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Performance Analysis of Solar Water Heating System with Plate Collector Integrated PCM Storage

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Abstract

Availability of solar energy as a renewable energy source is very abundant and inexhaustible. Solar water heater is an equipment that utilizes solar energy as a source of energy. The thermal performance of a solar water heater system using absorber plate with phase change material (PCM) as thermal energy storage is presented in this study. Two design of solar water heater collectors with absorber plate variations, i.e. an absorber plate with PCM storage and absorber plate without PCM storage were investigated experimentally and numerically simulation. First, the material properties of paraffin wax as PCM storage was analized analyticaly. Every shape model of solar water heater systems were imported and simulated at three variations of constant solar radiation, i.e. 400 W/m^2, 700 W/m^2, and 1000 W/m^2. The simulation using a computational fluid dynamic (CFD) fluent software. The results showed that the average collector efficiency between absorber plate with and without PCM storage is 70.98 % using experimental study and 67.73 % using numerical simulation study.

Keywords: Computational Fluid Dynamic (CFD); Fluent software; solar water heater system; Phase Change Material (PCM)

1. Introduction

The availability of solar energy as a renewable energy source is very abundant and inexhaustible. A solar water heater is an equipment that utilizes solar energy as a source of energy and has been used in various countries around the world. However, because there were still many shortcomings of existed solar water heater, various research on it were carried out. Research on solar water heating systems is considered very important because it is expected to be able to improve the efficiency and effectiveness of solar water heating technology. Previous research is an experimental study of solar water heater system with V-shaped plate absorber [1], two solar water heater systems were installed and tested at a low flow rate of 0.5 L/min and a high flow rate of 2 L/min. The results showed that the solar water heater system with a V-shaped plate absorber had a 3.6-4.4% better performance compared with that of the system with a flat-plate absorber.

On another side, a high temperature on the V-shaped plate surface causes heat losses to the collector surface to become large too, so needed thermal energy storage which can maximize the performance of the solar collector. Experimental performance investigation of a solar phase change material (PCM) has been presented and discussed by Pisut Thantong [2] in a tropical climate. The experiment has proved that the solar phase change material is energy efficient in terms of heat gain reduction and energy saving. Palacio [3] has presented a comparative experimental analysis of a conventional flat plate solar collector and an identical prototype with thermal storage system by PCM and the results indicate that the selection of the PCM and the contact conduction between the absorber and PCM are key factors to increase the collector performance respect to conventional flat plate solar collector.

Study towards improving charge/discharge rate of latent heat thermal energy storage has been studied by Yanping Du [4] has a result that the temperature of PCM-metal foams composite/case study of paraffin became more uniform, while the cold discharge rate was improved by approximately 8 times. Optimization of melting and solidification processes of PCM integrated collector storage solar water heater has been analyzed by Allouhi [5] with result optimize obtained when a mass flow rate of 0.0015 kg/s is used with a PCM thickness of 0.01 m and set the temperature of 313 K.

A study about simulated solar water heaters has been investigated by Badiei and Eslami [6] with a solar flat plate collector integrated with a layer of PCM and the resulting temperature distributions are analyzed during two different summer and winter days in Shiraz, Iran. Results show that although the system with PCM has lower output temperatures in the morning, hot water can be supplied in a longer duration in the evening while discharging.

In this study, a solar water heater that integrated a PCM storage as thermal energy storage (TES) with a thermosyphon system was simulated and investigated experimentally. Two modelings of solar water heater systems with two different heat collectors, i.e. an absorber

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plate with and without PCM storage was modeled and their performances were simulated numerically.

2. Literature Review

Solar water heater collectors are heat exchangers that convert solar radiation energy into thermal energy in water. Solar radiation was absorbed by a collector plate and transferred to the water. The water in the pipe flowed through the collector by inlet pipe which connected with storage water before. The water in the pipe of the collector was heated by heat transfer that happened of the collector [7]. Due to a temperature difference of water in the pipe, the water with higher temperature automatically goes up to the top collector and then flows to the storage water back, this matter called thermosyphon system. There are several factors that impact the system performance among others thermal insulation, the tilt angle of the collector, absorber plate and its design, selective coating, and working fluid. A schematic layout of a typical thermosyphon solar water heater is shown in Fig. 1.

In this study an absorber plate of solar water heater made from a thin metal sheet whose surface is black painted to maximize the solar radiation absorbed. Furthermore, a transparent glass sheet is used as covering the collector to transmit the short wave of solar radiation to the absorber plate and prevent heat escape from the collector. Due to the large amount of heat loss from the absorber plate to the glass surface, hence the solar water heater was integrated with phase change material (PCM) as thermal energy storage.

Experimental study about solar water heater thermosyphon system whose integrated with PCM has been done by Nadjib [8] using paraffin wax as the PCM, which the results indicate that the utilization of PCM effective enough as thermal energy storage. Due to its costs and physicochemical properties, paraffin wax is used in low water boiling point requirement applications, such as drying, heating, and household water heating. The main disadvantage is its low thermal conductivity, about 0.2 W/mK. The solution for this to mix PCM with high thermal conductivity materials, such as aluminum, copper, or carbon [9]. The properties of paraffin wax are shown in Table 1. Meanwhile, lists of thermal properties of some paraffin shown in Table 2.

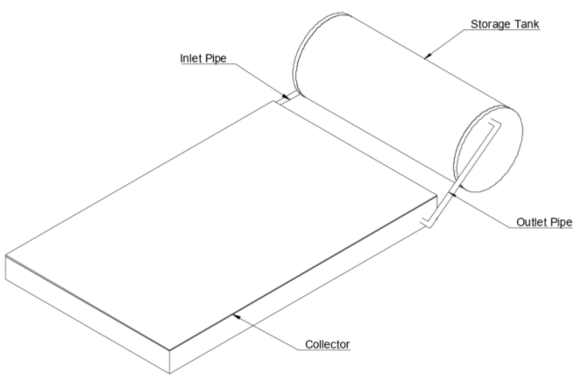


Figure 1. Schematic layout of a typical thermosyphon solar water heater

Table 1. Properties of paraffin wax

Property	Value	
	Solid	**Liquid**
Density, g/cm^3	0.861	0.778
Specific Heat, J/kgK	1900	2300
Melting Point, *Co*	55	
Latent Heat, kJ/kg	200 ± 10	

Table 2. Physical properties of some paraffin

Paraffin	Freezing Point / range (^{0}C)	Heat of fusion (kJ/kg)
6106	42-44	189
P116^c	45-48	210
5838	48-50	189
6035	58-60	189
6403	62-64	189
6499	66-68	189

Along with the times, solar water heater systems today use a thermosyphon principle. The experimental and simulations of the solar thermal system have been presented by Ka-Kui Tse [10] and the results reveal that the overall efficiency of the solar thermal system can be improved by further physical design optimization. As for validated between the mathematical method and experimental method indicated that the maximum temperature of hot water occurred at 4:00 p.m as 65.25^{0}C, 71.19^{0}C, and 69.46^{0}C, respectively [11]. Garnier [12] have been presented a computational fluid dynamic (CFD) analysis of internal flows and heat transfer regimes within the new collector configuration and compares its performance against previously developed prototypes using empirical testing.

From the studies discussed previously, it can be concluded that numerical simulation with a computational fluid dynamic (CFD) analysis is more important to do before presented the prototype of a product.

3. Research Methodology

In this research, the used methodology is the experimental method and numerically simulation method. In the experimental method, two designs of solar water heater thermosyphon systems with an absorber plate with and without PCM storage have been presented and tested their performances with dimensions shown in Fig. 2.

The experimental study scheme is shown in Fig. 3 where 2 solar water heater thermosyphon systems with an absorber plate with and without PCM storage have been tested their performances using a thermocouple to measure the amount of temperature and a weather station to measure the amount of solar radiation from 9 AM to 8 PM.

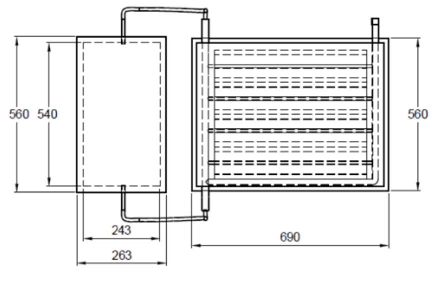


Figure 2. The dimensions of the thermosyphon system

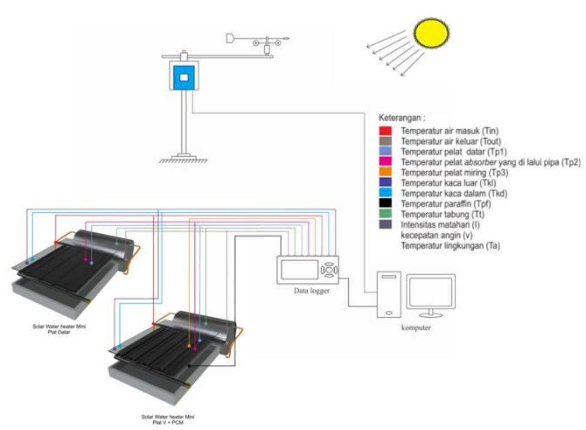
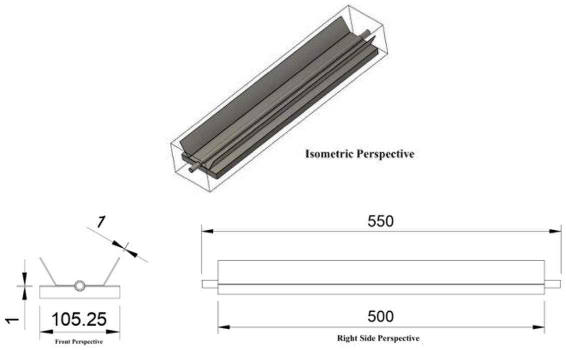
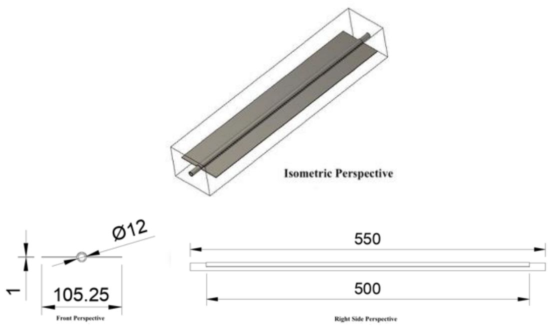


Figure 3. The experimental study schematic



a) Absorber plate with PCM storage

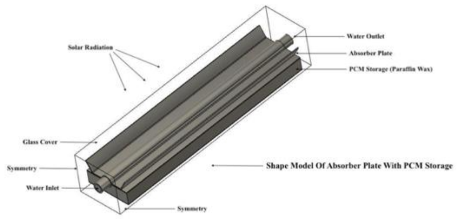


b) Absorber plate without PCM storage

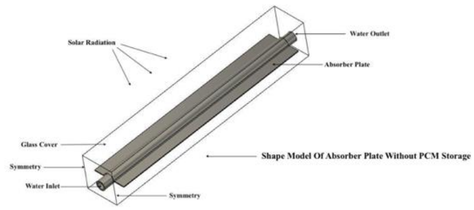
Figure 4. The dimensions of the thermosyphon system

Meanwhile, the numerical simulation uses a set computer with windows 10 pro 64 bit, processor core i7-7700, and RAM 32 GB specification and capable of running a CFD fluent software and geometry modeling software i.e. an ANSYS Fluent and Autodesk Fusion 360, respectively. The simulation method, two shape model of the solar water heater thermosyphon system which will be simulated with one series, i.e. pipe, absorber plate with or without PCM, water flow in a pipe, glass, and two sides symmetry on the left and right side with the dimensions as shown in the Fig. 4.This is done because one series considered to be typical with others.

The simulation scheme as shown in Fig. 5 where an absorber plate with and without PCM modeling has given water inlet and constant radiation variations i.e. 400 W/m^2, 700 W/m^2, and 1000 W/m^2. A different temperature between inlet and outlet will be shown by contours



a) Absorber plate with PCM storage



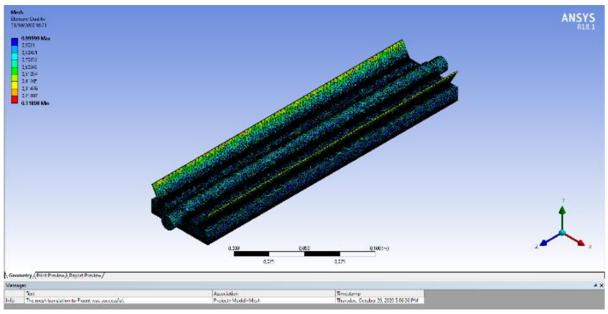
b) Absorber plate with PCM storage

Figure 5. The numerical simulation schematic

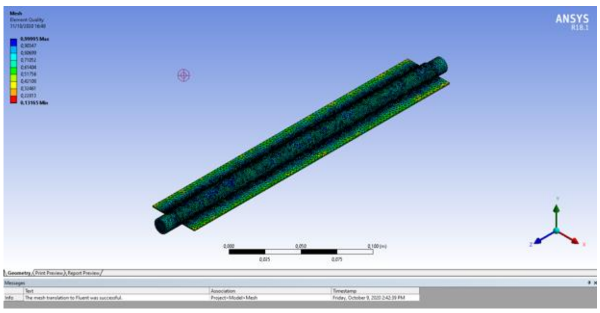
variations as a result of the simulation, likewise a contours temperature of the absorber plate, PCM, and water in the pipe.

Generally, the simulation run out based project schematic of fluid flow (fluent) from ANSYS Fluent, and each step be marked by the correct sign when done. The first step of the simulation is to draw or to import the geometry from another drawing software, provided that the file format of the geometry is compatible with ANSYS Fluent software (.iges or .step file) [13].

The simulation test kit consists of two shape model that was meshed of solar water heater collectors with absorber plate variations: a) Absorber plate with PCM storage and b) Absorber plate without PCM storage as shown in Fig. 6.



a) Absorber plate with PCM storage



b) Absorber plate with PCM storage

Figure 6. Meshed shape model of the absorber plate

The numerical calculation study i.e includes calculating the collector efficiency by comparing the useful energy with the product of surface area and solar radiation, as shown in Eq. 1 :

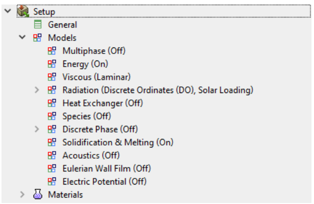
$$\eta = \frac{Qv}{Ac\,.I\tau} \qquad (1)$$

Where $I\tau$ is solar radiation (W/m^2) and Ac is collector surface area (m^2), meanwhile, the useful energy was calculated based on the simulation results of inlet and outlet water temperature at a certain flowrate. The useful energy Qv was defined by Eq.2 :

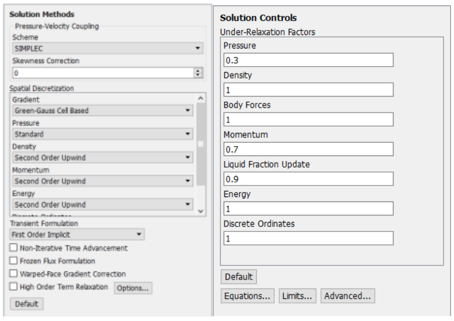
$$Qv = m.Cp.\Delta T \qquad (2)$$

Where m is flowrate (kg/s), Cp is the specific heat of water (J/kg.K), and ΔT is the temperature difference of inlet and outlet of water (°C).

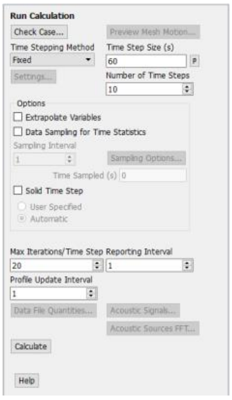
A simulation study of shapes model plate absorber with and without PCM storage was conducted under the same methods. Water flowed through a copper tube by inlet water with uniform 1 m/s velocity. Figure 7 shows (a) Setup model simulation; (b) Solution methods and solution control; and (c) Run calculation processes.



a.) Setup model simulation



b.) Solution method and control



c.) Run calculation processes

Figure 7. Used Simulation method

4. Result and Discussion

The research was conducted at the Renewable Energy Laboratory of the Mechanical Engineering Department, Hasanuddin University, Gowa. Experimental and numerical simulation tests of two design solar water heater collectors using an absorber plate with and without PCM storage.

The results of the experimental study that have been done of the absorber plate with and without PCM storage at the same time of day and condition i.e. October 11-13, 2020 are shown in Fig. 8. However, as a valid data with numerically simulation study, solar radiation has been chosen which ranges between 400 W/m^2, 700 W/m^2, and 1000 W/m^2 as a sample of solar radiation at three times a day i.e. morning or afternoon; before or after daylight; and the daylight.

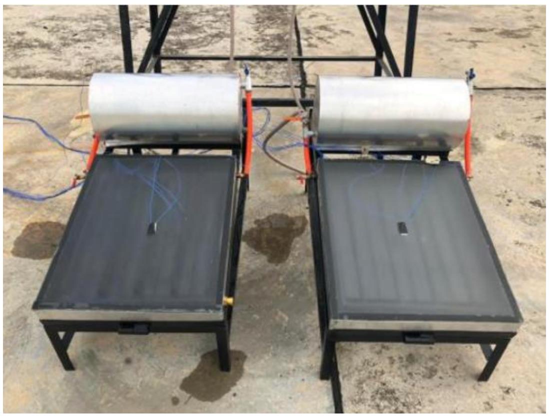
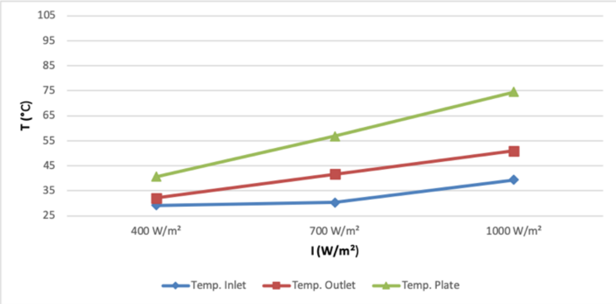


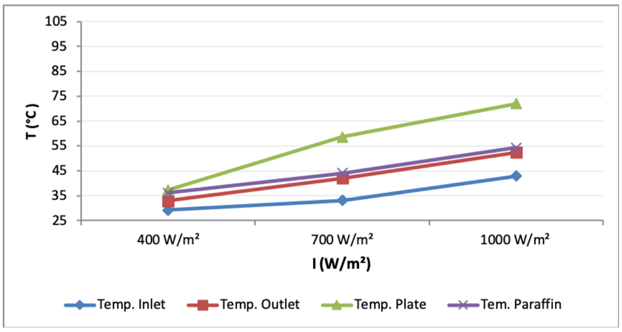
Figure 8. Absorber plate with PCM storage (left side) and without PCM storage (right side)

Figure 9 shows a comparison of inlet and outlet water temperature, plate temperature, and paraffin wax temperature as a PCM storage at three solar radiation variations as the results of an experimentally study. The outlet temperature from the absorber plate with PCM storage is higher than the absorber plate without PCM storage which the highest outlet water temperature of the absorber plate with PCM storage is 52.36 ^{0}C when compared with the absorber plate without PCM storage that is 50.97 ^{0}C. But in reverse with a maximum temperature of plate surface which the temperature of absorber plate without PCM storage is higher than absorber plate with PCM storage, which the maximum temperature of plate surface on absorber plate without PCM storage is 74.47 ^{0}C, while the maximum temperature of plate surface on absorber plate with PCM storage is only about 72.03 ^{0}C.

Meanwhile, the results of the simulation can access by contours, a difference temperature shown in contours of temperature. A temperature contours of absorber plate with and without PCM storage on constant radiation 400 W/m2 (a); A temperature contours of absorber plate with and without PCM storage on constant radiation 700 W/m2 (b); and A temperature contours of absorber plate with and without PCM storage on constant radiation 1000 W/m2 (c) is shown in Fig. 10.



a) Absorber plate without PCM storage



b) Absorber plate with PCM storage

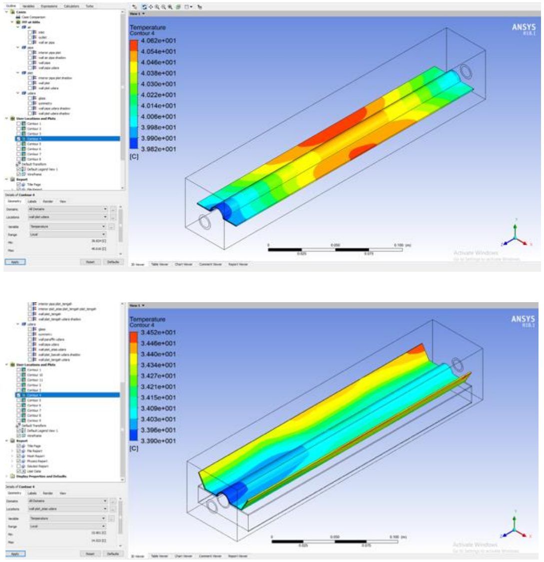
Figure 9. Inlet and outlet water temperature, plate, and PCM temperature

A temperature contours of water on absorber plate with and without PCM storage on constant radiation 400 W/m^2 (a); A temperature contours of water on absorber plate with and without PCM storage on constant radiation 700 W/m^2 (b); and A temperature contours of water on absorber plate with and without PCM storage on constant radiation 1000 W/m^2 (c) shown in Fig. 11.

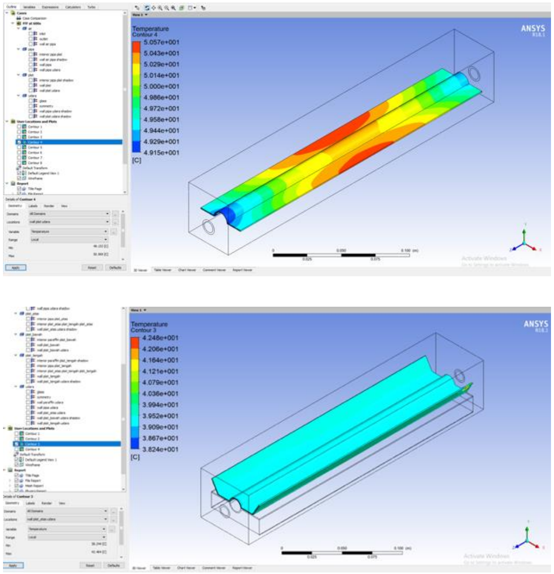
The temperature contours of paraffin wax on an absorber plate with PCM storage are shown in Fig. 12. In this study, simulation has given constant direct solar radiation too i.e. 400 W/m^2, 700 W/m^2, and 1000 W/m^2. Then it was obtained of a temperature comparison of water on every shape model was simulated.

Figure 13 shows a comparison of constant direct solar radiation variations on each simulated model and the results of the numerical simulation study. The water temperature from absorber plate without PCM storage is higher than absorber plate with PCM storage which the maximum water temperature of absorber plate without PCM storage is 102.04 ^{0}C on 1000 W/m^2 constant radiation when compared with absorber plate with PCM storage that is 73.85 ^{0}C on the same condition of the constant radiation. However, the heat was absorbed by the plate absorber with PCM storage was transferred to PCM storage partially.

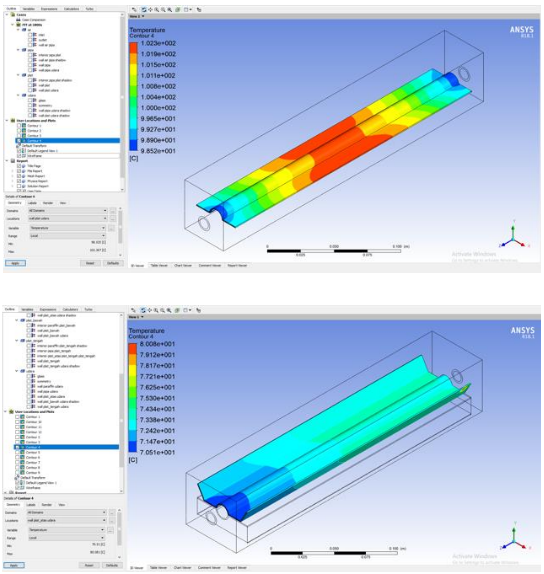
As shown in Fig. 13 where the average paraffin wax temperature as PCM storage even higher than the maximum paraffin temperature is 70.21 ^{0}C on 1000 W/m^2 constant radiation. So as the collector efficiency of the absorber plate with PCM storage is better than the absorber plate without PCM storage.



a) Temperature contours of absorber plate on radiation 400 W/m^2

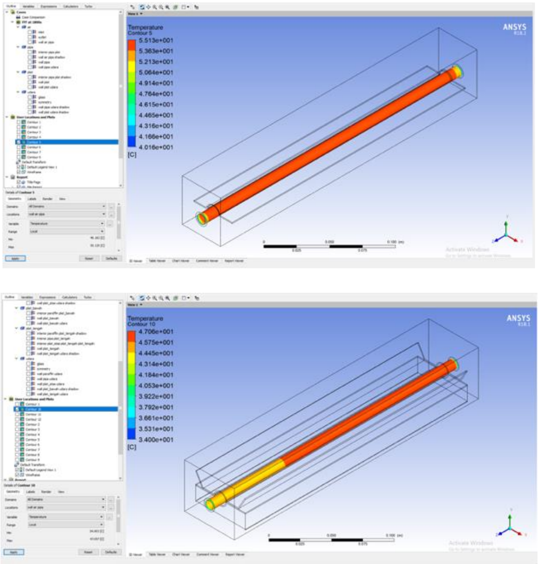


b) Temperature contours of absorber plate on radiation 700 W/m^2

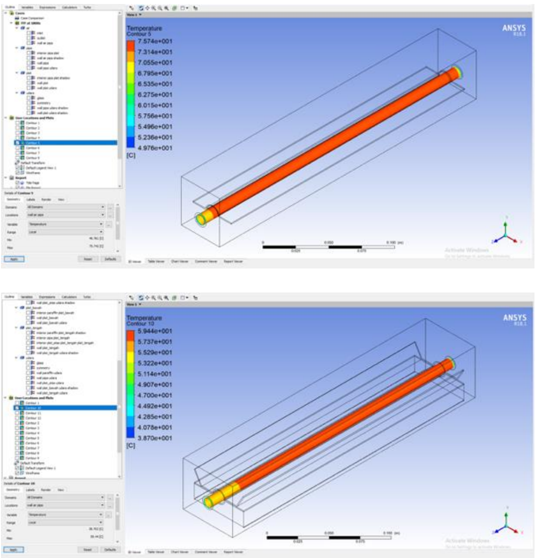


c) Temperature contours of absorber plate on radiation 1000 W/m^2

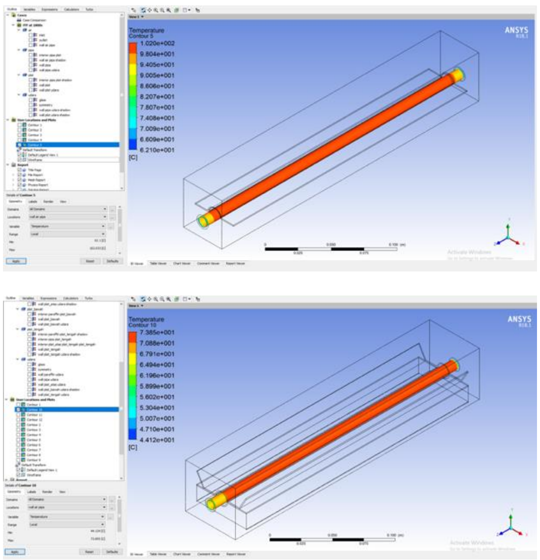
Figure 10. Temperature contours of the absorber plate



a) Temperature contours of water on radiation 400 W/m^2

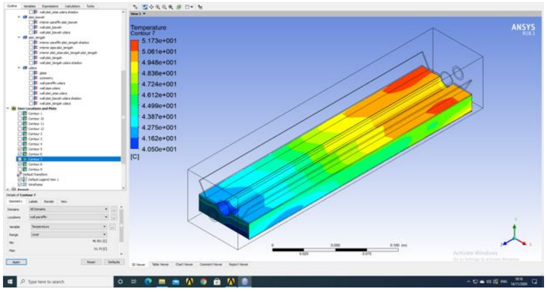


b) Temperature contours of water on radiation 700 W/m^2

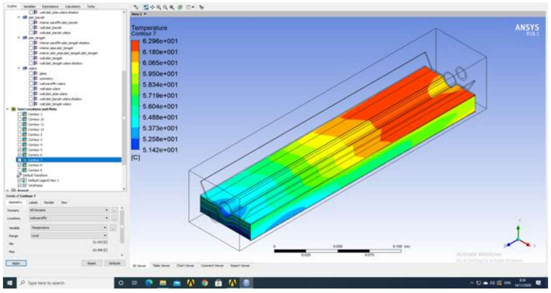


c) Temperature contours of water on radiation 1000 W/m^2

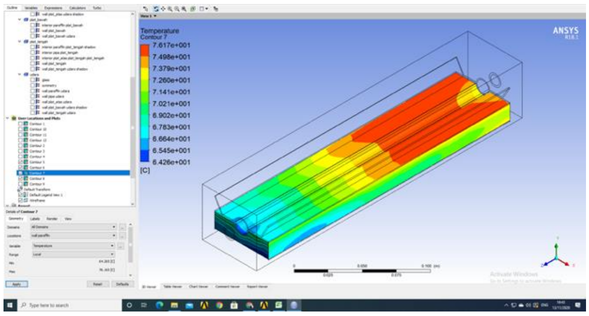
Figure 11. Temperature contours of water on absorber plate



a) Temperature contours of paraffin wax on radiation 400 W/m^2

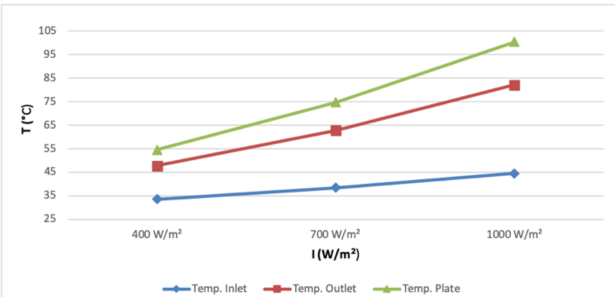


b) Temperature contours of paraffin wax on radiation 700 W/m^2

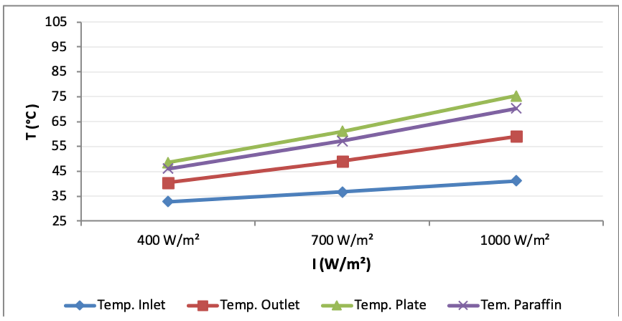


c) Temperature contours of paraffin wax on radiation 1000 W/m^2

Figure 12. Temperature contours of paraffin wax



a) Absorber plate without PCM storage



b) Absorber plate with PCM storage

Figure 13. Inlet and outlet water temperature, plate, and PCM temperature

Figure 13 shows a comparison of inlet and outlet water temperature, plate temperature, and paraffin wax temperature as a PCM storage at three constant solar radiation variations as the results of a numeric simulation study. The average water temperature from the absorber plate without PCM storage is higher than the absorber plate with PCM storage which the highest average outlet temperature of the absorber plate without PCM storage is 82.06 ^{0}C when compared with the absorber plate with PCM storage that is 58.99 ^{0}C. Likewise with the average plate surface temperature which 75.29 ^{0}C for absorber plate with PCM storage, lower than absorber plate without PCM storage as much as 100.39 ^{0}C.

Based on experimentally and numerically simulation study at the high constant solar radiation, the efficiency collector by absorber plate with and without PCM storage is shown in Fig. 14. The difference in collector efficiency using a simulation method tended to lower than using an experimental method. Using the experimental method, the collector efficiency was 70.36 % for the absorber plate without PCM storage and 71.61 % for the absorber plate with PCM storage. While using the simulation method, the collector efficiency was 67.14 % for the absorber plate without PCM storage and 68.33 % for the absorber plate with PCM storage. So, the average collector efficiency between absorber plates with and without PCM storage was 70.98 % using an experimental study and 67.73 % using a simulation study. Based on an experimental and numerical simulation study, the average collector efficiencies were 68.75 % for absorber plate without PCM storage and 69.97 % for absorber plate with PCM storage, so the absorber plate with PCM storage had a better performance than the absorber plate without PCM storage.

5. Results and Discussion

The absorptivity of the absorber plate with and without PCM storage was investigated. It was shown that the absorber plate with paraffin wax as PCM storage had better absorptivity if compared with the absorber plate without PCM storage. The absorber plate with PCM storage was applied in the experimental and numerical simulation study.

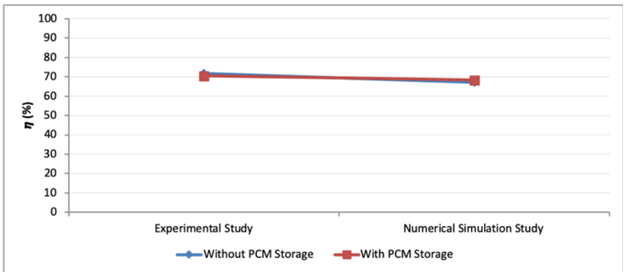


Figure 14. Collector efficiency of absorber plate with and without PCM storage

Two designs of solar water heater thermosyphon system with different absorber plate, i.e. absorber plate with PCM storage and absorber plate without PCM storage were investigated experimentally and numerically simulation. The results show that the solar water heater with a PCM storage absorber plate had a better performance. The average collector efficiency between absorber plates with and without PCM storage was 70.98 % for experimental and 67.73 % for numerical simulation. Applying for the absorber plate with PCM storage in a solar water heater thermosyphon system increases its performance due to the increased absorptivity of its absorber plate.

Acknowledgments

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