharge. The results from the analysis show that the total melting time was shorter than the solidification time due to the high thermal transmission coefficient during melting. The results also show that times for melting and solidification are nonlinear with change in mass flux and thickness of PCM.

Mohammad [2016] made a study on thermal energy storage system (TES) with phase change materials (PCMs). A transient thermal transmission and melting process in a PCMs are investigated by performing experiments in a rectangular chamber filled with paraffin wax as the PCM. Cylindrical copper tube with different geometries and orientations used as thermal source. Results show a nonlinear melting rate of the PCM and a wavy and non-uniform profile of the solid-liquid interface due to the development of convective motions within the liquid PCM. Results show considerable improvement in various thermo physical limitations of the PCMs with a small percent addition of Nano-particles.

Subramaniam [2016] presented a study on the output of solar flat plate collector with phase change material (PCM) in an Integrated Collector Cum Storage Solar Water Heater (ICSSWH) which uses enthalpy of fusion property as it accumulates energy by changing phases. Paraffin wax selected as PCM which is less expensive and long period-thermal efficiency. Results show that Integrated Collector Cum Storage Solar Water Heater (ICSSWH) solar flat plate collector with PCM gives high thermal efficiency than conventional storage system. PCM helped to keep water warm for more than period of 5 hours with minimum heat losses and conservation of energy.

Muhammad [2016] studied the effect of the Nano fluids on the thermal performance of the solar water collectors. The mixture of solid-liquid is called a Nano Fluid. The size of a Nanoparticle is 100 nm. The Nanoparticles mixed with water or ethylene glycol is used as a coolant in solar water heater.Nano fluids enhanced the thermal conductivity of the coolant and helped to increase the performance of the solar collectors. Nano fluids are not as effective as PCMs in storing thermal energy.

Mousa [2016] presented a study on the water desalination using flat plate solar collectors with phase change materials. The production of water was zero when there was no phase change material as there was no heat during night time. However, the process of desalination was achieved by using phase change materials which store thermal energy during daytime and releases thermal energy during night time. Phase change material (PCM) with melting temperature of 40°C stored more energy but shown a negative effect on the production. The flow rate of the water also affected the production of desalination. However high melting temperature of the PCM and lower water feed flow rate can improve the performance.

Ahmadi [2016] presented a study which investigated the thermal output of the flat plate solar collector using Graphene Nanoplatelets. The output of the flat plate solar collector was tested both experimentally and theoretically. The ultrasonic method has been used to disperse the Graphene Nano Platelets in deionized water and the results indicate that the Graphene Nano Platelets can increase the energy efficiency of the flat plate solar collectors. Graphene Nano Platelets can improve the thermal efficiency but they cannot store the thermal energy like PCMs.

Papadimitratos [2016] presented a study on a method which phase change materials(PCMs) integrated into evacuated tubes in a solar water heater. The heat pipes immersed into the PCMs which helped to keep the water warm for a long time even due to lack of insolation from the sun. Thermal insulation around the evacuated tubes helped to accumulate heat for longer periods. Two different phase change materials , Tritriacontane and Erythritol with melting temperatures 72°C and 118°C were used for the study. The dual PCM usage improved the output of the solar water heater in both normal operations and on-demand operation. The present study uses only one type of phase change material that too packed in aluminum cylinders and installed in the tank.

Hamed [2017] present a study on a transient flat plate solar collector with an integrated phase change material (PCM) which uses enthalpy of fusion storage property to store thermal energy. Thermal nature of the system predicted using a theoretical model based on first and second law of thermodynamics. An effective thermal conductivity gives the effect of natural convection on heat during melting. Study discusses the affect of PCM thickness on melting fraction, the energy and the exergy destroyed during charging and discharging processes. Results show that melting time is shorter than solidification time and the latent heat storage by using phase change material increased thermal energy to meet heat requirements at night and reduced the exergy efficiency. Study also proved that the system with the thermal unit has more advantage than a system without thermal storage unit.

Manjunath [2017] studied the effect of the new kind of organic phase change material on energy storage. A specific grade of refined BITUMEN used as a phase change material. The new phase change material used in energy storage has concurrently working thermal -absorbing units such as solar water heater and thermal energy storage unit consists of the phase change material which is packed in spherical capsules. The new phase change material achieved high temperatures, it also reduced the Charging time and the arrangement of having a sequence of forced (active) and natural (passive) circulation for a closed loop operation has better results when correlated to single arrangement charging. The model produced better results with PCMs which uses enthalpy of fusion storage than conventional storage system which uses sensible heat storage system.

Xie [2017] presented a study on research methods and thermal transmission improving mechanisms on water tanks integrated with phase change materials (PCMs). Study explains various functions of the water tanks with phase change material and provides the understanding of the research and development of water tanks with phase change material along with promotion of functions water tanks with PCMs in solar heating systems.

Kumar [2017] presented a study of an active thermal storage system with phase change materials (PCM) a solar drying kiln based on the melting and solidification of PCM. The study uses a double glass glazing prototype solar kiln with a water storage tank with PCM placed inside a high-density polyethylene containers. An evacuated tube collector array with the help of solar energy heats water to obtain the melting and solidification temperature curves of PCM during charging and discharging process of water. Results show that reduction of heat in the system using paraffin wax is less than fatty acid based PCM. Study conclude that PCM is suitable for designing an active thermal storage systems.

Raj Kumar [2017] investigated the melting and solidification processes of paraffin wax as a phase change material (PCM) in a latent heat storage unit by performing experiments. PCM filled in a spiral with twisted tape. Study concentrates on temperature variations along the axial distances in PCM, thermal transmission coefficient and thermal flow rate. Experiments shows influence of increase in inlet temperature and the mass flux of the coolant on charging and discharging processes of the PCM. Study concludes that thermal behavior of phase change material improved by including Nanoparticle with PCM which increases thermal conductivity that leads to increase in thermal energy storage.

Kee [2018] presented a study on incorporating the solid-liquid organic phase change materials in solar water heaters as to overcome the restrictions of low thermal stability and conductivity. Many studies made to overcome those problems. The study reviewed and made an analysis on the influence of polymer/porous materials composition, nanoparticles loading and photo-absorption properties of photo thermal energy conversion material on the thermal stability, thermal conductivity and light absorption of composite PCMs. The study improved the properties of the existing PCMs and lead to discovery of the new PCMs. The study conclude that PCMs with a melting temperature range of 40-70°C are suitable for soalr water heaters (SWH).

3. THEORETICAL MODEL AND GOVERNING EQUATIONS

The model developed in this study extensively relies on the Saleh [2012] model. The MATLAB code developed follows the computer code developed by Saleh [2012]. The model in the study allows for transient ambient temperature and irradiance, as obtained by measurement, for input to the simulation whereas the original Saleh [2012] model uses step-function ambient temperature and irradiance. The model developed in this study also considers the effect of phase change material (PCM) on thermal storage system.

This study uses a five element model to depict the transient behavior of the flat plate solar collector similar to that outlined in Zima and Dziewa [2011]. This study decomposes the flat plate collector in five elements, glass cover, the air gap between cover and absorber, fluid, absorber and the insulation layer, which are perpendicular to the fluid flow direction. Figure 3.1 shows the five different elements. Each element is divided into n-nodes in the direction of flow and an energy balance is performed on each element to derive a governing equation. The storage tank containing PCM is treated as a separate element.

Figure 3.1, shows the 5 different elements used to investigate the transient behavior of the collector. Transparent cover receives insolation from the sun. The irradiance passes through the cover and across the air gap where it strikes the absorber plate. The plate heats the fluid flowing through the tubes. Insulation is used to minimize the heat loss to the surroundings.

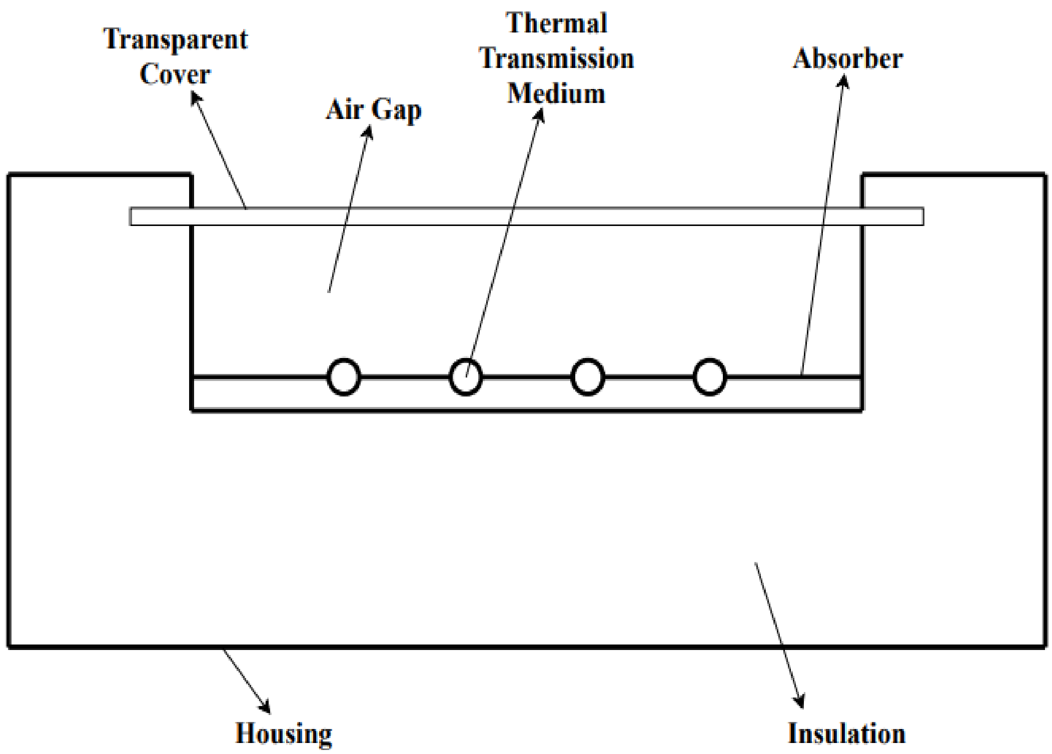

Fig. 3.1. Schematic of five different elements of the solar flat plate collector.

3.1 Mathematical Model Development

Following the approach of Zima and Dziewa [2011] and Saleh [2012], an energy balance is performed for a typical node in each element. A general energy balance is given by:

$$\frac{dE_{st}}{dt} = \dot{E}_{in} - \dot{E}_{out} \tag{3.1}$$

where dE_{st}/dt is the change of energy stored in the element, $\dot{E}_{in}$ is the rate of energy transfer in, and $\dot{E}_{out}$ is the rate of energy out. If n nodes are considered in the direction of flow then the total number of nodes the model contains is a result of $(5 \times n)$ nodes. An additional node is required to describe the tank.

Investigation of the flat plate collector made simple by some assumptions under transient conditions :

- The mass flux in the collector tubes is considered uniform so that total mass of fluid flowing through the collector is equally distributed in each tube.
- Thermal transmission in the system between layers is one-dimensional.
- Thermal transmission with the flow direction is zero, mass transfer in the reason for the energy transmission in the direction of flow.
- Thermal transmission from the edges of the collector is negligible.
- The properties of glass and insulation are considered to be stable. Their effect is independent on the investigation of the transient behavior of the collector.
- Change in temperature results change in thermo-physical properties of the fluid, air gap and absorber i.e., properties changes with a change in temperature.
- The radiation from the sky and ambient conditions are transient i.e., changes with time .

- Similar ambient temperature results in thermal loss from front and rear.
- The sky acts as blackbody at an equivalent sky temperature.
- Dust and dirt due to atmospheric air accumulated on the collector are negligible.

3.1.1 Transparent Glass Cover

The temperature of the glass cover depends on the thickness of the glass. For the glass with minimum or small thickness allows the uniform temperature through it. Derivation of the governing equation is derived depending on the glass properties. An energy balance under a differential volume of thickness δ_c and area of ($p\Delta$z) used to derive governing equation. Thermal transmission in the glass due to convection between the glass and the ambient temperature in addition to insolation from the absorber as shown in figure 3.2.

The governing equation for transparent glass cover from equation 3.1 can be written as:

$$c_g \rho_g V_g (\frac{dT_g}{dt}) = [h_{g,am}(T_{am} - T_g) + h_{r1}(T_{ab} - T_g) + h_{c1}(T_a - T_g) + \alpha G] p \Delta z \tag{3.2}$$

where:

c = specific heat of the fluid

V = volume of the fluid

T = temperature

t = time

h = heat transfer coefficient

ρ = density of the fluid

α = absorption coefficient

G = thermal flow rate of insolation

p = tube pitch

Δz = spatial size of control volume

subscripts:

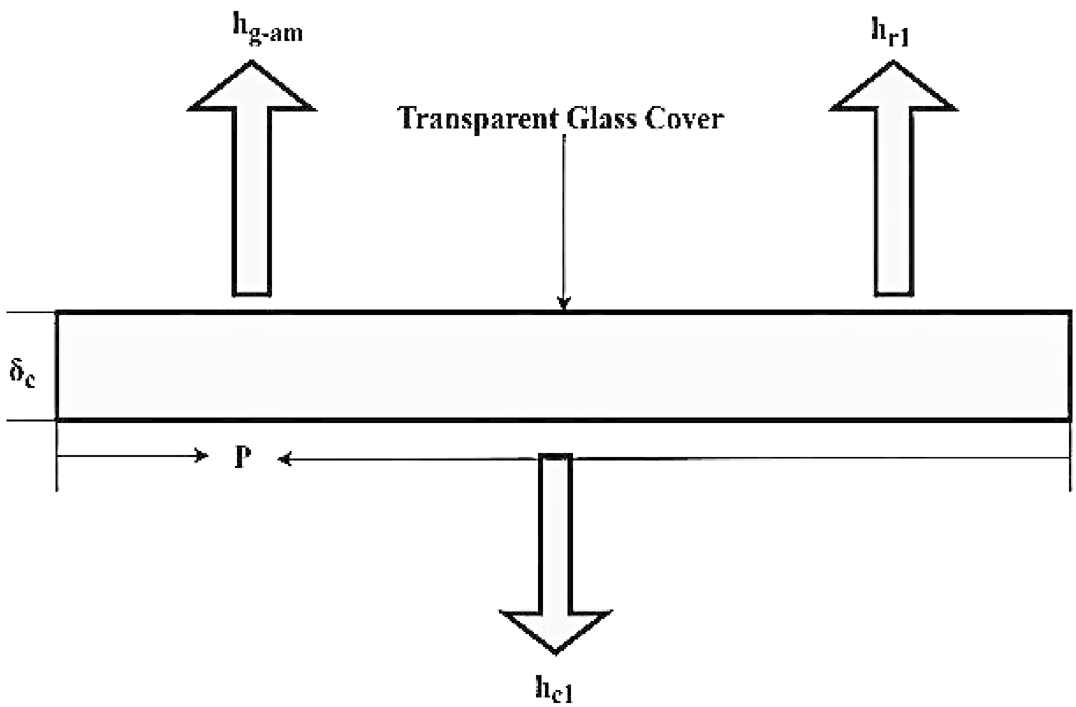

Fig. 3.2. Schematic of thermal transmission in the transparent glass cover.

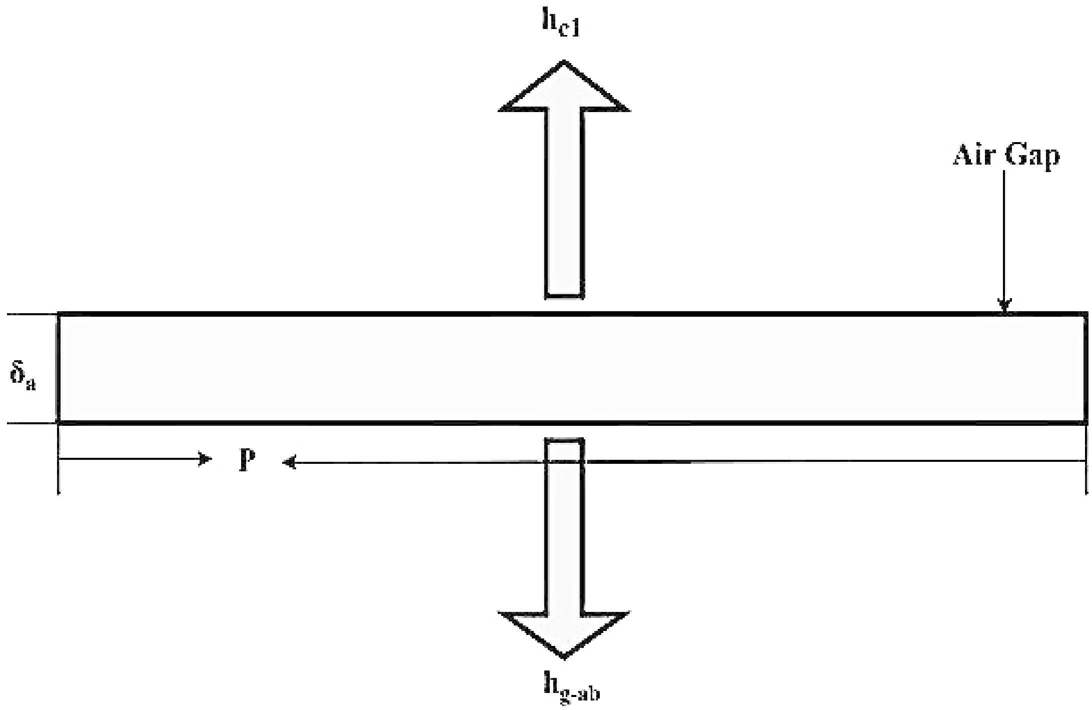

Fig. 3.3. Schematic of thermal transmission in the air gap between cover and absorber.

am = ambient

g = glass cover

a = air gap

ab = absorber

r = radiation

c = convection

3.1.2 Air Gap

A gap for air passage is present in between cover and absorber of the collector. Analysis carried out considering the collector control volume and thermo-physical

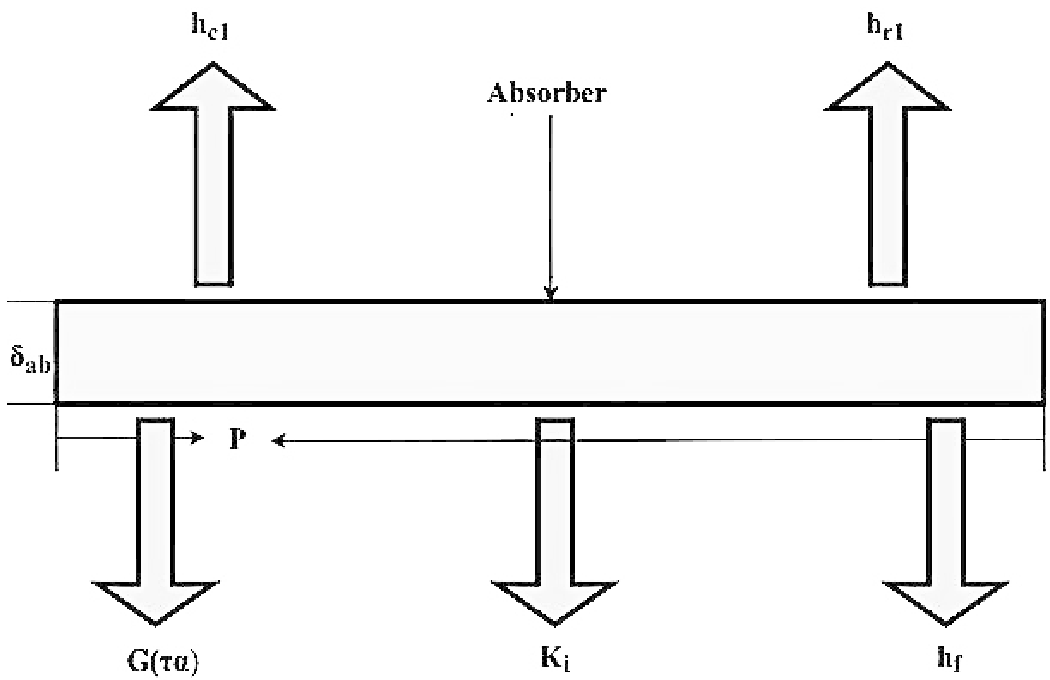

Fig. 3.4. Schematic of thermal transmission in the absorber.

properties of air. Analysis concludes that convection causes the thermal transmission through the gap between cover and absorber. The air gap is shown in figure 3.3. The governing equation for the air gap from equation (1) represented as:

$$c_a(T_a)\rho_a(T_a)V_a(\frac{dT_a}{dt}) = [h_{c1}(T_g - T_a) + h_{g.ab}(T_{ab} - T_a)]p\Delta z \tag{3.3}$$

3.1.3 Absorber

The absorber zone which shown in figure 3.4 investigated with the application of the heat energy balance equation.Thermal energy balance equation developed by considering the transient thermo-physical properties of the absorber material and the insolation on the absorber zone through the control volume of the collector, emission between the absorber and the glass cover, the conduction through the absorber and the insulation zone and the thermal transmission by convection with the flow of fluid, results in the following equation:

$$\begin{aligned} c_{ab}(T_{ab})\rho_{ab}(T_{ab})V_{ab}\frac{dT_{ab}}{dt} &= [G(\tau\alpha) + h_{r1}(T_g - T_{ab}) + h_{c1}(T_a - T_{ab}) \\ &\quad +(\frac{k_i}{\delta_i})(T_i - T_{ab})]p\Delta z + \pi d_{in} h_f \Delta z(T_f - T_{ab}) \end{aligned} \tag{3.4}$$

where:

$\tau\alpha$ = effective transmittance-absorption coefficient

k = thermal conductivity

δ = thickness

d = diameter

subscripts:

i = insulation

f = working fluid

in = inner

3.1.4 Insulation

The insulation zone shown in figure 3.5 investigated with thermal energy balance equation at collector control volume considering the insulation material properties to be constant. The properties considered for the analysis on the insulation zone are the conduction thermal transmission between the insulation and the absorber with the emission between the insulation and surroundings with ambient temperature.

The governing equation for the insulation zone from equation (1) represented as:

$$c_i\rho_i V_i(\frac{dT_i}{dt}) = h_{i.am}(T_{ab} - T_i) + (\frac{k_i}{\delta_i})(T_{ab} - T_i) \tag{3.5}$$

3.1.5 Working Fluid

Variation depending on time in total energy and the thermal transmission to control volume of fluid taken into consideration. Figure 3.6 shows the energy balance

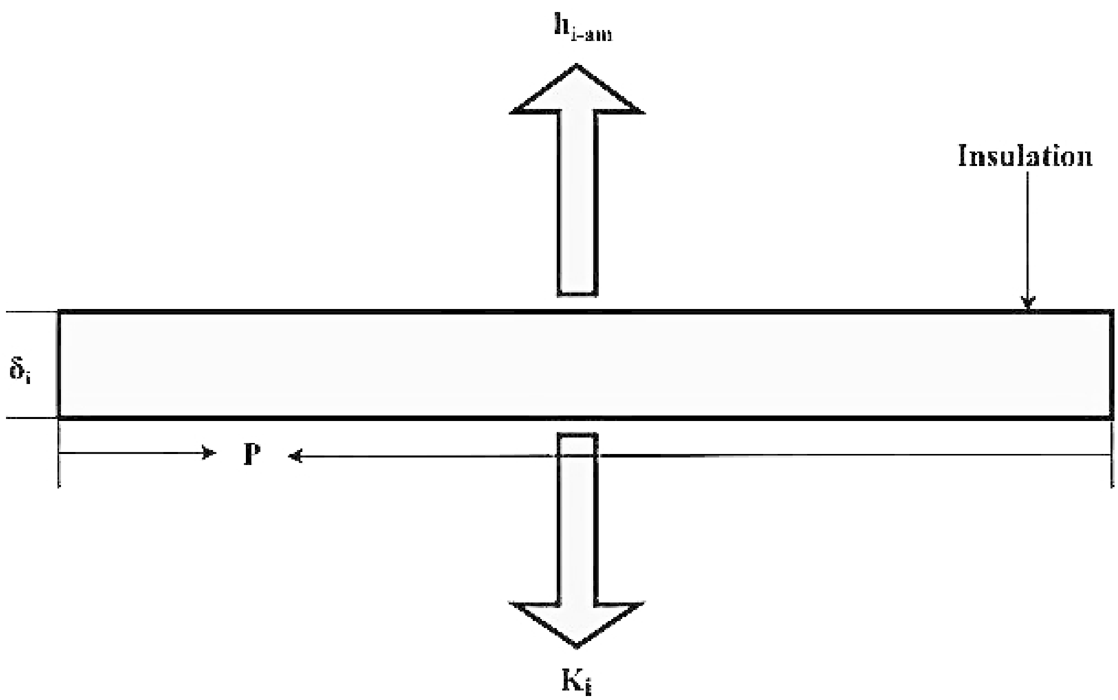

Fig. 3.5. Schematic of thermal transmission in the insulation.

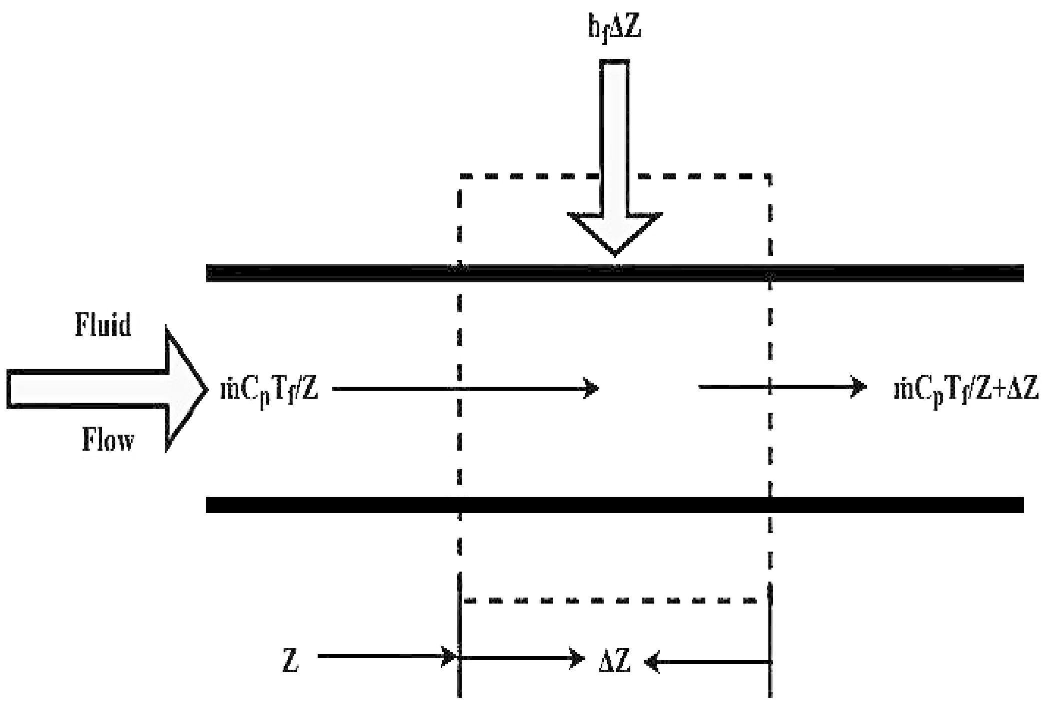

Fig. 3.6. Schematic of a energy balance in a control volume of the working fluid in the flat-plate solar collector.

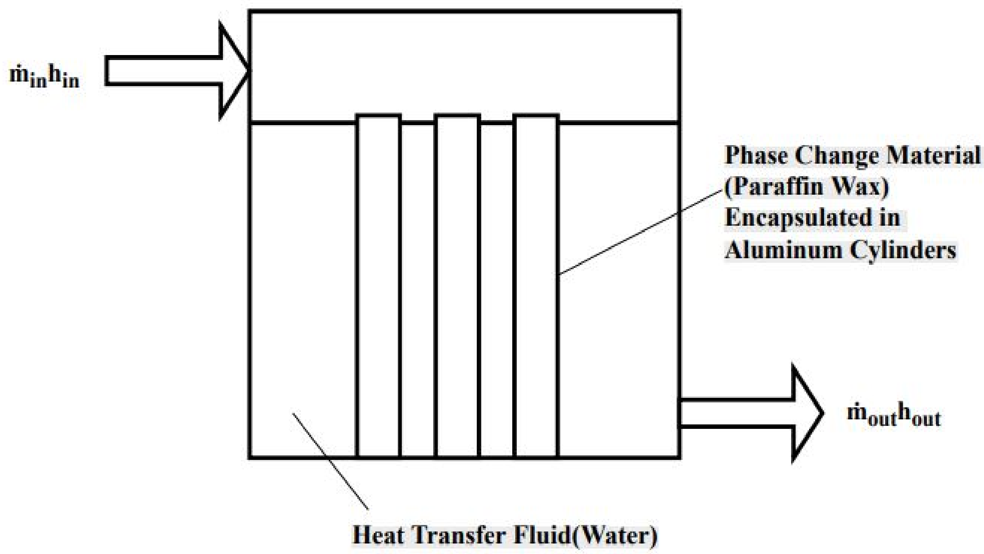

Fig. 3.7. Schematic of a storage tank with phase change material.

of the working fluid in a control volume of collector which works under transient properties of the working fluid can be represented as:

$$c_f(T_f)\rho_f(T_f)A(\frac{\partial T_f}{\partial t}) = \pi d_{in} h_f(T_{ab} - T_f) - \dot{m} c_f(T_f)(\frac{\partial T_f}{\partial z}) \tag{3.6}$$

where A is the pipe cross-sectional area and $\dot{m}$ is working fluid mass flow rate.

3.1.6 Storage Tank with PCM

Figure 3.7 shows the storage tank with phase change material. The equation for the storage tank is obtained from the application of first law of thermodynamics for a control volume. The equation is represented as follows:

$$c_{tank} m_{tank} \frac{dT_{tank}}{dt} = h_{loss} A_{tank}(T_{am} - T_{tank}) + \dot{m}_{total} c_f(T_{f,N} - T_t) \tag{3.7}$$

where

$$c_{tank} m_{tank} = c_{water} m_{water} + c_{drum} m_{drum} + c_{PCM} m_{PCM} \tag{3.8}$$

For the PCM,

$$(cm)_{PCM} = f(cm)_{PCM,s} + (1-f)(cm)_{PCM,l} \tag{3.9}$$

where subscript s indicates solid and subscript l indicates liquid, and f is the fraction of solid. Note that when $T < T_{melt}$, $f = 1$ and $T > T_{melt}$, $f = 0$. At $T = T_{melt}$, $0 < f < 1$.

3.1.7 Phase Change Materials

To illustrate the behavior of phase change materials consider a system containing water and PCM. The system is considered to lumped or isothermal so that the temperature of water and the PCM are the same. Enthalpy of fusion has the unique property of absorbing heat and releasing heat by changing phases i.e., from solid to liquid and liquid to solid. The following equations leads to the calculation of the change in the temperature of the water from time 1 to time 2:

$$T_{sys,2} = \frac{Q}{m_w c_w + m_{pcm,s} c_{pcm,s}} + T_{sys,1}, \quad \text{when} \quad T_{sys} < T_m \tag{3.10}$$

$$T_{sys,2} = \frac{Q}{m_w c_w + m_{pcm,l} c_{pcm,l}} + T_{sys,1}, \quad \text{when} \quad T_{sys} > T_m \tag{3.11}$$

In the above equations,

T_{sys} = temperature of the system, i.e. water + PCM

Q = amount of heat added

T_m = melting temperature of the phase change material = 56°C

m_w = mass of the water = 74 kilograms.

m_{pcm} = mass of the phase change material = 22.4 kg

c_w = specific heat of water = 4186 J/kg-K

$c_{pcm,s}$ = specific heat of phase change material in solid state = 2140 J/kg-K

$c_{pcm,l}$ = specific heat of phase change material in liquid state = 2900 J/kg-K

When $T = T_{melt}$, the heat added (lost) causes the PCM to melt (solidify) not change

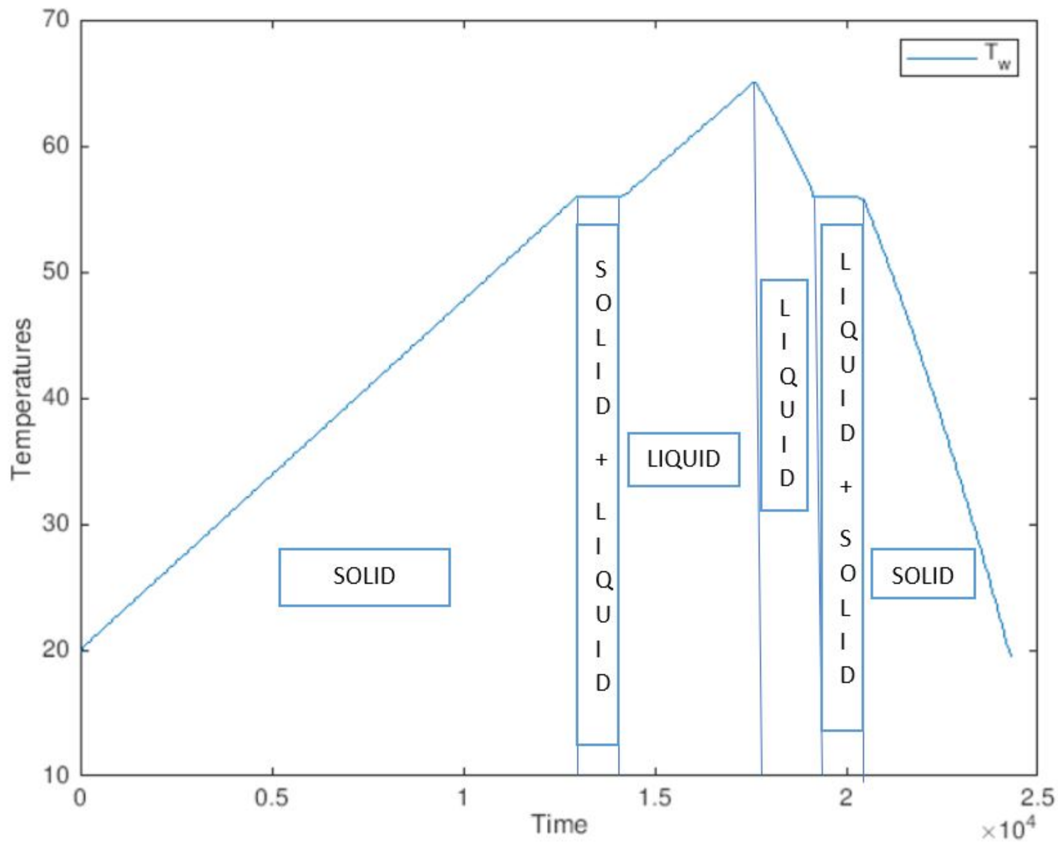

Fig. 3.8. Temperature variation of system (water+PCM) during heating and cooling process.

temperature. The entire amount of material melts when the heat input equals the latent heat of fusion, i.e., $Q = m_{pcm} \times L$. For paraffin wax, $L = 160$ kJ/kg.

Enthalpy of fusion is one of the best methods to store thermal energy. Thermal energy is stored by changing phases from liquid to solid and liquid to solid vice versa. Enthalpy of fusion is higher than sensible heat storage due to the high change in enthalpy during the change in phase. Enthalpy of fusion provides more storage density compare sensible heat storage with less temperature change during charging and discharging process. Figure 3.8 shows the behavior of the PCM. PCM will be in solid state until melting temperature is reached. Temperature will be constant for a while until the PCM melts completely and then temperature reaches maximum due to heat input and then begins to decrease slowly due to heat loss. Again the temperature will be constant for a while until liquid changes to solid after reaching solid state phase change material releases thermal energy to the coolant in the reservoir.

Equation 3.10 represents the charging process of the PCM, during this period PCM absorbs thermal energy and the system temperature rises. Once the melt temperature is reached, the PCM changes its state i.e., solid to liquid. When all the PCM changes phase from solid to liquid, sensible heating resumes and the temperature rises. Equation 3.11 represents the discharging process of the PCM. Initially the system temperature decreases, due to sensible cooling, until the solidification temperature is reached. During this stage stored energy during charging process released to the fluid in the reservoir by changing its state from liquid to solid. The stored energy is the enthalpy of fusion. During this stage phase change material will be in both solid-liquid phase. High amount of thermal energy will be released at this stage.

3.2 Numerical Formulation

A finite difference method leads to solution for the partial differential equations developed in the system. A forward and backward difference system replaces the time and dimensional derivatives, viz.

$$\frac{dT_m}{dt} = \frac{T_{m,j}^{t+\Delta t} - T_{m,j}^{t}}{\Delta t} \tag{3.12}$$

$$\frac{dT_f}{dz} = \frac{T_{f,j}^{t+\Delta t} - T_{f,j-1}^{t+\Delta t}}{\Delta z} \tag{3.13}$$

where m = indicator values g, a, ab, f, and i and j is the node number in the flow direction

The equations in the system represented with the following formula [Zima and Dziewa, 2011] and Saleh [2012]:

$$\begin{aligned} T_{g,j}^{t+\Delta t} &= (\frac{1}{F_j \Delta t})(T_{g,j}^{t}) + (\frac{B_j}{F_j})(T_{am}^{t+\Delta t}) + (\frac{C_j}{F_j})(T_{ab,j}^{t+\Delta t}) \\ &+ (\frac{D_j}{F_j})(T_{a,j}^{t+\Delta t}) + (\frac{E}{F_j})(G^{t+\Delta t}) \end{aligned} \tag{3.14}$$

$$T_{a,j}^{t+\Delta t} = (\frac{1}{H_j \Delta t})(T_{a,j}^{t}) + (\frac{G_j}{H_j})(T_{g,j}^{t+\Delta t} + (T_{ab,j}^{t+\Delta t}) \tag{3.15}$$

$$\begin{aligned} T_{ab,j}^{t+\Delta t} &= (\frac{1}{Q_j \Delta t})(T_{ab,j}^{t}) + (\frac{K_j}{Q_j})G^{t+\Delta t} + (\frac{L_j}{Q_j})T_{g,j}^{t+\Delta t} \\ &+ (\frac{M_j}{Q_j})T_{a,j}^{t+\Delta t} + (\frac{O_j}{Q\text{-}j})T_{f,j}^{t+\Delta t} + (\frac{P_j}{Q_j})T_{i,j}^{t+\Delta t} \end{aligned} \tag{3.16}$$

$$T_{f,j}^{t+\Delta t} = (\frac{1}{U_j \Delta t})T_{f,j}^{t} + (\frac{R_j}{U_j})T_{ab}^{t+\Delta t} + (\frac{S_j}{U_j \Delta z})T_{f,j-1}^{t+\Delta t} \tag{3.17}$$

$$T_{i,j}^{t+\Delta t} = (\frac{1}{X_j \Delta t})T_{i,j}^{t} + (\frac{V_j}{X_j})T_{ab}^{t+\Delta t} + (\frac{W_j}{X_j})T_{am}^{t+\Delta t} \tag{3.18}$$

$$
\begin{aligned}
T_{tank}^{t+\Delta t} &= \frac{\dot{m}_{tot}c_p(t_f)}{m_{tank}c_{tank}}\Delta\tau(T_{f,n}^t - T_{tank}^t) + h_{tank,amb}\frac{A_{tank}}{m_{tank}c_{tank}} \\
&\quad \times\Delta\tau(T_{am}^t - T_{tank}^t) + T_{tank}^t
\end{aligned}
\tag{3.19}
$$

where j = 1,2,....N is the number of nodes in the direction of flow.

In the above equations the coefficients are defined as:

$$
\begin{gathered}
B_j = \frac{h_{g,am,j}}{c_g\rho_g\delta_g}, C_j = \frac{h_{r1,j}}{c_g\rho_g\delta_g}, D_j = \frac{h_{c1,j}}{c_g\rho_g\delta_g}, E = \frac{\alpha}{c_g\rho_g\delta_g} \\
F_j = \frac{1}{\Delta t} + B_j + C_j + D_j \\
J_j = c_{ab}(T_{ab})_j\rho_{ab}(T_{ab})_j[p\delta_{ab} + \pi(r_{out}^2 - r_{in}^2)] \\
K_j = \frac{p(\tau\alpha)}{J_j}, L_j = \frac{h_{r1,j}p}{J_j}, M_j = \frac{h_{c,1},p}{J_j} \\
O_j = \frac{\pi d_{in}h_{f,j}}{J_j}, P_j = \frac{pk_i}{J_j\delta_j} \\
G_j = \frac{h_{c1,j}p}{c_a(T_a)_j\rho_a(T_a)(p\delta_{ab} + \pi r_{out}^2)}, H_j = \frac{1}{\Delta t} + 2G_j \\
Q_j = \frac{1}{\Delta t} + L_j + M_j + O_j + P_j \\
R_j = \frac{\pi d_{in}h_{f,j}}{c_f(T_f)_j\rho_f(T_f)_jA}, S_j = \frac{\dot{m}_f}{\rho_f(T_f)_jA} \\
U_j = \frac{1}{\Delta t} + R_j + \frac{S_j}{\Delta z}, V = \frac{2k_i}{c_i\rho_i\delta_i^2} \\
W_j = \frac{2h_{i,am,j}}{c_i\rho_i\delta_i}, X_j = \frac{1}{\Delta t} + V + Wj
\end{gathered}
\tag{3.20}
$$

The iteration procedure can be stopped by meeting all temperatures through the error criteria in the model proposed:

$$
\mid \frac{T_{j,(k+1)}^{t+\Delta t} - T_{j(k)}^{t+\Delta t}}{T_{j,(k+1)}^{t+\Delta t}} \mid \leq \vartheta \tag{3.21}
$$

where: T is the evaluated temperature in node j, ϑ is an acceptable tolerance of iteration (e.g. 10^{-4}), and k = 1, 2 is the iteration counter for every single time step. The time step is selected so the numerical simulation is stable

3.3 The Heat Transfer Correlations

The following formulae are used to complete the model [Zima and Dziewa, 2011] and Saleh [2012].

The emission between absorber and glass cover, Duffie and Beckmann [2006] is given by

$$h_{r1,j} = \frac{\sigma(T_{ab,j}^2 + T_{g,j}^2)(T_{ab,j} + T_{g,j})}{(\frac{1}{\varepsilon_{ab}}) + (\frac{1}{\varepsilon_g}) - 1} \tag{3.22}$$

where h is the thermal transmission coefficient, σ is the Stefan-Boltzmann constant, and ε is the emissivity.

The air gap which is inclined has the free convection.

$$h_{c1,j} = \frac{Nu_{a,j} k_{a,j}}{\delta_a} \tag{3.23}$$

Hollands [1976] developed formula to calculate the Nusselt number used in the above equation.

$$\begin{aligned} Nu_{a,j} &= 1 + 1.44[1 - \frac{1708[\sin(1.8\beta)]^{1.6}}{Ra_j \cos(\beta)]}] * [1 - (\frac{1708}{Ra_j \cos(\beta)})]^{+} \\ &\quad +[(\frac{Ra_j \cos(\beta)}{5830})^{1/3} - 1]^{+} \end{aligned} \tag{3.24}$$

with

$$Ra = \frac{g\beta\Delta T L^3}{\upsilon\alpha} \tag{3.25}$$

where Ra = Rayleigh number, β = the thermal expansion coefficient, L = the length of the pipe, υ = the kinematic viscosity, α = the thermal diffusivity. The sections expressed by "+" in the above formula must be recognized only they assume positive values. Zero value taken in case of negative assumption.

Duffie and Beckmann [2006] developed equation to calculate convection on the external surface of the cover and insulation.

$$h_{c2} = \frac{Nu_{am} k_{am}}{\delta} \tag{3.26}$$

where

$$Nu_{am} = 0.86 Re_{am}^{\frac{1}{2}} Pr_{am}^{\frac{1}{3}}, \delta = \frac{4ab}{\sqrt{a^2 + b^2}} \tag{3.27}$$

and Re = Reynolds number and Pr = Prandtl number. a and b are length and width of the collector, respectively, in meters.

The thermal transmission coefficient on the outer surface of the glass is given by

$$h_{g,am,j} = \frac{\sigma\varepsilon_g(T_{g,j}^4 - T_{sky}^4)}{T_{g,j} - T_{am}} + h_{c2} \tag{3.28}$$

The thermal transmission coefficient on the outer surface of the insulation is given by

$$h_{i,am,j} = \frac{\sigma\varepsilon_g(T_{i,j}^4 - T_{sky}^4)}{T_{i,j} - T_{am}} + h_{c2} \tag{3.29}$$

with the sky temperature calculated using $T_{sky} = 0.0552T_{am}^{1.5}$.

The thermal transmission on the inner surface of the collector tube is given by

$$h_{c1,j} = \frac{Nu_{f,j}k_{f,j}}{d_{in}} \tag{3.30}$$

The calculations of Nusselt number obtained using the empirical Heaton formula by Duffie and Beckman [2006], i.e.,

$$Nu_{f,j} = Nu_{\infty} + \frac{a(Re_{f,j}Pr_{f,j}(d_{in}/L))^m}{1 + b(Re_{f,j}Pr_{f,j}(d_{in}/L))^n} \tag{3.31}$$

which is valid for

$$1 < Re_{f,j}Pr_{f,j}\frac{d_{in}}{L} \leq 1000 \tag{3.32}$$

For fully developed flow in the tubes exposed to constant heat flux, the values of Nu, a, b, m, and n are 4.4, 0.00398, 0.0114, 1.66, and 1.12 are assumed.

4. EXPERIMENT APPARATUS AND PROCEDURE

This section describes the experiment apparatus and details the specific procedure followed to obtain results presented in Chapter 6.

4.1 Description of Experiment Apparatus

The core experiment apparatus used in the study was built by a 2014 mechanical engineering senior design team [Gaskill, 2014] with some modifications. The modifications to the core experiment include: new piping, a new pump, new data acquisition system along with reconfiguration of the cart for improved access and maneuverability.

4.1.1 Flat Plate Collector

Flat plate collectors made of SunMaxx Silicon Inc shown in figure 4.1 which is a simple and most popular design used in domestic heating system using solar power. Flat plate collector made with a simple idea which includes the heating of the dark colored flat plate using insolation from the sun.The dark colored flat plate gains thermal power which is transferred to the coolant which are in the form of water, air, or other fluids. The size of the collector is 2 m $\times$ 1 m. i.e., length 2 meters and width 1 meter respectively. The flat-plate collector consists of the following major parts :

- Absorber plate - designed to maximize absorbtion of solar irradiance.
- Glass cover - limits radiative and convective thermal loss from the surface with transparent layer that transfers emission to the absorber.
- 8 copper tubes - transfer fluid along the collector.

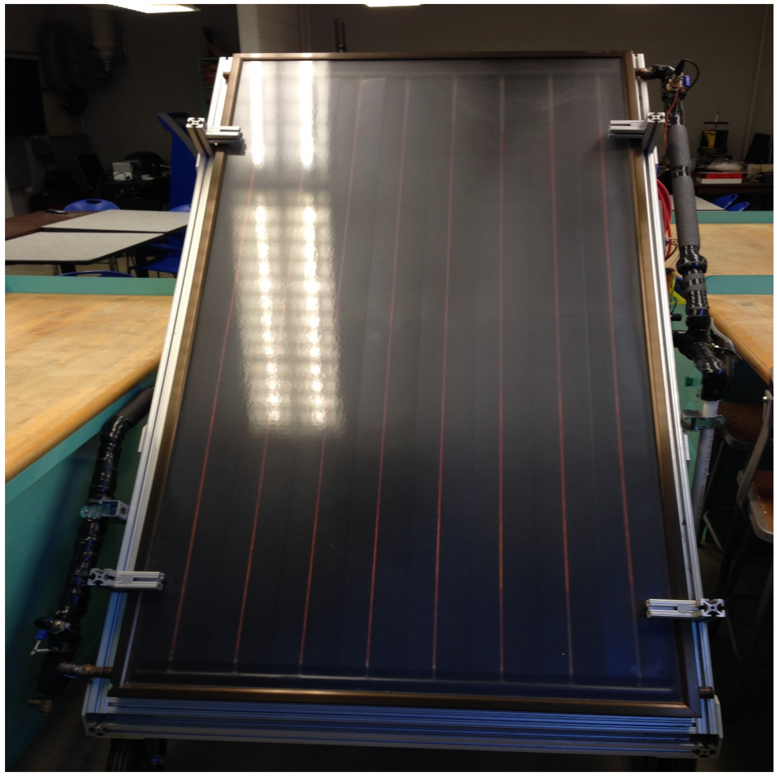

Fig. 4.1. Flat plate collector with copper tubes.

- Support structure - to protect and enclose all components
- Insulation - minimize thermal losses from sides and bottom.

4.1.2 Reservoir

The reservoir is a steel drum with a capacity of 113.56 liters which is equal to 30 gallons. The reservoir has an outer diameter of 0.48895 m height of 0.7366 m. The thickness of the reservoir wall is 0.0012 m. The reservoir covered with insulation in order to minimize the heat losses to surroundings. Water used in this study as working fluid.

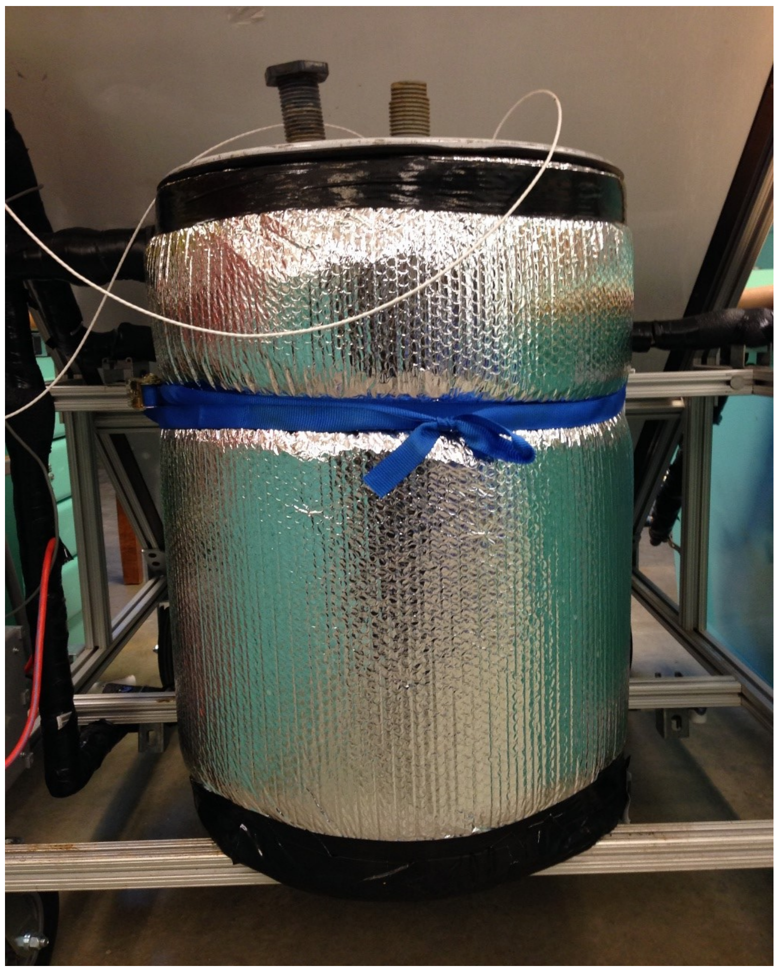

Fig. 4.2. Reservoir covered with insulation.

Fig. 4.3. Heat exchanger with phase change material (PCM).

Fig. 4.4. Heat exchangers fixed inside the reservoir.

4.1.3 Heat Exchangers

Heat Exchangers are cylinders made up of aluminium with an inner and outer diameters being 0.05115 m and 0.05715m. Height and thickness of the heat exchanger wall are 0.5386 m and 0.006 m. Heat exchangers are filled with paraffin wax in order to use the enthalpy of fusion storage property to keep water warm even during periods of reduced or no insolation. Heat exchangers are arranged inside the reservoir as shown in the figure. Heat exchangers are filled with phase change materials from the opening on the top the cylinders. After filling, the cylinders are sealed.

4.1.4 Phase Change Materials

Phase change materials (PCMs) are considered as latent heat storage units. PCMs can store and release energy by the changing from solid to liquid and liquid to solid vice versa by melting and solidifying at a certain temperature. PCMs have high enthalpy or latent heat of fusion. The unique property of the phase change materials helps to keep the water warm even in the absence of the solar radiation. Paraffin wax, an organic phase change material, is shown in figure 4.5.

Paraffin wax is inexpensive, readily available, and non-toxic. The paraffin wax used in this study has the following properties:

- melting temperature = 56°C
- enthalpy of fusion = 160 kJ/kg
- specific heat capacity for solid = 2140 J/kg-K
- specific heat capacity for liquid = 2900 J/kg-K

4.1.5 Solar Irradiance Meter

Solar irradiance meter shown in figure 4.6 is an instrument made by Seaward Technologies. Solar irradiance meter is designed to measure the irradiation which is

Fig. 4.5. Paraffin wax filled in aluminium cylinders.

[https://en.wikipedia.org]

Fig. 4.6. Solar irradiance meter.

Fig. 4.7. Flow rate valve.

coming from the sun and collector the flat plate collector. The irradiance can measure up to 5000 data points. The irradiance meter can measure data with three different intervals i.e., 1 minute, 30 minutes and 60 minutes. One minute interval is considered in this study i.e., data for every minute is taken. Data collected transferred to a computer using data cable.

4.1.6 Flow Rate Valve

Figure 4.7, shows the valve which adjusts the rate of flow in the tank. The flow rate plays a major role in the study. The rotation of The black knob at the bottom

Fig. 4.8. Water pump.

either clockwise or anticlockwise direction helps to adjust the flow rate. The clockwise rotation is used to increase the flow rate and the anticlockwise rotation is meant to decrease the flow rate. The flow rate can be varied from 0.5 Gallon per Minute to 3.5 Gallon per Minute. For this study, a constant flow rate of 1.5 Gallon per Minute is considered.

4.1.7 Water Pump

A small 3-speed water pump is used as shown in figure 4.8. The main purpose of the pump is to pump the water from reservoir to collector.The pumped water flow

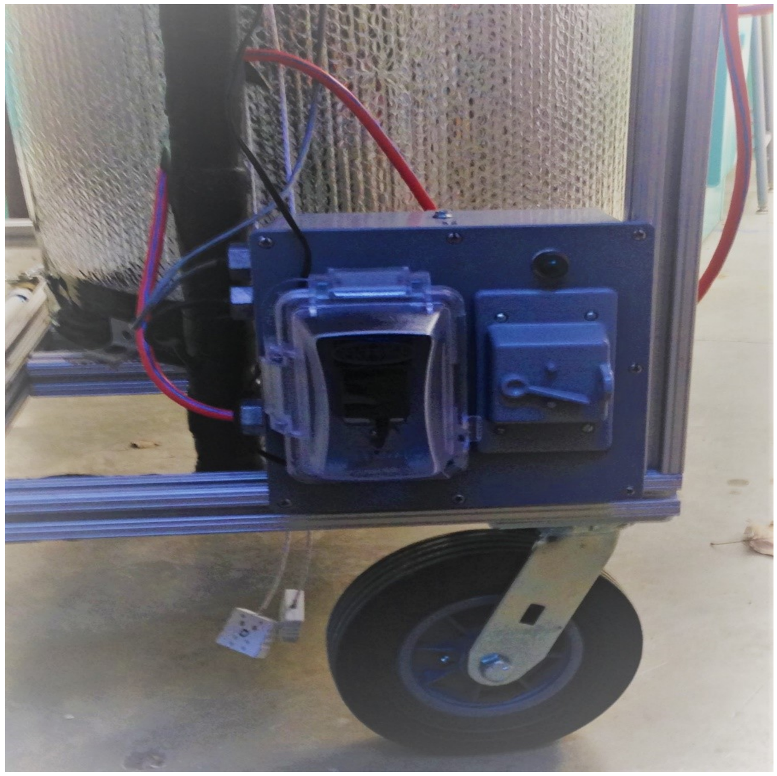

Fig. 4.9. Main power source.

through the copper tubes which are mounted in the flat plate collector absorb heat from the solar irradiance and return to the reservoir. The water pump can be operated at three different speeds. The speed of the water pump can be adjusted using the "RED" button which can be seen in the figure. The water pump is operated at speed 2 for this study. The water pump gets the power from the main power source.

4.1.8 Main Power Source

The water pump can be operated using the power from the main power source as shown in figure 4.9. The orange color extension chord which is 100 meters in length has a plug at another end can be connected to a power source. The capacity of the main power source is 12 volts. The water pump can be operated by the "ON/OFF"

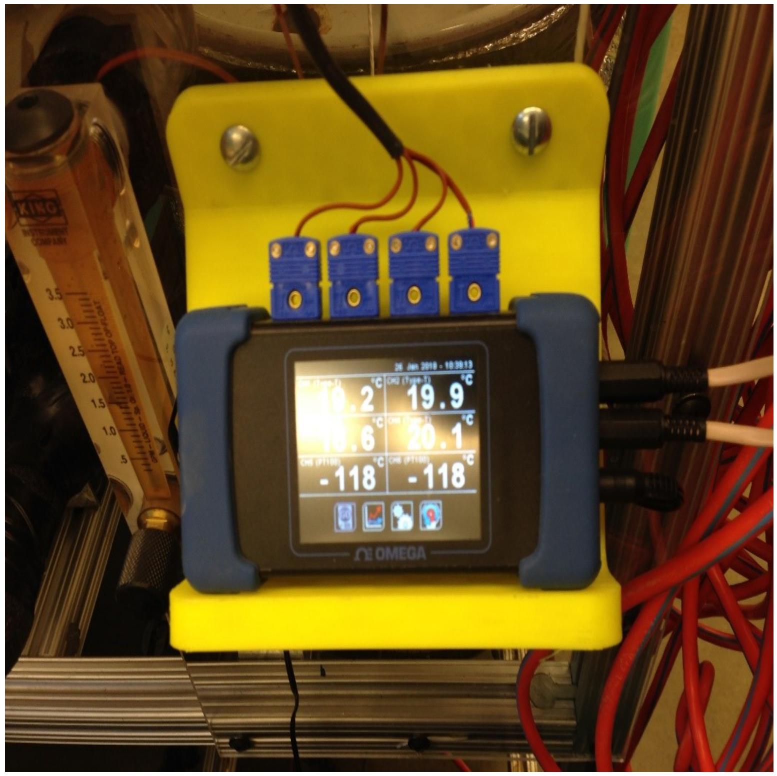

Fig. 4.10. Data logger.

which is connected to the main power source. The water pump remains "ON" during experiment.

4.1.9 Sensor

Thermocouples and Resistance Temperature Detectors are used as sensors to measure the temperature of the coolant and phase change materials(PCMs). Data logger made by Omega Engineering used to measure the temperatures. The data logger consists of 6 channels, 4 of them measure the inlet, outlet, coolant temperature in the tank and ambient temperature. The remaining 5 and 6 channels measures the temperature of the phase change materials. Data logger and various sensors are shown in the following figures 4.10 to 4.15. Data can be stored in an SD card and transferred to the computer.

Fig. 4.11. Inlet temperature sensor.

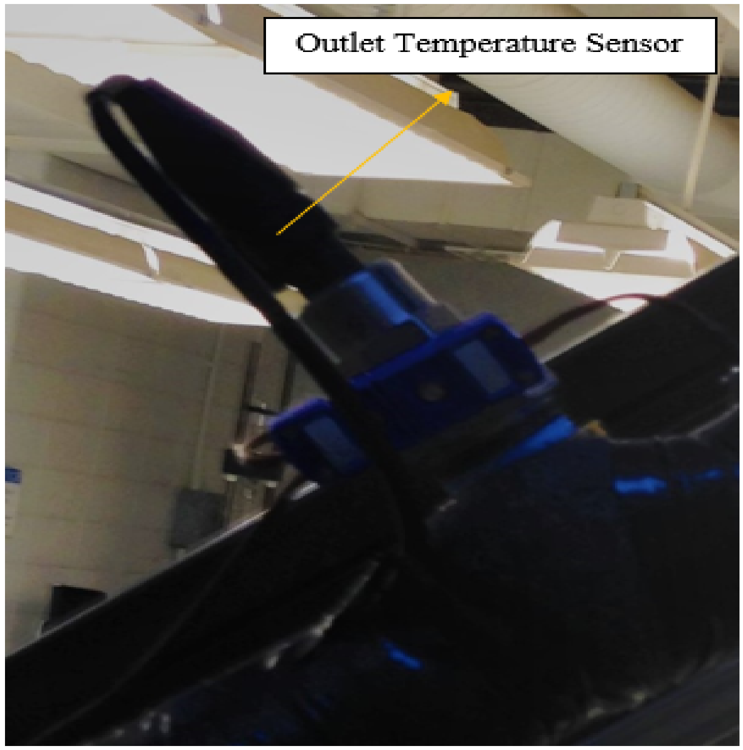

Fig. 4.12. Outlet temperature sensor.

The inlet temperature sensor is located at the lower left side of the collector obtained by channel 1. The temperature of the coolant entering to the collector is measured using the inlet temperature sensor.

The outlet temperature sensor is used measure the temperature of the water out of the collector which is obtained by channel 2.The outlet temperature is located upper right side of the collector.

The sensor inside the tank is used to measure the water temperature inside the tank by channel 3.

The ambient temperature sensor measures the ambient temperature which located below the collector and temperature is obtained by channel 4.

Figure 4.15 shows the resistance temperature detectors (RTD's) of the inner and outer cylinders. The RTD's measure the temperature of the phase change materials. The temperatures are obtained by channel 5 and channel 6.

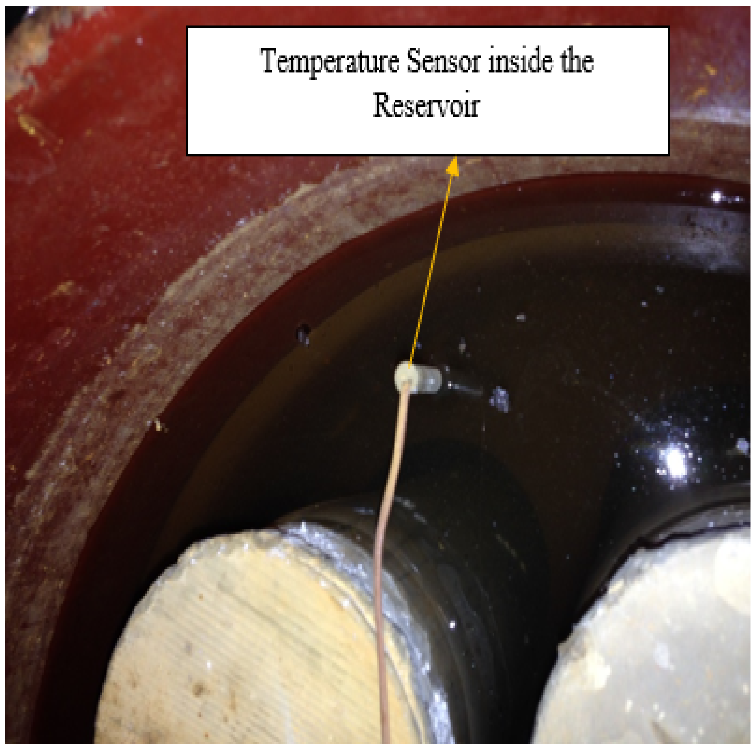

Fig. 4.13. Temperature sensor inside the tank.

Fig. 4.14. Ambient temperature sensor.

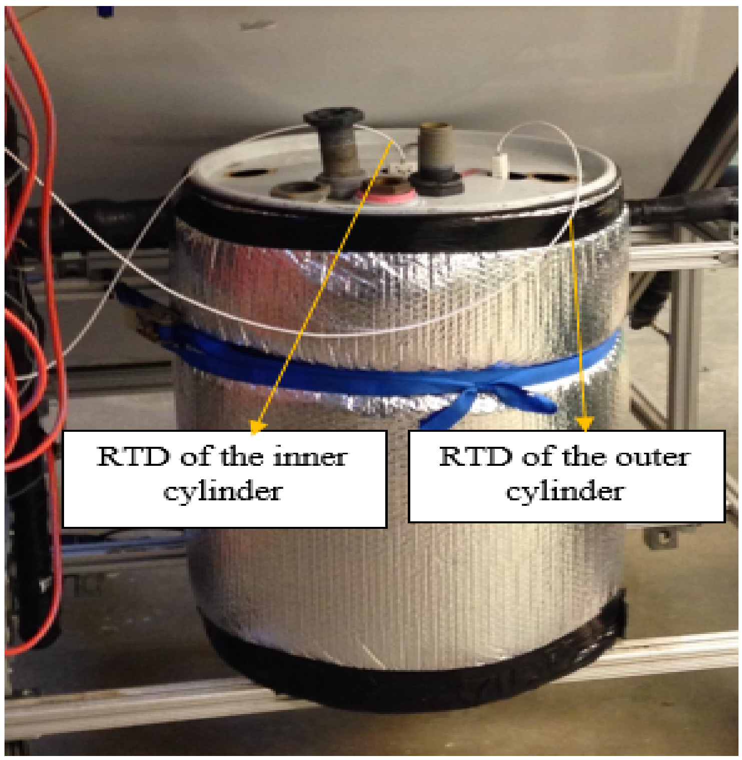

Fig. 4.15. Resistance temperature detectors (inner cylinder and outer cylinder).

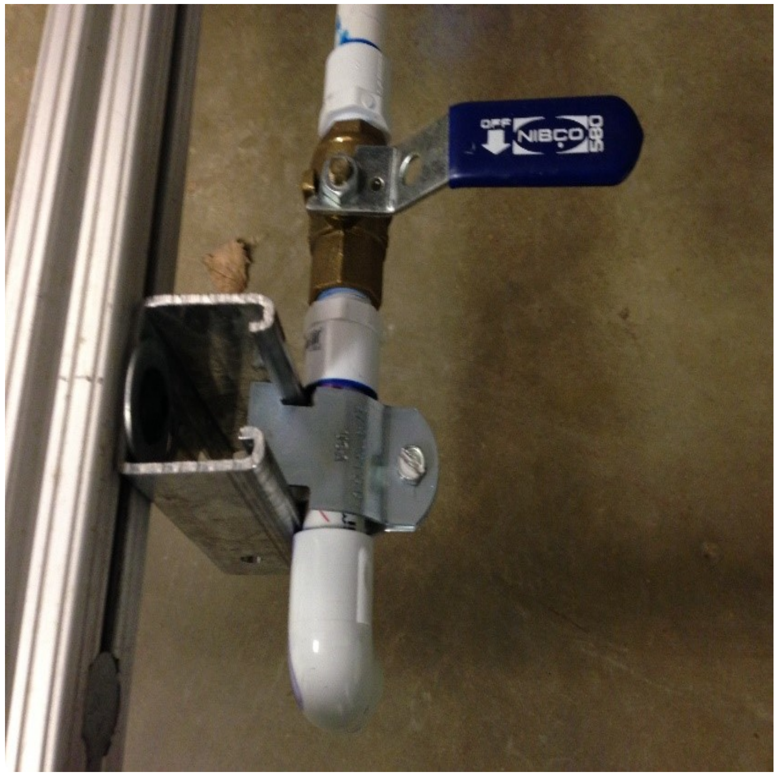

Fig. 4.16. Water drain.

The SD card is inserted into the data logger during the experiment. The data automatically saved to the SD Card during the experiment. The data from the experiment is transferred after the experiment is done to a computer.

4.1.10 Water Drain

Water drain which located below the reservoir helps to drain water from the reservoir.

4.1.11 Frame

The flat plate collector with thermal storage is shown in the figure 4.17. The wheels made of rubber at the bottom of the apparatus makes easy the movement

Fig. 4.17. Flat plate solar collector with thermal storage.

irrespective of weight. The frame supports both collector and reservoir. The collector is mounted at a fixed 45° degree angle.

4.2 Experimental Procedure

The main goal of the experiment is to keep the water warm even in the absence of the solar irradiance using phase change materials and compare with the theoretical model developed.

The experiments are performed in two different ways i.e., with cylinders filled with PCM in the reservior and without the cylinders in the reservior. In both cases, the experiments are performed for a steady flow rate of 1.5 GPM. The water was one for the entire experiment. The experiments are performed in the dock area outside ET 115, Engineering Technology Computer Science Building (ETCS), Purdue University Fort Wayne.

4.2.1 Experimental Procedure without PCM

- First of all the reservoir filled with water by using a hose at the dock area. The water level should be filled below the top tip of the temperature sensor which is inside the reservoir. The amount of water in the tank is approximately 100 L.

- Inlet, outlet, reservoir sensor and ambient temperatures are connected to their respective channels i.e., the inlet to channel 1, the outlet to channel 2, reservoir sensor to channel 3 and ambient temperature sensor to channel 4.

- The flow rate adjusted to 1.5 gallons per minute by using the adjustable knob with a 12V DC water pump by connecting the plug to a power source.

- The apparatus carefully wheeled outside under the shade and run for a while till the inlet, outlet and reservoir sensor gets to equilibrium. The apparatus faced towards the south in order to receive more solar radiation.

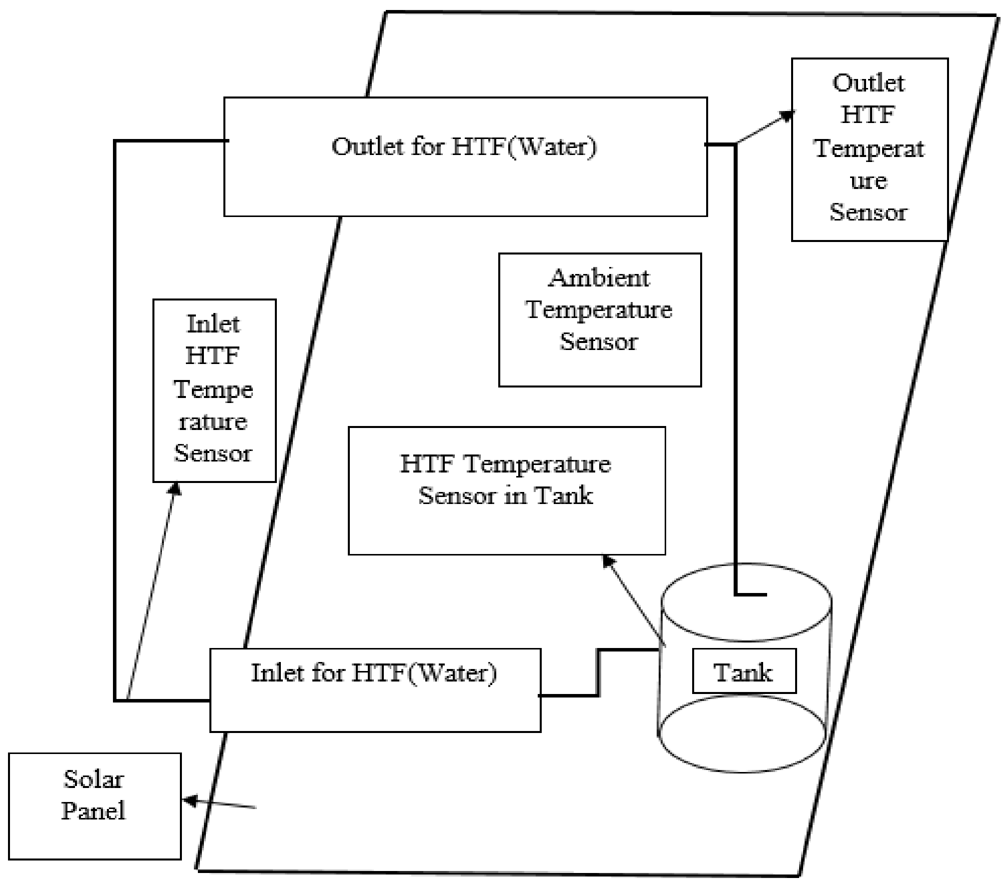

Fig. 4.18. Schematic of a flat plate collector without PCM.

- Once the equilibrium conditions are achieved, the SD card inserted into the data logger by adjusting the settings. The data collected by data logger for every minute automatically and saved to SD card provided.

- Solar irradiance meter fixed to flat plate collector at an angle of 45^o.The irradiance meter is set to collect data for every minute.

- Both data logger and solar irradiance meter are started at the same time and left undisturbed for the entire experiment time.

- The apparatus left outside for 24-hours. Note: For the 2-hr experiment, the apparatus place in the sun for one hour and then moved to the shade for one hour.

- After completing the experiment, data from data logger is transferred to the computer via the SD card.

- Solar irradiance meter also removed. To transfer data from irradiance meter to the computer drivers are needed. The drivers are available in the compact disc (CD) provided in the box. A data cable can be used to transfer data from irradiance meter to computer.

- After transferring the data, the water in the reservoir should be drained using the water drain provided at the bottom of the reservoir.

- The apparatus is wheeled back inside the building.

4.2.2 Experimental Procedure with PCM

- The experimental procedure is almost same and the only difference is wax cylinders are added to the reservoir. To record the temperature of wax cylinders, two more channels in the data logger are utilized. The new channels record tempertures from Resistance Temperature Detectors (RTDs).

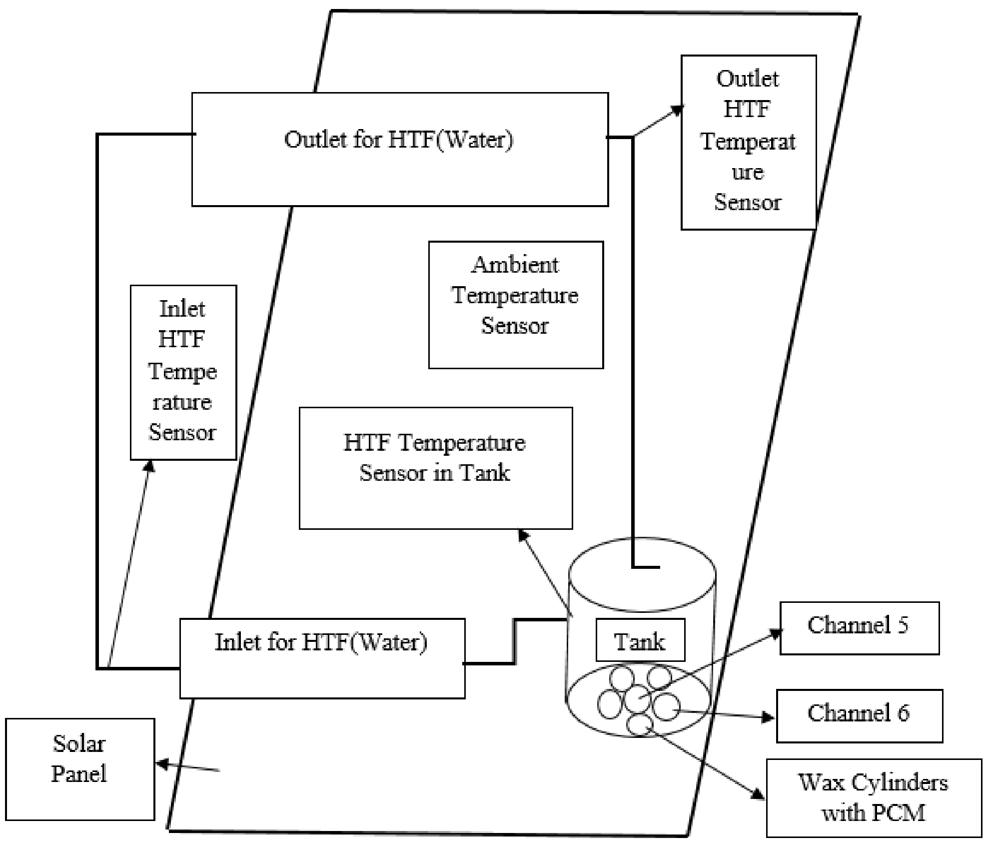

Fig. 4.19. Schematic of a flat plate collector with PCM.

- Aluminum cylinders filled with phase change material (paraffin wax) called heat exchangers are installed into the reservoir. Six of such cylinders are installed into the reservoir.

- The reservoir filled with water by using a hose at the dock area. The water level should be filled below the top tip of the temperature sensor which is inside the reservoir and the water level should not come in contact with RTDs.

- Inlet, outlet, reservoir sensor, ambient temperatures and Two RTDS (one for inner cylinder and one for outer cylinder as shown in figure 4.19) are connected to their respective channels i.e., inlet to channel 1, outlet to channel 2, reservoir sensor to channel 3, ambient temperature sensor to channel 4, inner heat exchanger to channel 5 and outer heat exchanger to channel 6

- The flow rate adjusted to 1.5 gallons per minute by using the adjustable knob with a 12V DC water pump by connecting the plug to a power source.

- The apparatus is carefully wheeled outside under the shade and run for a while till the inlet, outlet and reservoir sensor gets to equilibrium. The apparatus is faced towards the south in order to receive more solar irradiance from the sun.

- Once the equilibrium is obtained than the SD card inserted into the data logger by adjusting the settings. The data collected for every minute automatically and saved to SD card provided.

- Solar irradiance meter fixed to flat plate collector at an angle of 45^o.The irradiance meter is set to collect data for every time.

- Both data logger and solar irradiance meter are started at the same and left undisturbed for the entire experiment.

- The apparatus left undisturbed outside for 24 hours.

- After completing the experiment, data from data logger is transferred to the computer via the SD card.

- Solar irradiance meter also removed. To transfer data from irradiance meter to the computer drivers are needed. The drivers are available in the compact disc (CD) provided in the box. A data cable can be used to transfer data from irradiance meter to computer.

- After transferring the data, the water in the reservoir should be drained using the water drain provided at the bottom of the reservoir.

- The apparatus is wheeled back inside the building.

5. MATLAB PROGRAM FOR THE THEORETICAL MODEL

The model developed extensively based on the Saleh [2012] model. A MATLAB Code generated follows the mathematical model by Saleh [2012]. The model in the study allows for transient ambient temperature and irradiance for the simulation whereas Saleh [2012] model simulates constant or step-function ambient temperature and irradiance. The model also study the effect of phase change material (PCM) on thermal storage system. The physical dimensions of the flat plate collector are taken as constants which are used as inputs. The developed model can be used for all flat plate collector with single cover without any changes in the model.

MATLAB code run by the following inputs:

- number of nodes (along the direction of fluid flow)
- total fluid mass flow rate
- time interval
- initial temperature
- tank volume

The boundary conditions, incident solar radiation and ambient temperature, are time-varying for the mathematical model developed. The incident solar radiation and ambient temperature are recorded from experiment and read into the computer code at fixed time intervals–in this case 1 minute. Linear interpolation is used to determine the incident solar radiation and ambient temperature at each time step.

The subroutine for the thermal storage with phase change material (PCM) was written and inserted into the main code for the flat plate collector. The inputs taken for thermal storage are constants. Thermal storage is time-dependent. MATLAB R2017a utilized in generating a code for the model.

Solution for the model developed is given by MATLAB along with the temperature distribution under transient conditions for any cross-section in collector with initial time being zero. Temperature distribution is given till time entered by user. The flow chart which is shown in figure 5.1 gives the details of various steps involved in the code. Important input data is given in Table 5.1.

Table 5.1.
Inputs given to MATLAB Code

Name	**Symbol**	**Value**	**Unit**
number of nodes	n	8	–
volume flow rate	$\dot{V}$	1.5	GPM
time interval	t_{int}	120|1440	minutes
initial temperature of the tank	T_i	experiment	°C
volume of the tank	V_{tank}	75-105	L
number of tubes	N	8	–
diameter of the inner tube	d	9.9/1000	m
length of tubes	L	1900/1000	m

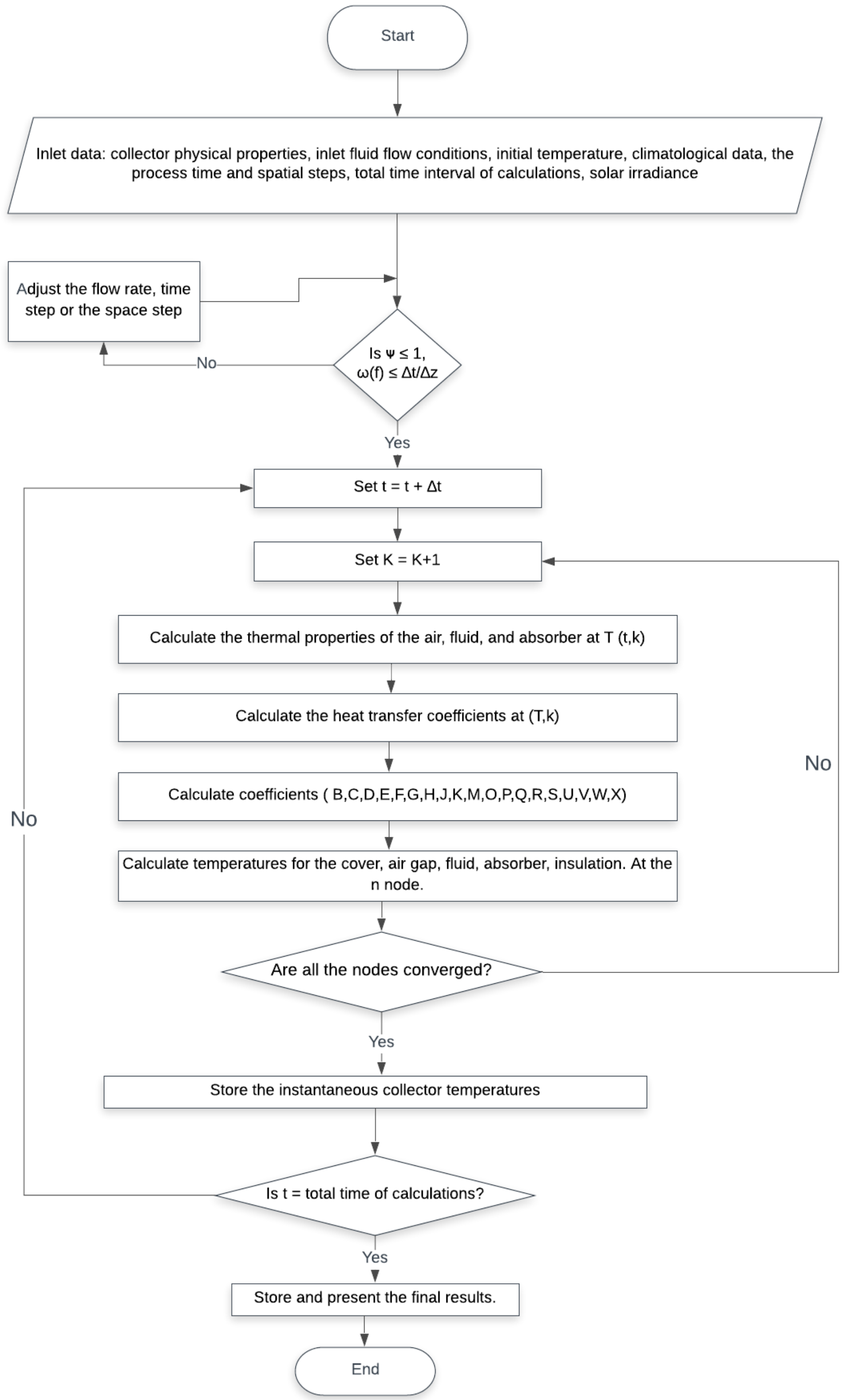

Fig. 5.1. MATLAB Code flow chart.

6. RESULTS AND DISCUSSION

Measured and numerical results are presented in the following sections. Three different cases of experiments are performed with and without phase change material (PCM) in the reservoir. A 2-hour and 24-hour experiment without phase change material (PCM) in the reservoir are performed. A 24-hour experiment with phase change material (PCM) in the reservoir performed. Three different set of results (measured results, numerical results and comparison between both measured and numerical results) for each experiment are presented. A numerical comparison with a 9-hour experiment carried with and without PCM under steady conditions to study the effect of PCM on thermal storage.

Numerical results are generated using the MATLAB code by [Saleh, 2012] model. MATLAB code from the previous model [Saleh, 2012] used as a guide to obtain numerical results. In the numerical model, 8-nodes (in the direction of flow) with a time difference of $\Delta t = 0.1$ seconds, wind speed of 5 m/s are considered. Heat transfer coefficient due to conduction and radiation from absorber and surroundings on insulation is taken as 10 W/m^2-K. Heat gained by fluid i.e., water in the reservoir and steel drum both are considered whereas previous model only considered about gained by the water. The interpolations for every 0.1 seconds time difference are obtained. A volume of 95-100 L are considered. The remaining parameters are similar to previous model [Saleh, 2012]. Results obtained by considering the mentioned parameters are almost similar to measured results.

6.1 2-Hour Experiment without PCM

The first experiment was performed at the loading dock area outside ETCS building, Purdue University Fort Wayne on 11/11/2017 in between 1 pm to 3 pm. The

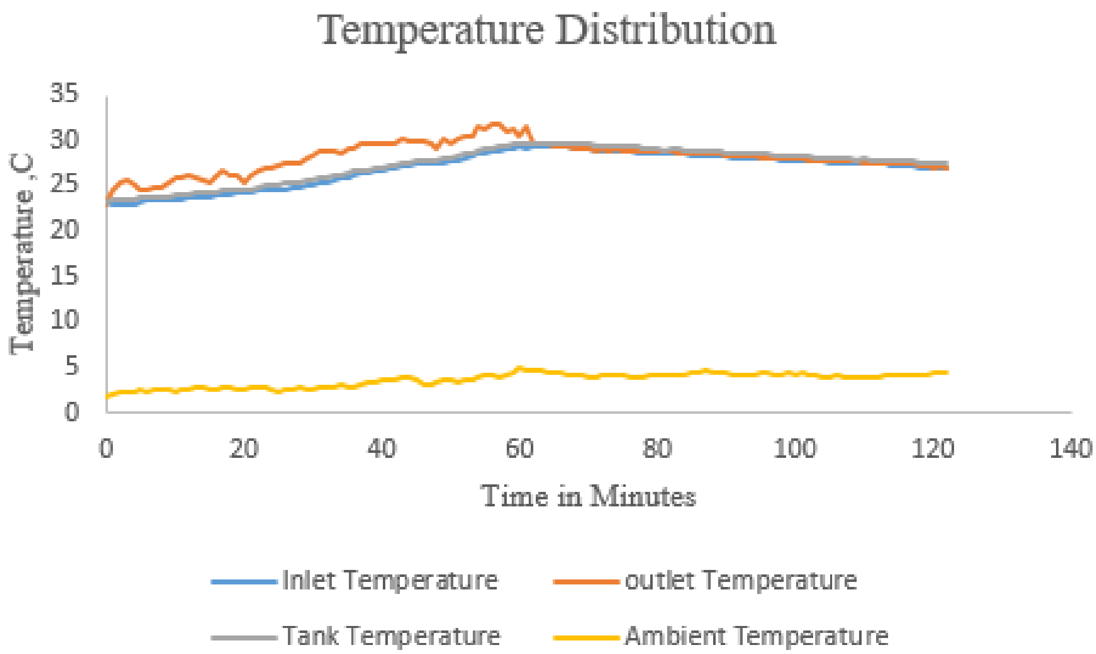

Fig. 6.1. Measured temperature distribution for a 2-hour experiment without PCM.

water in the tank is approximately 95 L and the flow rate is 1.5 GPM. The experiment started only after the system reached equilibrium. The apparatus was placed in the sun for one hour and then wheeled into the shade for one hour.

Figure 6.1 shows the temperature distribution for 2-hour experiment. The curves in the figure shows the results obtained from the sensors connected to thermocouples at the inlet, outlet, reservoir and ambient. The curve shown in blue color gives the inlet temperature of the coolant. The curve in red gives outlet temperature whereas grey and yellow curves show the reservoir or tank temperature and ambient temperature respectively.

Figure 6.2 shows the irradiance, tank and ambient temperature distribution for the 2-hour experiment (one hour under the sun and one hour under shade) without phase change material (PCM) in the reservoir for every minute. This data was read in by the MATLAB code and plotted in figure 6.2. The results show that there is

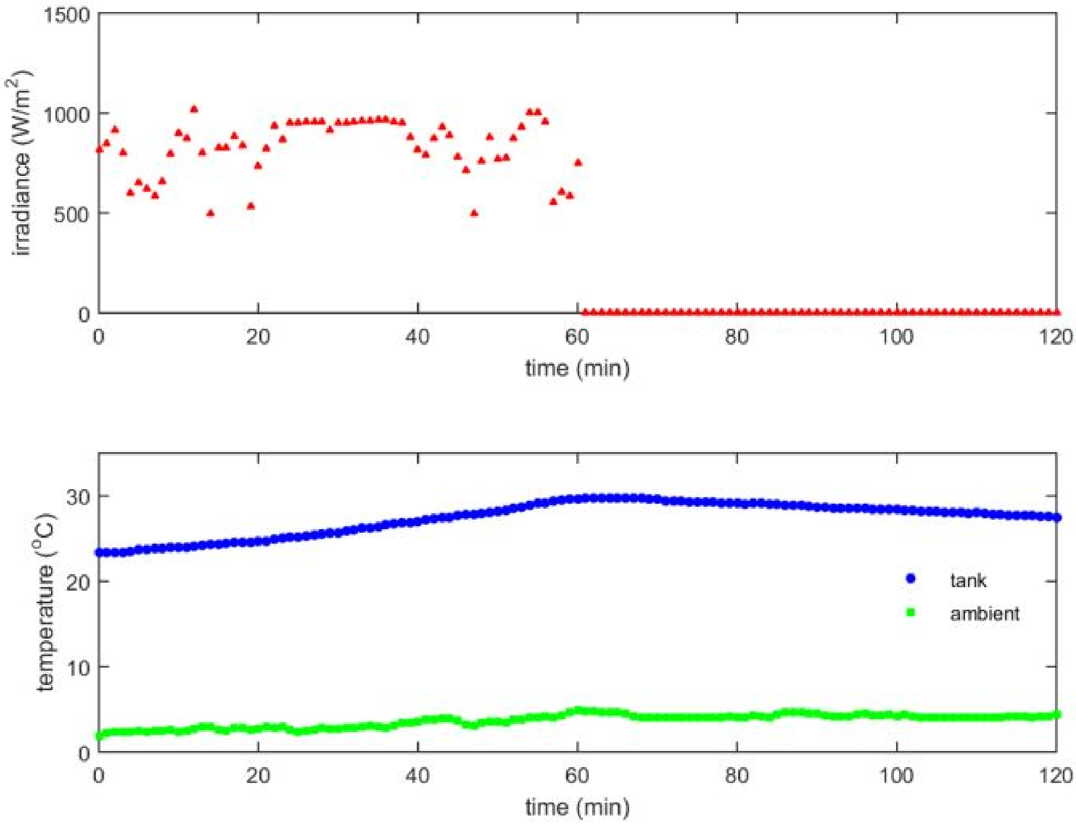

Fig. 6.2. Measured irradiance and temperature distribution for a 2-hour experiment without PCM.

negligible insolation from the sun under the shade during this time the fluid i.e, water started losing thermal energy which is collected under the sun. Thermal energy is absorbed when the appartus is under the sun and lost while in the shade. The measured results show that loss of thermal energy is high when there is no phase change material (PCM) in the reservoir. Results from the figure shows that even though there is increase in ambient temperature in the shade, thermal losses from the reservoir still cause the tank temperature to decrease.

Numerical results shown in figure 6.3 are obtained from simulation. Figure 6.3 shows the ambient temperature, irradiance, and temperatures at the center node

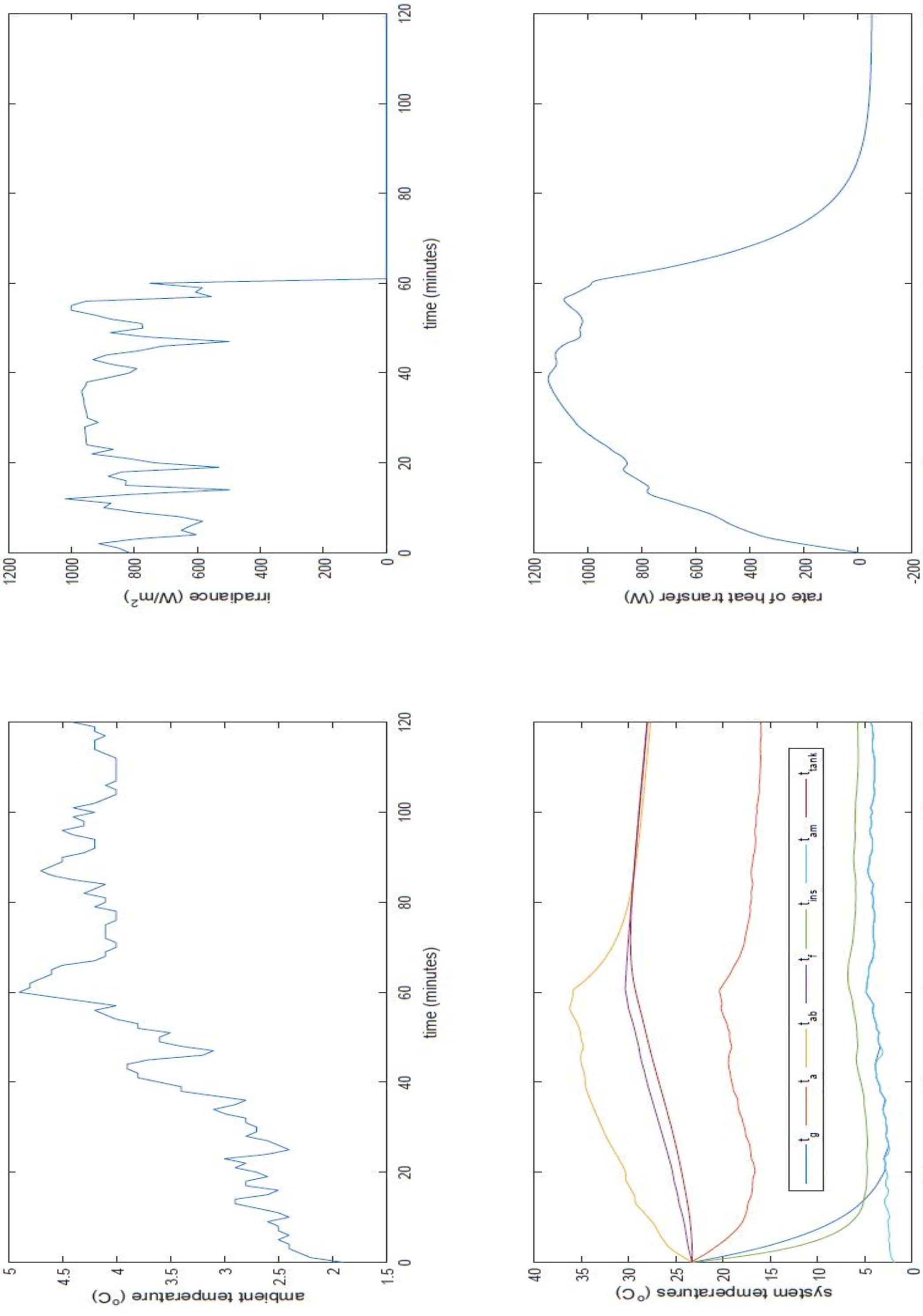

Fig. 6.3. Numerical results for a 2-hour experiment without PCM.

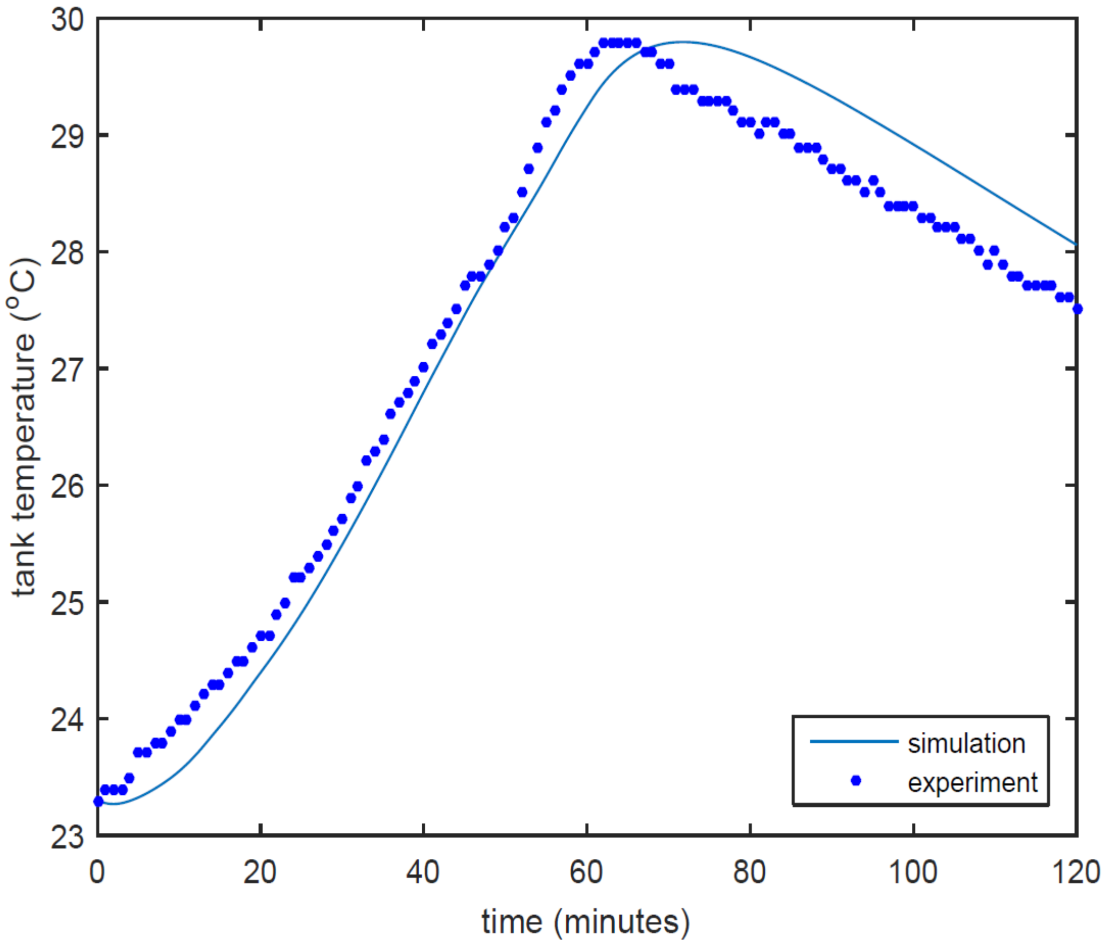

Fig. 6.4. Comparison between measured and numerical results 2-hour experiment without PCM.

(middle of the collector) of all the elements in the collector. Also shown is tank temperature and the rate of heat transfer from the heated water to the water in the tank. The results obtained are given at 0.1 s intervals. The highest temperature calculated, 36.19°C, is on the absorber plate as expected. The glass cover temperature approaches the ambient temperature. The temperature of the air gap between the glass cover and the absorber plate falls between the those two temperatures.

Figure 6.4 shows the comparison between measured results and numerical results. Both measured and numerical results show good agreement. The heat loss coefficient is set to 10 W/m^2-K in the simulation to match the measured results. Agreement between the simulation and measured results could potentially be improved using different values for the heat loss coefficient. A heat loss coefficient of 10 W/m^2-K is used in subsequent models.

6.2 24-Hour Experiment without PCM

The second experiment was performed at the loading dock area outside ETCS building, Purdue University Fort Wayne. The experiment was started at from 8:58 am on 11/27/2017 continued until 8:58 am on 11/28/2017 The water in the tank is approximately 100 L and the flow rate is 1.5 GPM. The experiment started only after the system reached equilibrium. The apparatus was placed in the courtyard and left undisturbed for 24 hours. The pump ran throughout the entire experiment.

The temperature variation over the 24 hour interval is shown in figure 6.5. From the figure 6.5, the inlet temperature curve is shown with a blue color curve, the outlet temperature is shown with an orange color curve, the water temperature inside the tank is shown with ash color curve and the ambient temperature curve is shown with a yellow curve. Outlet refers to the exit from the collector after heating. Inlet refers to the entrance into the collector after leaving the storage. The outlet temperature curve is always higher in the presence of solar irradiance as compared with the inlet temperature, as the collector heats the water. The inlet temperature is slightly less than the tank temperature, due to slight heat loss after leaving the tank. Without incident solar radiation, the water temperature approaches the ambient temperature.

Figure 6.6 shows the irradiance, tank and ambient temperature distribution for the 24-hour experiment without phase change material (PCM) in the reservoir for every minute. This data was read in by the MATLAB code and plotted in figure 6.6. At night (or times of very little solar irradiance) the irradiance meter recorded values of $<$100 W/m^2 or ERR. These values were set to zero, for consistency. The results show that at night the irradiance is negligible and the water started losing

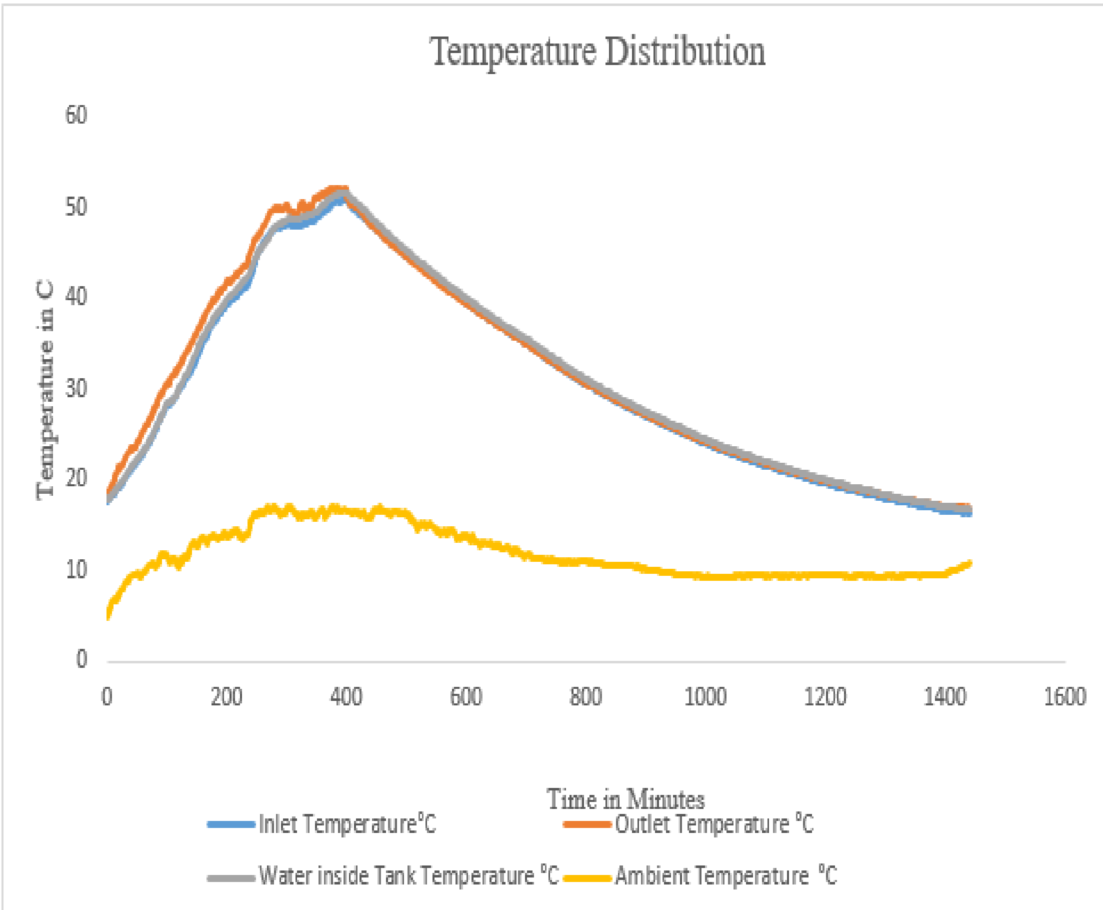

Fig. 6.5. Measured temperature distribution for a 24-hour experiment without PCM.

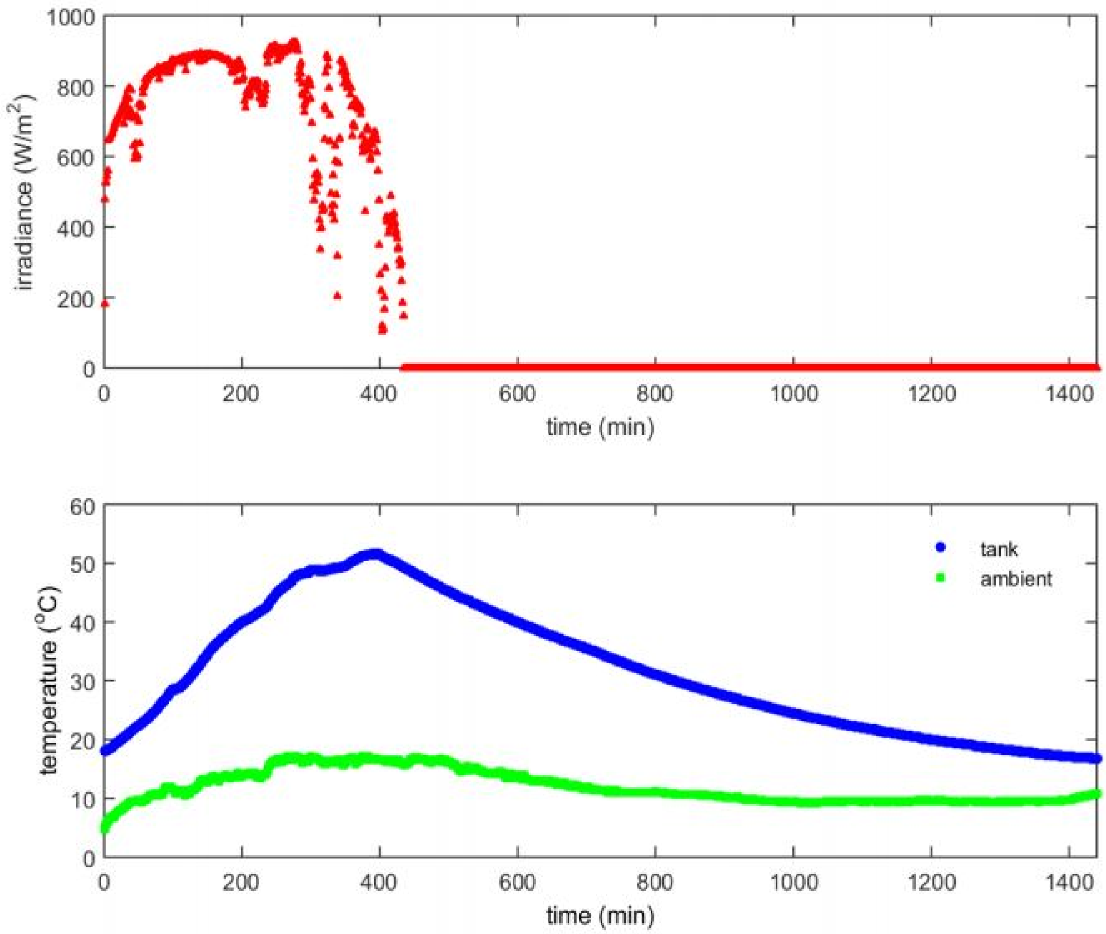

Fig. 6.6. Measured irradiance and temperature distribution for a 24-hour experiment without PCM.

thermal energy which is collected under the sun. Thermal energy is absorbed when the appartus is under the sun and lost at night. The measured results show that loss of thermal energy is high when there is no phase change material (PCM) in the reservoir.

Numerical results shown in figure 6.7 are obtained from simulation. Figure 6.7 shows the ambient temperature, irradiance, and temperatures at the center node (middle of the collector) of all the elements in the collector. Also shown is tank temperature and the rate of heat transfer from the heated water to the water in the tank.

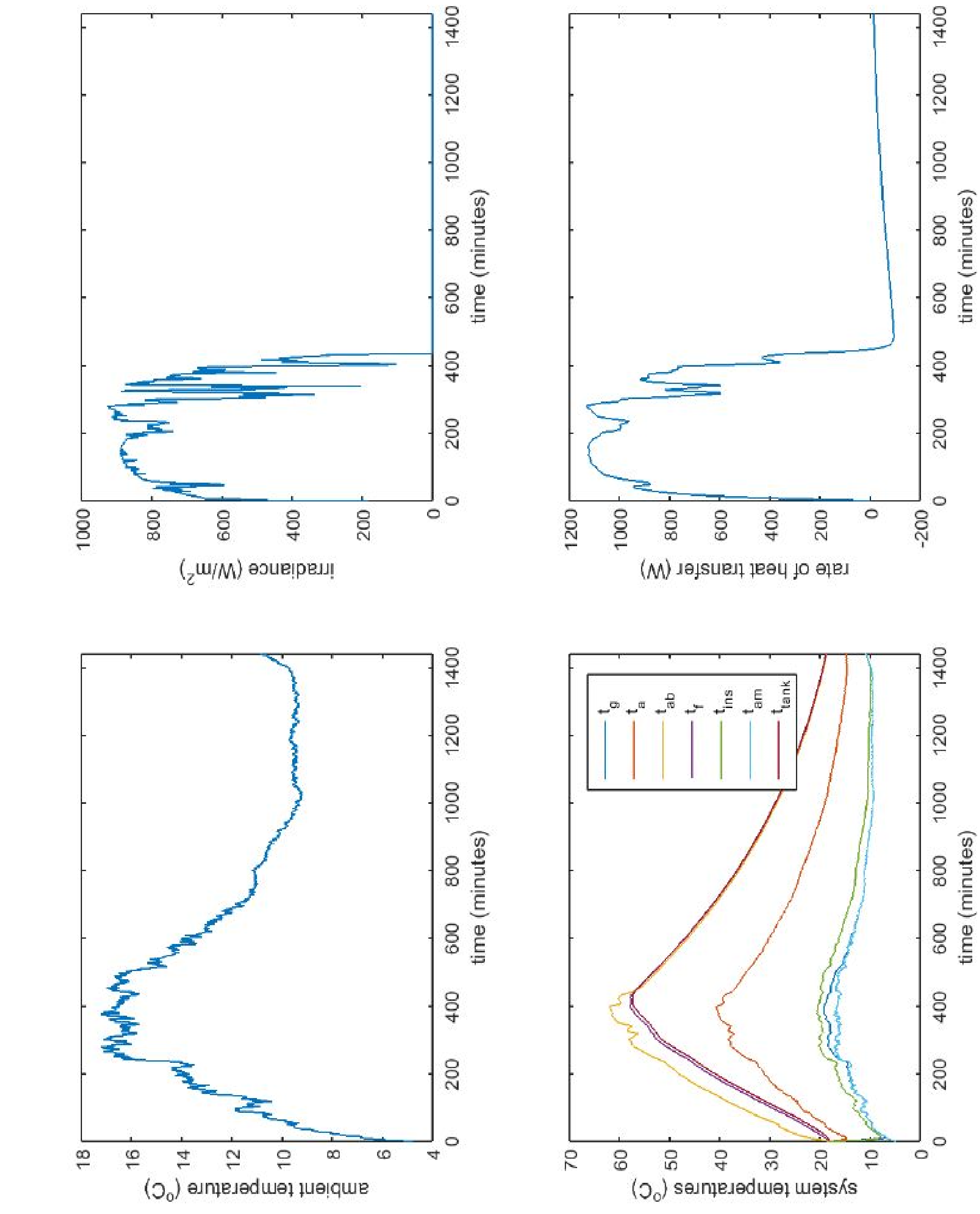

Fig. 6.7. Numerical results for a 24-hour experiment without PCM.

The results obtained are given at 0.1 s intervals. The highest temperature calculated, 62.11°C, is on the absorber plate as expected. The glass cover temperature and the insulation temperature approach follow the ambient temperature. The temperature of the air gap between the glass cover and the absorber plate falls between the those two temperatures. In the absence of incident solar radiation, the water from the tank is at a higher temperature than the water leaving the collector, hence the rate of heat transfer is negative, i.e., the tank is heating the water at the outlet of the collector. This suggests that to prevent heat loss, the pump should be turned off at night.

Figure 6.8 shows the comparison between the measured results and numerical results. The agreement between the measurement and simulation during the daytime (period of high solar irradiance) is excellent. However, the simulation predicts a higher maximum tank temperature (57.3°C) compared to measurement (51.6°C). This suggests that heat loss from one of elements in collector is not being modeled properly. The overall rate of cooling for the simulation and experiment shows good agreement.

6.3 24-Hour Experiment with PCM

The third experiment was performed at the loading dock area outside ETCS building, Purdue University Fort Wayne. The experiment was started at 8:43 am on 11/29/2017 to 8:43 am on 11/30/2017 and data was collected every minute. The tank contained five aluminum cylinders with 22 kg of parrifin wax (PCM) and approximately 75 L of water. The flow rate throughout the experiment is 1.5 GPM. The experiment started only after the system reached equilibrium. The apparatus was placed in the courtyard and left undisturbed for 24 hours. The pump ran throughout the entire experiment.

From the figure 6.9, the inlet temperature curve is shown with blue color curve, the outlet temperature is shown with orange color curve, the water temperature inside the tank is shown with ash color curve, the ambient temperature curve is shown with yellow curve, the inner resistance temperature detector (RTD) is shown by navy blue

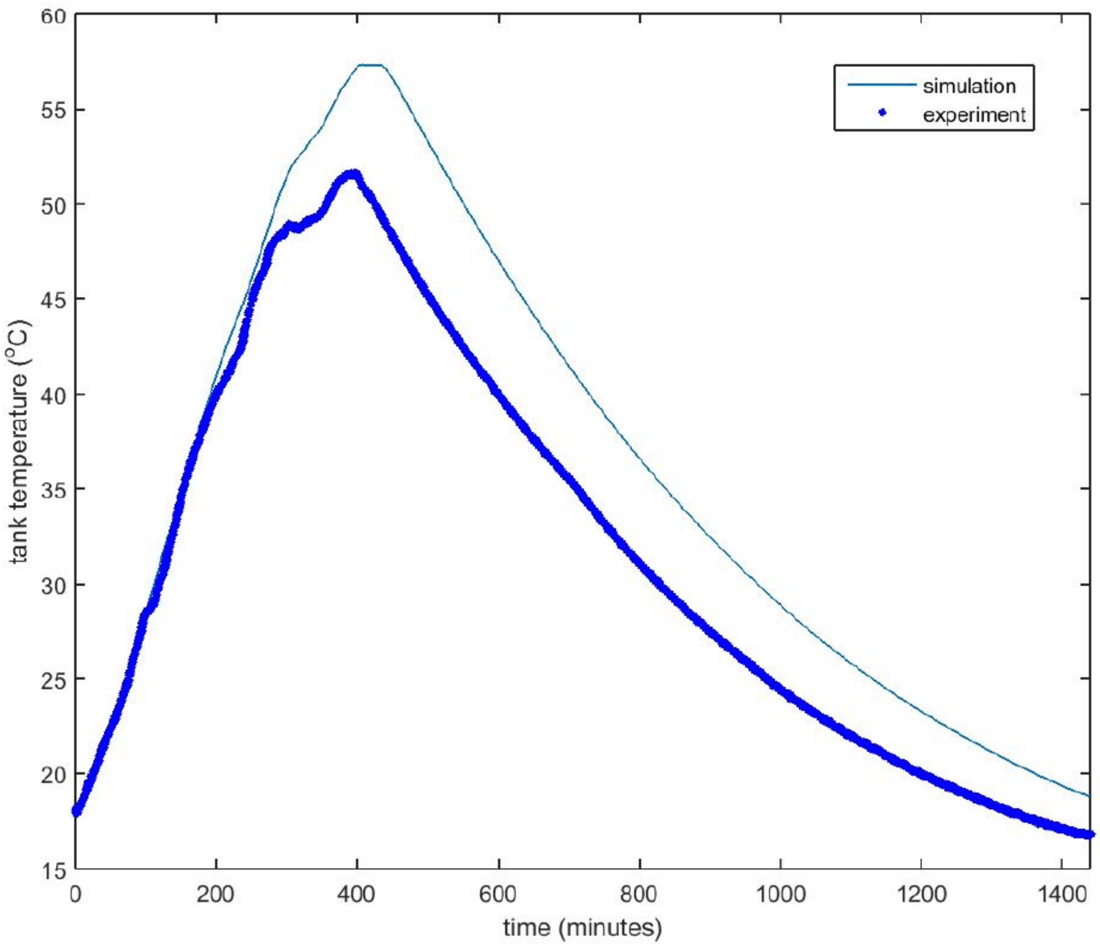

Fig. 6.8. Comparison between measured and numerical results 24-hour experiment without PCM.

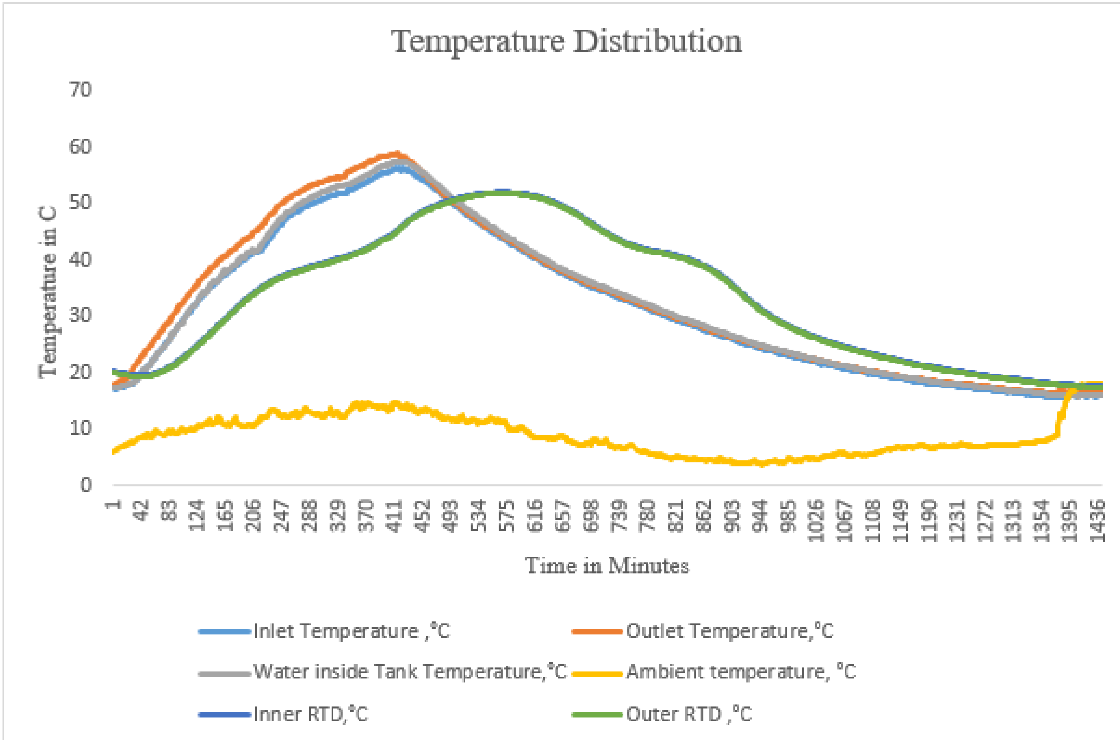

Fig. 6.9. Measured temperature distribution for a 24-hour experiment with PCM.

curve and the outer resistance temperature (RTD) is shown by green curve. The temperatures recorded by the RTDs in the cylinders are approximately the same, hence the curves lay on top of one another, with the inner cylinder temperature being only slightly higher. The difference between the water temperature in the tank and the cylinder temperature indicates that the assumption to model the entire temperature is not correct. The cylinders filled with paraffin wax have the ability to store heat longer than the water in the tank. The maximum temperature recorded for water in the tank is 57.5°C. The maximum temperature recorded for the cylinder is 52.1°C, which is less than the melt temperature of 56°C, suggesting that the wax in the cylinder did not undergo a phase change.

Figure 6.10 shows the irradiance, tank and ambient temperature distribution for the 24-hour experiment with phase change material (PCM) in the reservoir for every

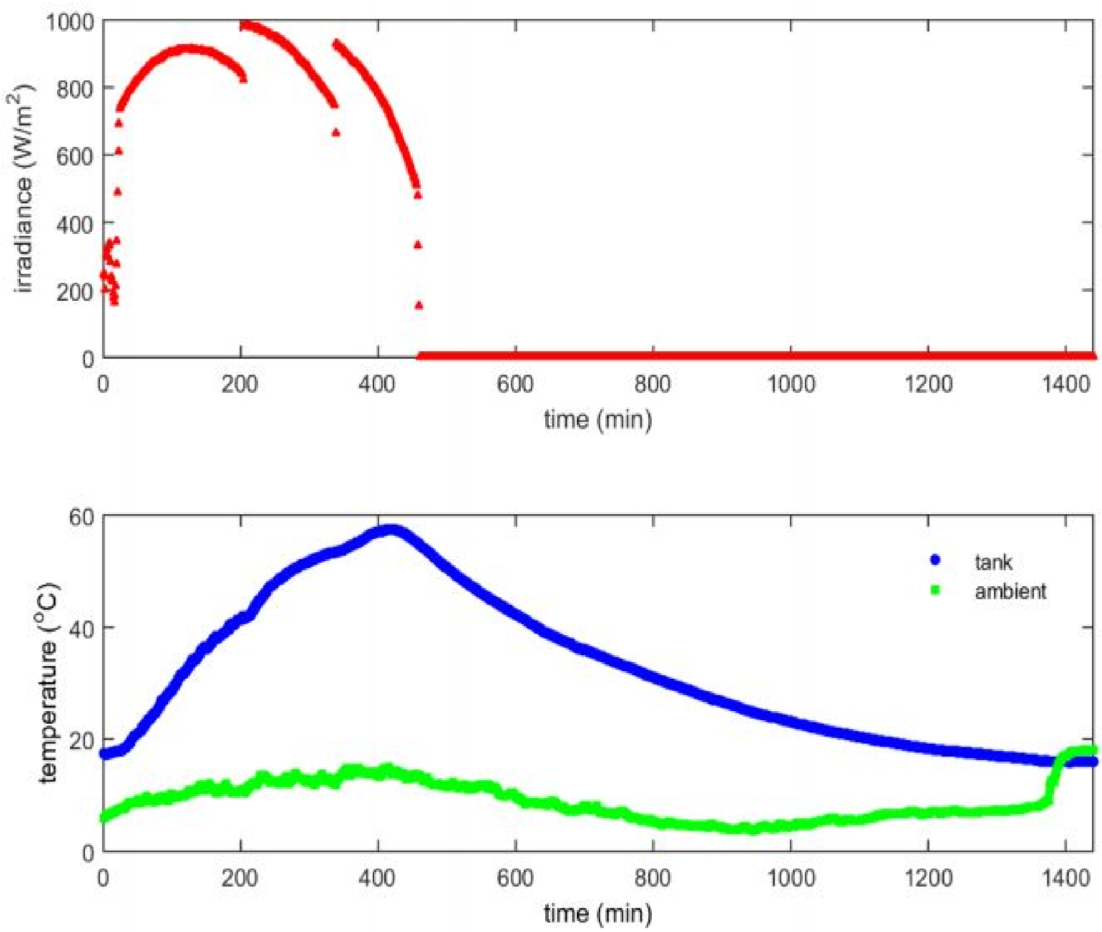

Fig. 6.10. Measured irradiance and temperature distribution for a 24-hour experiment with PCM.

minute. This data was read in by the MATLAB code and plotted in figure 6.10. At night (or times of very little solar irradiance) the irradiance meter recorded values of <100 W/m^2 or ERR. These values were set to zero, for consistency. The results show that at night the irradiance is negligible and the water started losing thermal energy which is collected under the sun. Thermal energy is absorbed when the appartus is under the sun and lost at night.

Numerical results shown in figure 6.11 are obtained from simulation. Figure 6.11 shows the ambient temperature, irradiance, and temperatures at the center node

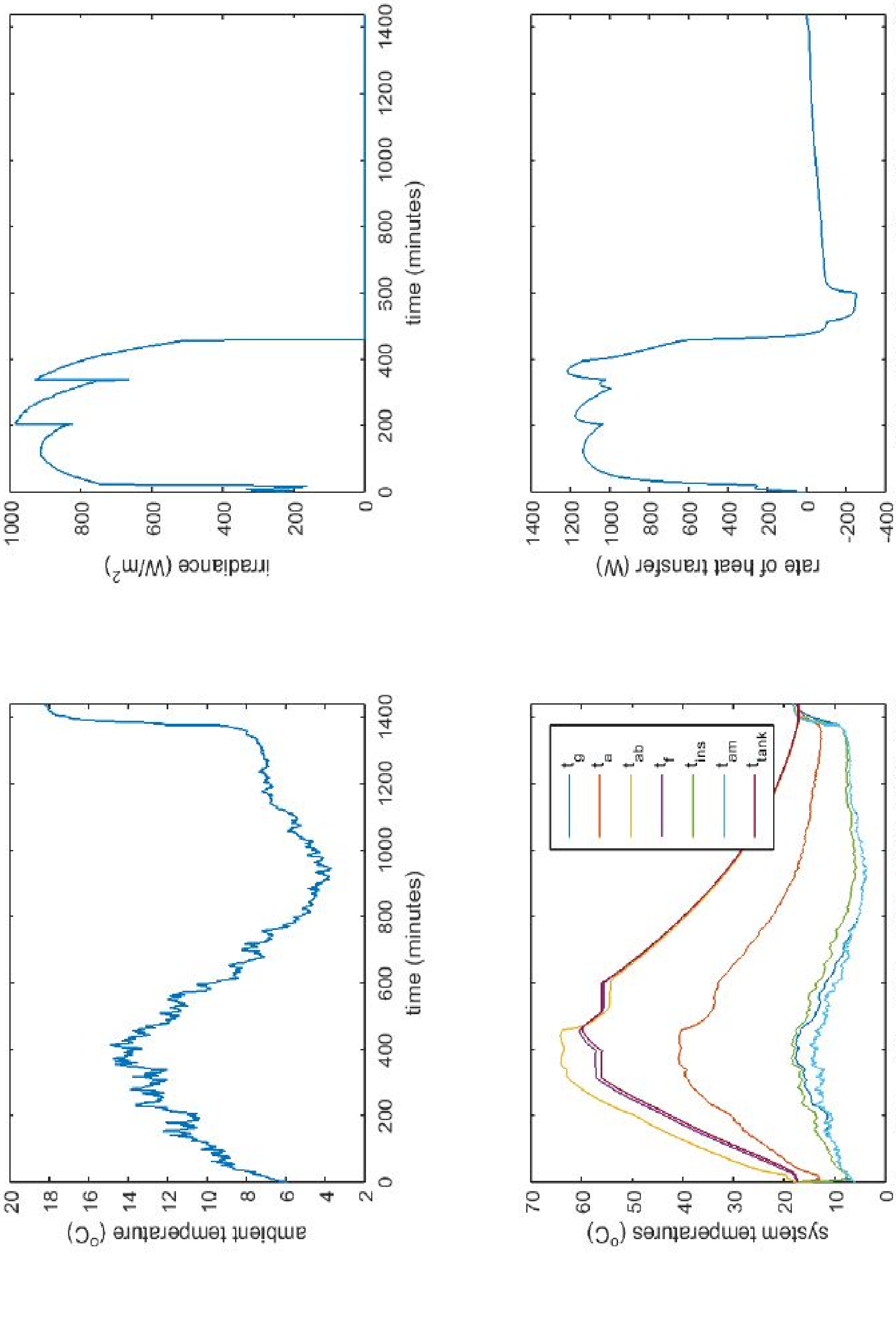

Fig. 6.11. Numerical results for a 24-hour experiment with PCM.

(middle of the collector) of all the elements in the collector. Also shown is tank temperature and the rate of heat transfer from the heated water to the water in the tank. The results obtained are given at 0.1 s intervals. The highest temperature calculated, 64.12°C, is on the absorber plate as expected. The glass cover temperature and the insulation temperature approach follow the ambient temperature. The temperature of the air gap between the glass cover and the absorber plate falls between the those two temperatures. Figure 6.11 shows that the simulation captures the melting-sensible heating-solidification of the paraffin wax. In the absence of incident solar radiation, the water from the tank is at a higher temperature than the water leaving the collector, hence the rate of heat transfer is negative, i.e., the tank is heating the water at the outlet of the collector. This suggests that to prevent heat loss, the pump should be turned off at night.

Figure 6.12 shows the comparison between the measured results and numerical results. The agreement between the measurement and simulation during the daytime (period of high solar irradiance) is excellent. However, the simulation predicts a higher maximum tank temperature (59.83°C) compared to measurement (57.2°C). The figure shows that sensible heating of the water and PCM in the tank occurs from 0 to 313 minutes, then at a temperture of 56°C the PCM melts. Once the 22 kg of PCM is melted, sensible heating of the water and PCM occurs until the temperature reaches 59.83°C at 461 minutes. After reaching a maximum temperature, sensible cooling, phase change (solidification) at 56°C, and further sensible cooling occurs.

6.4 Numerical Comparison with PCM and without PCM

A numerical study made to analyze the effect of the phase change material (PCM) on thermal storage. The run time of the experiments is 9 hours. Two different cases, with and without PCM, are considered. For the first case, without PCM, the tank is filled with 50 L of water. In the second case, with PCM, the tank is filled with 50 L and 22 kg of paraffin wax. The flow is constant at 1.5 GPM. The irradiance is

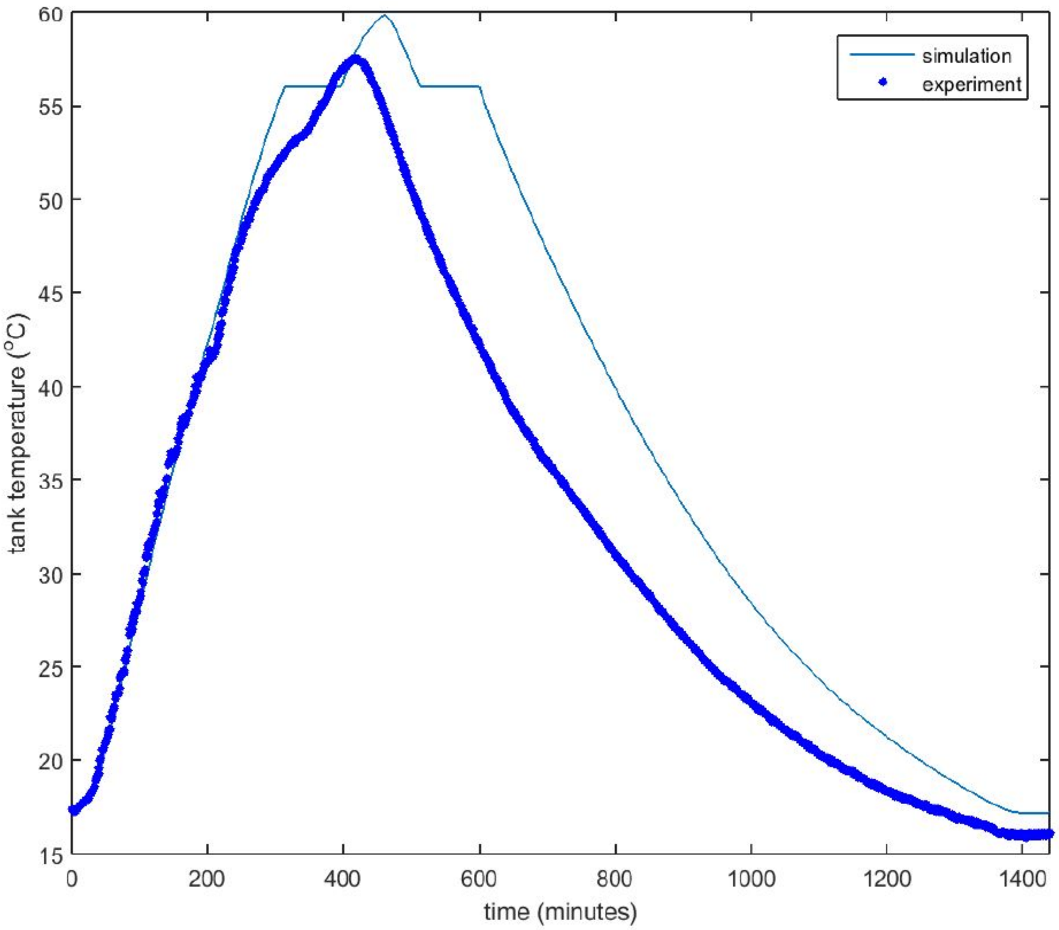

Fig. 6.12. Comparison between measured and numerical results 24-hour experiment with PCM.

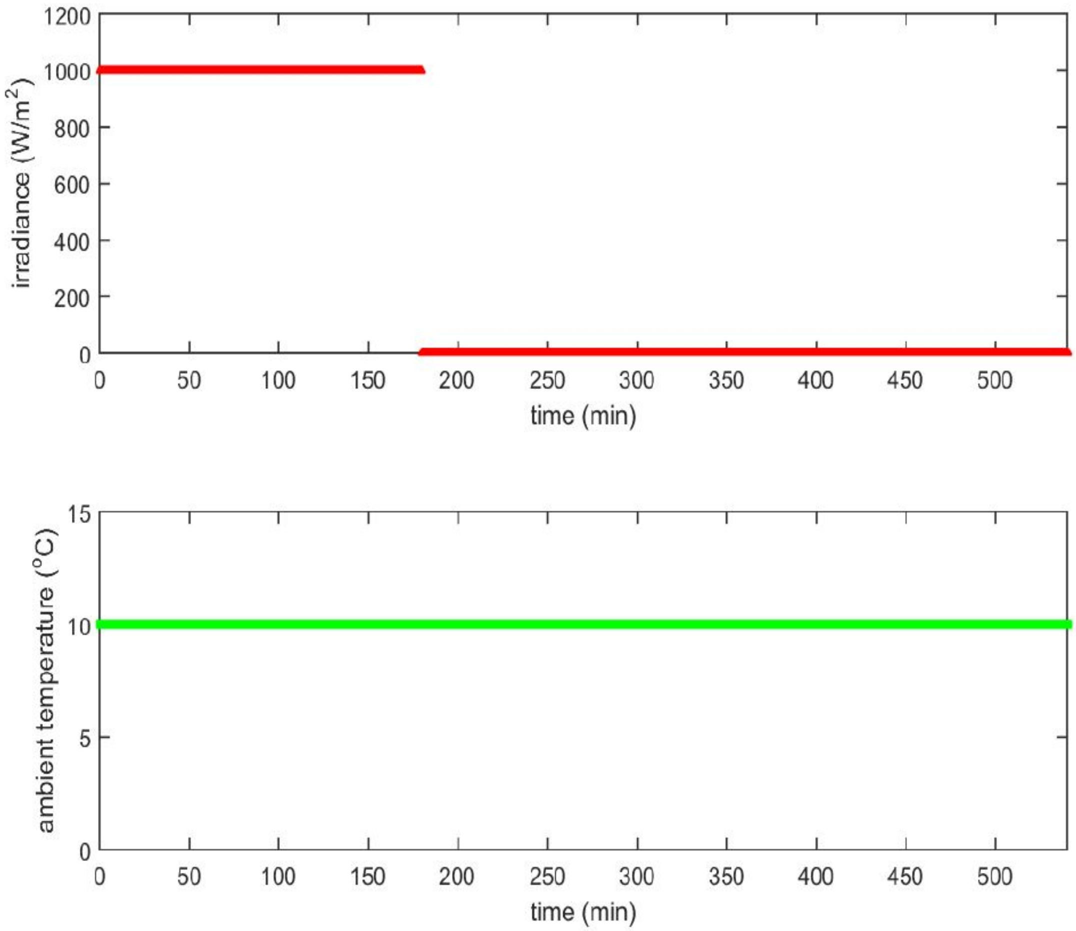

Fig. 6.13. Numerical irradiance and ambient temperature for a 9-hour experiment with and without PCM.

taken as 1000 W/m^2 for three hours and 0 W/m^2 for next 6 hours, while the ambient temperature is constant at 10°C throughout the experiment as shown in figure 6.13.

Numerical results obtained shown in figures 6.14 to 6.16. Note that the amount of water in the tank is 50 L for both simualtions, but the second simulation (with PCM) has additional thermal mass in the tank. Less thermal mass to heat results in higher heating rate and higher temperature. In this simulation, the PCM does not completely melt, i.e., just about 90% of the PCM changed phase from solid to liquid, before cooling occured, thus the temperature of the tank did not rise above 56°C.

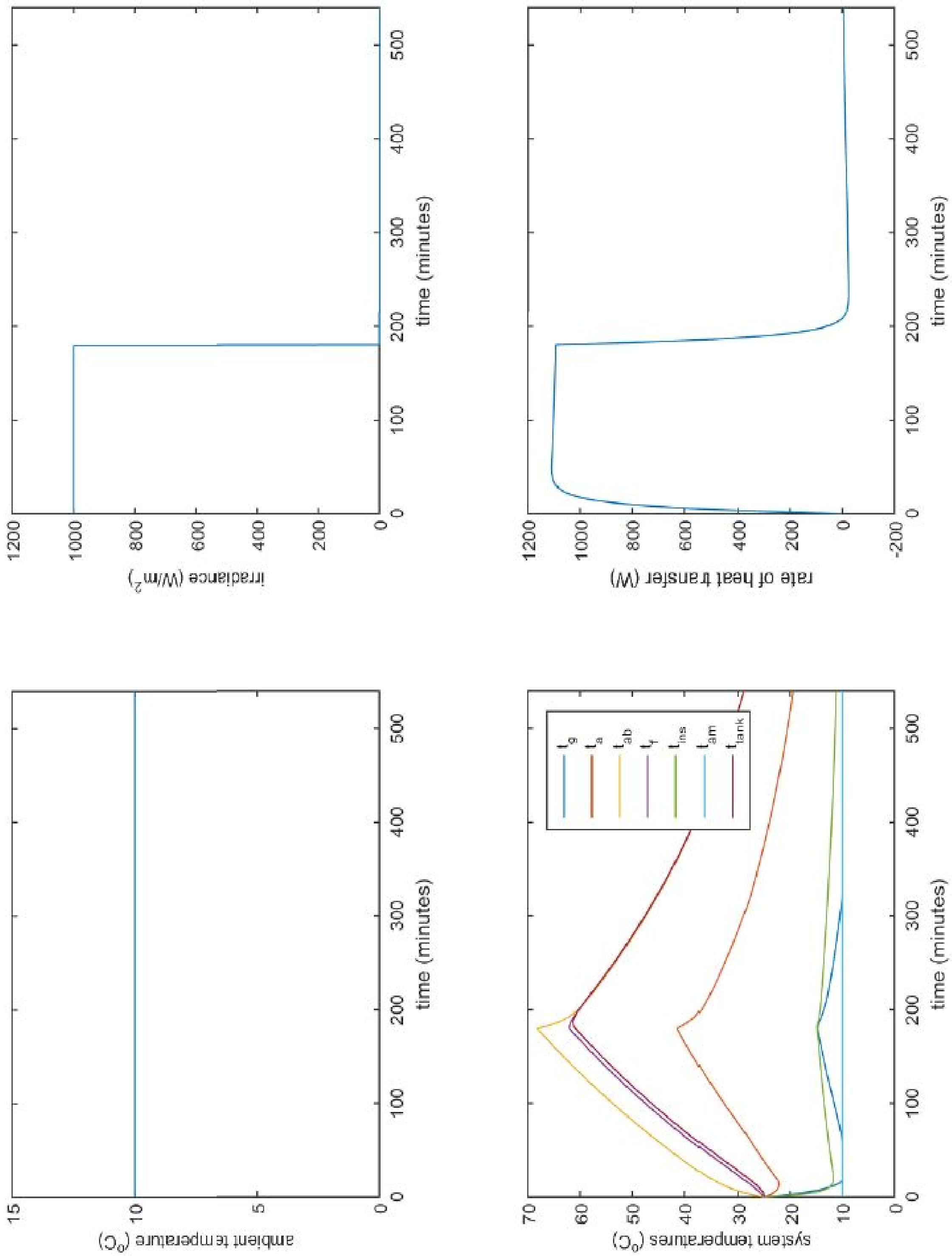

Fig. 6.14. Numerical results for a 9-hour experiment without PCM.

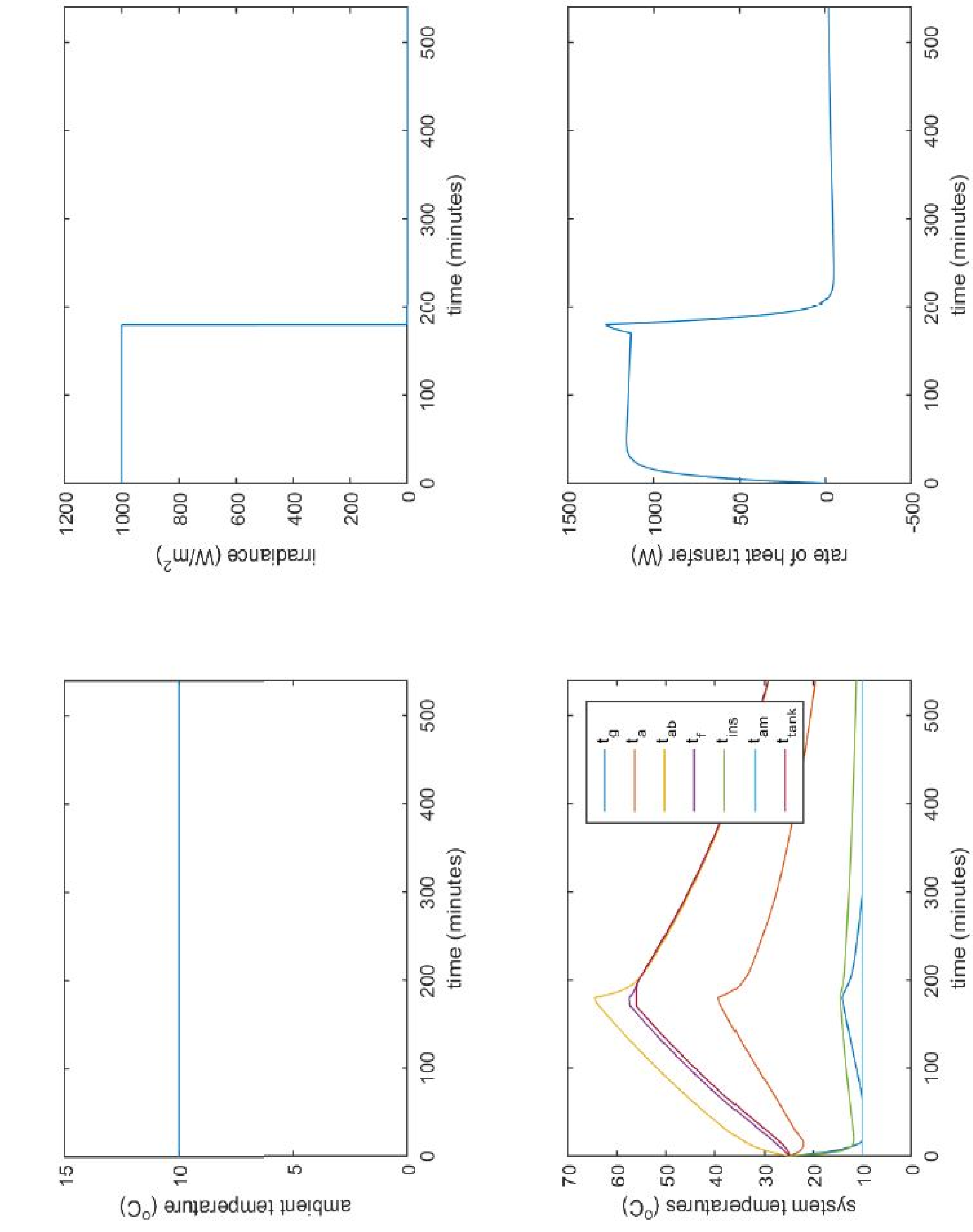

Fig. 6.15. Numerical results for a 9-hour experiment with PCM.

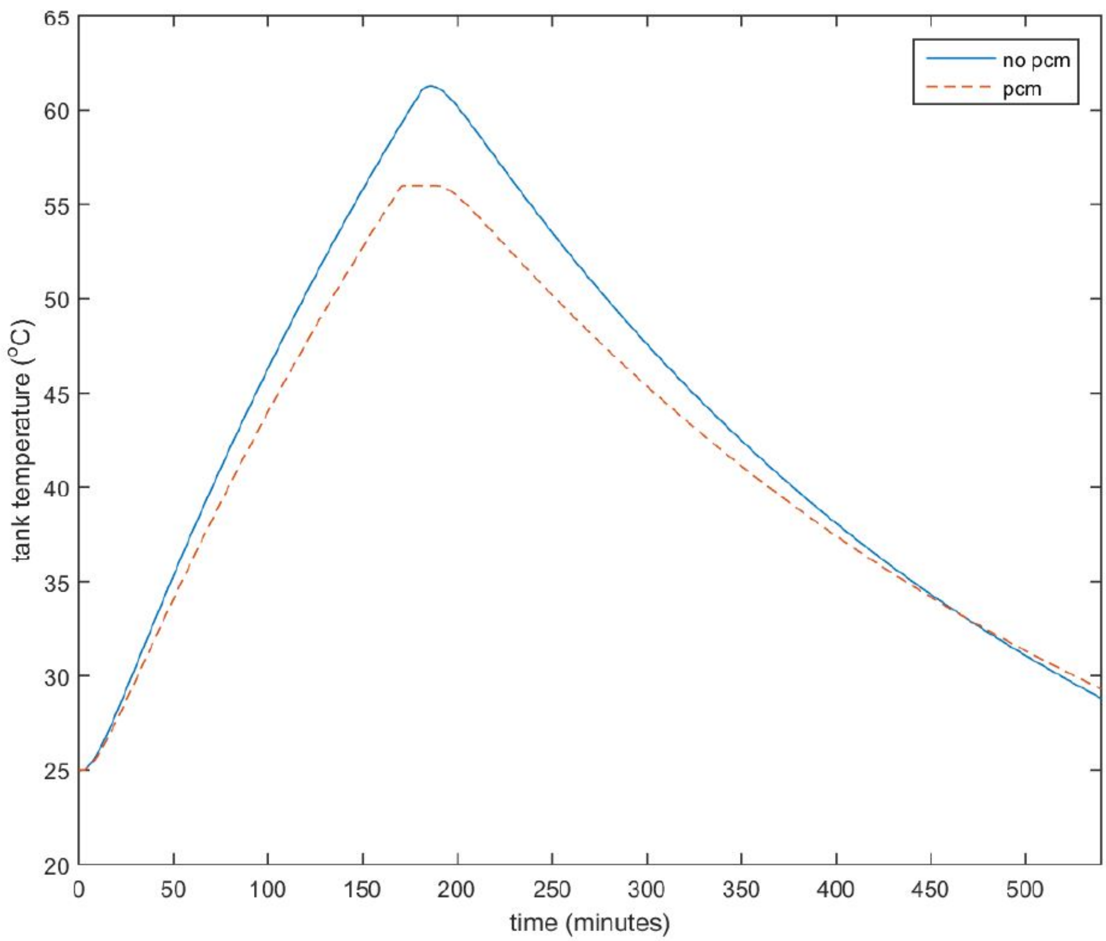

Fig. 6.16. Comparison of numerical results 9-hour experiment with and without PCM.

After the solar irradiance drops off, it is clear that the PCM continues to heat the water in the tank as evindent by the spike in the rate of heat transfer.

Figure 6.16 shows the comparison of the tank temperature with and without PCM. The maximum temperture of water in the tank is higher for the case of no PCM compared to the case with PCM. This is because the tank without PCM has less thermal mass, thus it heats up more rapidly and achieves a higher temperature. Change of phase occurs in the system with PCM when the temperature of the tank reaches 56°C–this occurs at 171 min. Only 90% of the phase change material melts before cooling occurs and PCM begins to solidify. Once the PCM completely solidifies, sensible cooling occurs. Comparison of the rate of cooling in figure 6.16 shows that the system with PCM cools at slower rate than the system with PCM.

7. CONCLUDING REMARKS

A study of a flat plate collector with a thermal storage system is performed. Both experiment and numerical simulation are performed. This study allows for transient ambient temperature and irradiance from the experiment to be used as input to the numerical simulation. The numerical simulation also allows for thermal storage via phase change material. The experiment apparatus used in this study was initially built by a Purdue University Fort Wayne senior design team. Modifications to the initial experiment include new pipings, a new pump, new data acquisition system along with reconfiguration of the cart for improved access and maneuverability.

A computer code is generated using the mathematical model. Numerical simulations are performed for two different cases i.e., with and without phase change material (PCM) in the reservoir for two different time periods i.e, 2-hour and 24-hour. First, a 2-hour experiment is performed to study to set parameters in the code, such as the heat loss coefficient between the tank and the ambient. Verification and validation of the obtained numerical results are done by comparing with previous numerical simulations and measured results obtained from the actual experiment. Both numerical and measured results show good agreement. The performance of the solar water heater equipped with flat plate collector and thermal storage system can be predicted.

The study also concludes that the performance of the solar water heating can be enhanced using phase change material. The model and simulation are flexible and can be used to design more effective systems to supply heated water using energy from the sun.

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