Thermal Performance of a Heat-Pipe Evacuated-Tube Solar Collector

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Abstract The heat pipe solar water heater utilizes an evaporator to capture heat which is then used to heat water in the condenser section. The greater the heat that is able to be absorbed on the evaporator, can improve the overall performance of the solar water heater. Fins are added to the evaporator to increase the heat absorption area, but the shape of the fins can also affect the amount of heat absorbed. This research was conducted to determine the effect of fin shape on heat absorption in the evaporator section. Fins on the evaporator are made in a circular and flat shape with a width of 43 mm, a length of 516 mm for a flat fin and a diameter of 43 mm totaling 50 for a circular fin. From the test results it was found that the circular fin can reduce thermal resistance 43.48% greater than the flat fin and 9.89% of the solar water heater heat pipe without fins.

Keywords Heat pipe · Vacuum tube · Solar collector

1 Introduction

In general, the energy used in various human activities is energy that comes from fossils. In fact, fossil fuel combustion can cause serious health and developmental harms through its emission of carbon dioxide (CO_2) which is toxic for humans and the major pollutant of climate change [1]. In Indonesia for example, Surabaya is one

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of the most populated and polluted city, second only to Jakarta. The main air pollutants found in Surabaya is carbon monoxide (CO), lead (Pb), nitrogen oxyde (NO_2), ozone (O_3), particulate matter (PM) and sulfur dioxide (SO_2) [2]. This pollutant mainly produced by vehicle engines, industrial activity and diesel electricity generators.

Indonesia is a tropical country in equator. Solar energy has enough potential to generate electrical energy since Indonesia has average sunshine of 6–7 h per day and can be utilized through solar panel for electrical energy for 5–6 h a day [3]. One of the uses of sunlight is as a source of electricity. Sunlight is also used as an energy source in heating water, both hot water in households and hot water in hotels using a solar water heater [4].

The solar water heater that is widely used is a solar water heater conventional where the working fluid is circulating in the solar collector using a pump so that it still uses electrical energy, which mostly comes from fossil energy. To reduce the use of electrical energy sourced from fossils, many have been developed solar water heaters using evacuated tube collectors that utilize natural fluid circulation. Because the circulation of the working fluid in the evacuated tube collectors only takes advantage of the effect of gravity and the vapor and liquid trajectory on the path, which causes dryness and the collector becomes malfunctioning [5].

To solve the problem of fossil energy, a heat pipe finned with the axis of the capillary developed as a tube was collector tube for solar water heater. The capillary axis is a porous medium that can separate the vapor path leading to the condenser and the liquid passage leading to the evaporator, where the capillary axis is one of the factors that greatly determines the performance of the heat pipe which of course will also affect the performance of the solar water heater [6].

According to N. Putra, et al., the development of a heat pipe with a capillary axis is *screen mesh* still not optimal because the *screen mash* has low capillarity so that the working fluid circulation is not optimal which results in the transfer of heat to the condenser is also not optimal. In addition, the collector is only a pipe cylinder, so that a lot of sunlight is still overlooked due to the limited area of the sun's heat catchment [7].

The research of solar collectors is currently focused on innovation and modifying current solar collector. For example the evacuated tube solar collector with u-tube [8], evacuated tube solar collector based on mini channels [9], evacuated tube solar collector with a variety of absorber tube shape [10], and even incorporating some technology into a solar collector such as nanofluid [11, 12] and phase change material [13, 14].

2 Experimental Setup

The solar collector is made using a copper heat pipe with a diameter of 10 mm length 700 mm. The insulator part is made using a glass tube with the size of the outer diameter is 60 mm and a length of 600 mm. This tube is closed with a plange

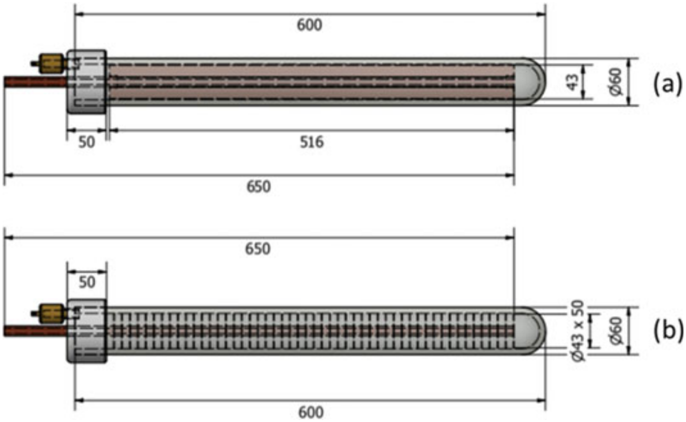

Fig. 1 Flat fin (**a**) and circular (**b**) heat pipe

equipped with a vacuum valve as shown Fig. 1. This solar collector section will be fitted into a water heating system based on finned heat pipes.

This water heating system consists of 4 (four) tubes, each of which contains a heat pipe. The evaporator part of the heat pipe inserted in a pipe with a diameter of 100 mm as a place to accommodate heated water as shown in Fig. 2. The detailed tube collector of the designed water heater presented in Table 1.

The heat pipe of the designed water heater made from oxygen-free copper with 700 mm in length and 10 mm in diameter. The working fluid used in the solar collector water heater is purified water and pressurized below 5×10^{-3} Pa. The maximum working temperature for this specific material is 300 °C. The vertical

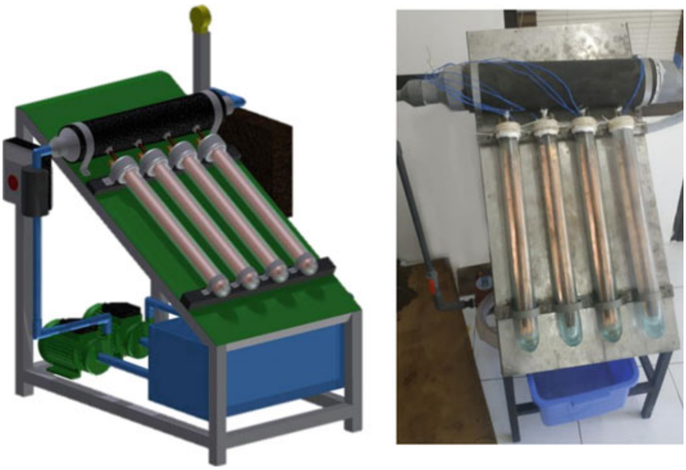

Fig. 2 Water heating system with solar collector based on heat pipe fin

Table 1 Tube collector specification

Length	Outer diameter	Weight	Material	Pressure
600 mm	60 mm	1100 gr	Glass	<1 atm

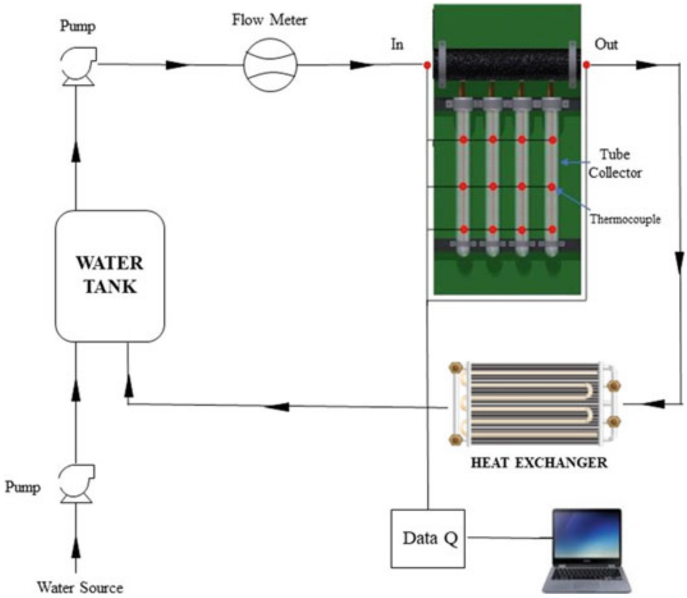

Fig. 3 Solar collector experimental scheme

installation angle for the heat pipe varied at 20°–70°. There are 2 type of fins used in the sun collector. It has 50 pieces of circular fin with 43 mm diameter and a sheet shaped fin with 516 mm in length and 43 mm in wide. The experimental scheme is presented in Fig. 3.

The experimental setup of the solar collector is referred to the real application of the solar collector. The water from water source streamed into the condenser section of the solar collector to catch the heat through natural convection process. Hot water coming from the condenser section called the water output then cooled in the heat exchanger to be streamed back to the condenser section. The pump is needed to vary the water flow rate. The data obtained from this experiment is evaporator temperature, condenser temperature, water output temperature, and the water flow rate. The data obtained using thermocouples through the data acquisition system into the laptop using LabView application.

Heat received by heat pipe depends on the solar heat flux and heat pipe surface area. Figure 4 shows the solar heat flux measured with solar energy meter from 9.00 am to 2.30 pm WITA.

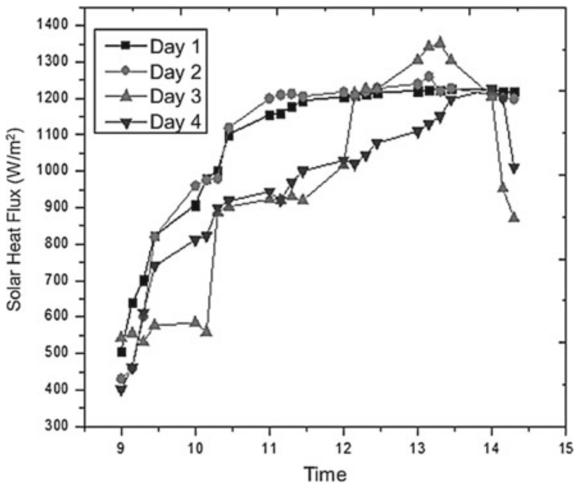

Fig. 4 Solar heat flux

The graph in Fig. 4 shows that the solar heat flux is tend to increase from 9 am to around 2 pm central Indonesia time. The results are affected by the weather that changes almost every day. The highest average solar heat flux obtained in 4 days is recorded at around 2 pm even though the highest solar heat flux recorded at 1 pm in the third day.

The graph in Fig. 5 shows the temperature distribution of evaporator section, Fig. 6. Shows the temperature distribution of condenser section, and Fig. 7. Shows the water output temperature distribution on flat and circular fin heat pipe. The graph shows that the temperature of each section is increasing every hour from 9 am to 2.00 central Indonesian time. The highest temperature recorded in each graph occurred around 2 to 2.30 pm. The highest evaporator temperature obtained

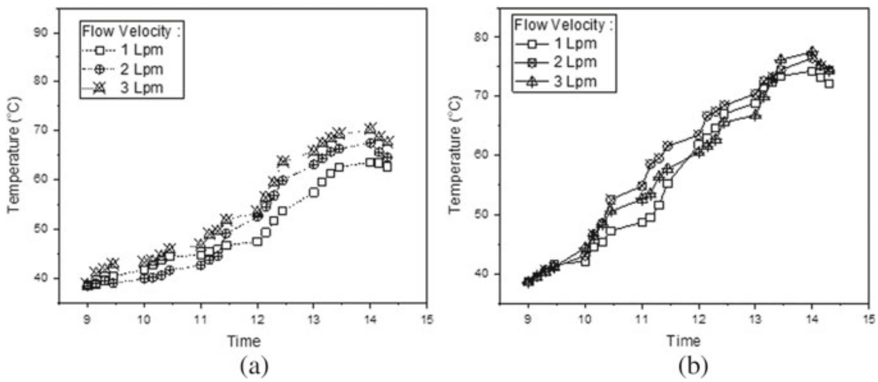

Fig. 5 Evaporator temperature of flat fin (**a**) and circular fin (**b**) evaporator temperature with water flow velocity variable

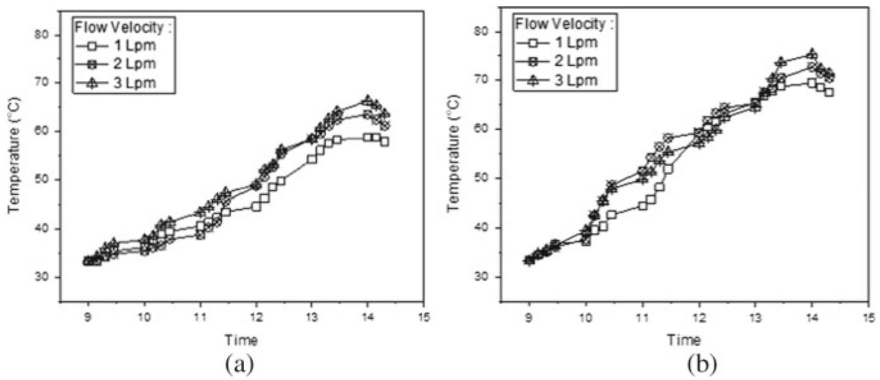

Fig. 6 Condenser temperature on flat fin (**a**) and circular fin (**b**) with water flow velocity variable

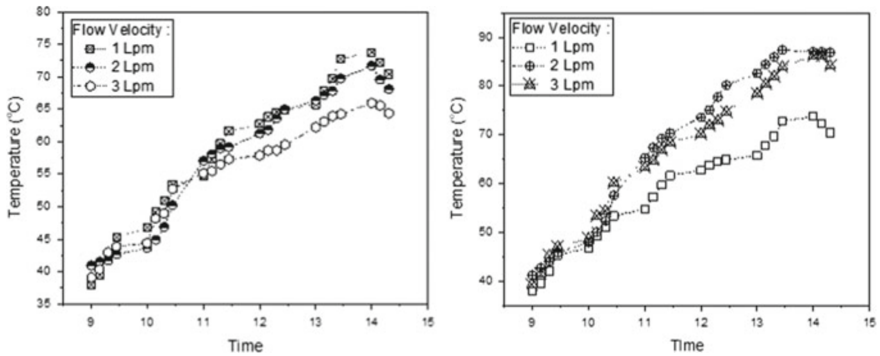

Fig. 7 Water output temperature on flat fin (**a**) and circular fin (**b**)

is 70.27 °C at 3 Lpm using flat fin heat pipe and 77.56 °C at 3 Lpm using circular fin heat pipe. The highest condenser temperature obtained is 66.33 °C at 3 Lpm using flat fin heat pipe and 75.34 °C at 3 Lpm using circular fin heat pipe. The highest water output temperature obtained is 73.75 °C at 1 Lpm using flat fin heat pipe and 86.88 °C at 2 Lpm using circular fin heat pipe.

The water flow velocity mainly affect the heat transfer process at the condenser section and water output temperature. Based on the mathematical model provided by Sabharwall et al., mass flow rate and velocity affect heat transfer coefficient. Increase in mass flow rate while maintaining constant velocity resulting in a decrease in the value of the heat transfer coefficient. But, the increase in mass flow rate results the increase of velocity, could improve the heat transfer coefficient [15]. The substantial advantage on heat transfer could obtained by increasing velocity. But, the result shows that the water output temperature at the highest water flow velocity recorded lower than lower water flow velocity. This result could caused by the water flow itself. Increase in heat transfer rate is more significant under turbulent flow condition [16].

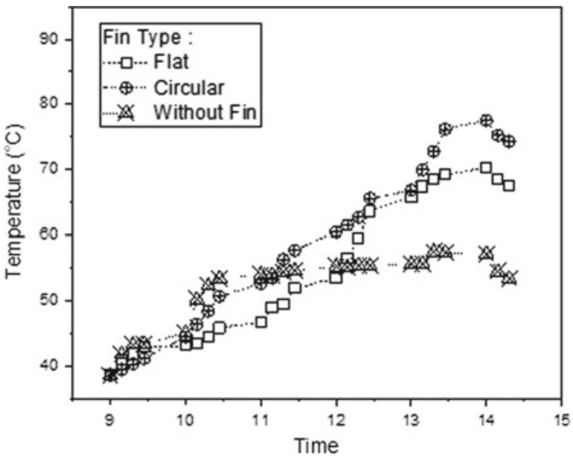

Fig. 8 Evaporator temperature comparison based on fin shape at 3 Lpm water flow velocity

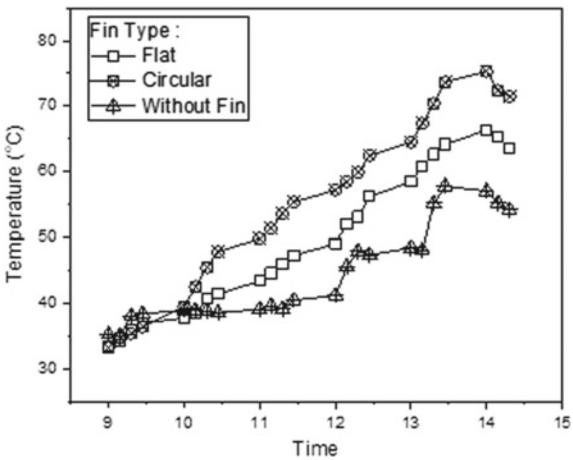

Fig. 9 Condenser temperature comparison at 3 Lpm water flow velocity

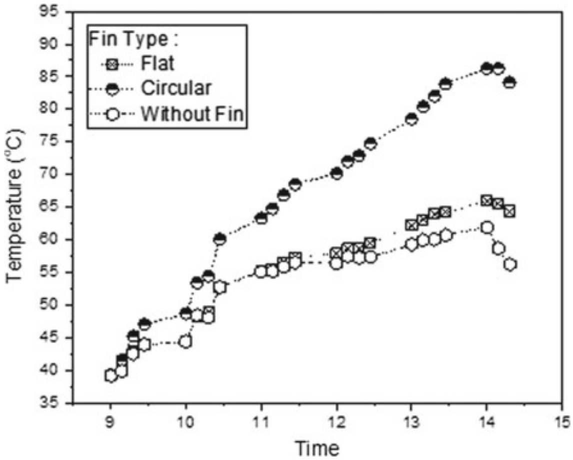

Fig. 10 Comparison of output water temperature based on fin shape at 3 Lpm water flow velocity

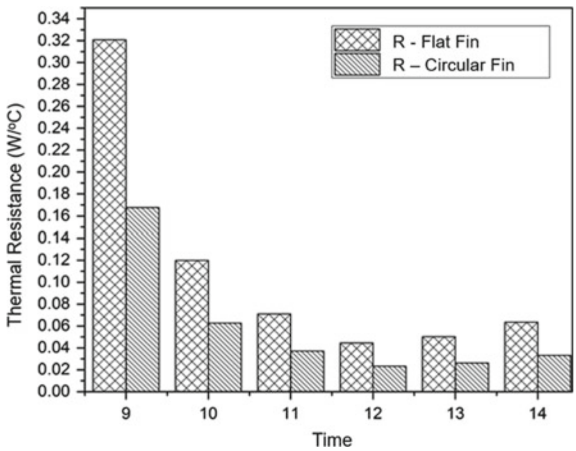

Fig. 11 Thermal resistance comparison between flat fin and circular fin solar water heater

The graph provided above are temperature data comparison between evaporator section, condenser section and water output temperature based on fin shape at 3 Lpm water flow velocity as showed in Figs. 8. 9, 10. From the evaporator graph, it shows that the temperature of heat pipe with flat fin, circular fin, and without fin is pretty much similar in 9 am to 10 am central Indonesia time. Daghigh et al. in their research about solar collector stated that the greater the solar energy, the greater the heat captured by the heat pipe solar collector [17]. The data obtained is directly proportional to the solar heat flux provided in Fig. 4 especially for the evaporator section which directly capture the heat from the solar heat flux. The circular heat pipe shows the higher temperature than the flat fin and without fin heat pipe starting from 1 pm to 2 pm central Indonesia time. This phenomena occurred because the circular fin heat pipe has wider surface area to handle the solar heat flux.

From the experimental data obtained, solar water heater thermal resistance based on fin shape obtained. The thermal resistance comparison between flat fin and circular fin solar water heater can be seen in Fig. 11.

The use of flat and circular fins in the Solar Water Heater provides different thermal resistance values, namely the use of circular fins gives a thermal resistance value of 91.28% lower than the use of horizontal fins at 3 Lpm conditions. The same conditions also occur at 2 and 1 Lpm flows where the thermal resistance of the heat pipe on the Solar Water Heater with circular fins is lower than that of the solar water heater with flat fins.

The graph in Fig. 11 shows that the thermal resistance is reduced while the temperature data shows temperature increase between 9 to 12 am central Indonesia time and the thermal resistance increases with increasing temperature after 12 pm. Some research has similar pattern on thermal resistance result. Chen et al. research has the same data trend. They found that as the heat load is increasing, the thermal resistance is decreasing [18]. Meanwhile, in Septiadi et al. research about heat resistance stated that this behaviour happened only before the heat pipe reach maximum heat load. After the maximum heat load passed, the heat resistance will

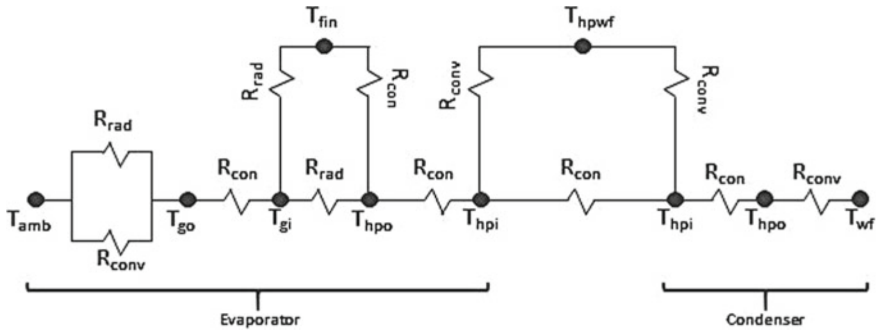

Fig. 12 Electrical analogy of tube evacuated heat pipe

increase as the heat load increase [19]. This behaviour happened after 12 pm which can be concluded that the heat load at that time was the maximum heat load can be handled by the heat pipe since based on the data, the temperature keep increasing until 14 pm.

Electrical analogy in Fig. 12 shows the heat transfer process with heat resistance occurred during the process. This electrical analogy contains the process of transferring heat from the sun and air (T_{amb}) to the outer surface of the glass (T_{go}) and by conduction, heat enters the inner surface of the glass (T_{gi}). The space in the evacuated tube is in a vacuum. Hence, heat transfer from the inner surface of the glass occurs radiantly to the fins (T_{fin}) and the outer surface of the heat pipe (T_{hpo}), after which the heat transfers to the inner surface of the heat pipe (T_{hpi}) by conduction. This process occurred in the evaporator section of the solar collector.

Heat that is on the inner surface of the heat pipe (T_{hpi}) is transferred along the heat pipe and transferred by convection to the working fluid of the heat pipe (T_{hpwf}). After the working fluid changes in phase to vapor and moves to the condenser, the steam heat transfers by convection to the inner surface of the heat pipe on the condenser (T_{hpi}) and conduction moves to the outer surface of the heat pipe (T_{hpo}) until finally the heat transfers conventionally to the water flow (T_{wf}). This process occurred in condenser section of the heat pipe.

According to Elsheniti et al. thermal resistance on the solar collector is closely related to the heat loss in the solar collector manifold. The mathematical model combining liquid film in the evaporator and nucleate in pool boiling calculation and other mathematical model presented by Elsheniti et al. has a huge correlation with heat pipe heat rate. In order to get both thermal resistance value, the heat pipe heat rate value must be obtained with calculations involving the heat loss manifold value [20].

3 Conclusion

The conclusions obtained from this study are as, the addition of fins on the evaporator can reduce thermal resistance on the solar water heater. The flat fin can reduce thermal resistance 9.89% and the circular fin can reduce the thermal resistance 43.48% compared to the finless evaporator. The fin shape of the solar water heater affects heat absorption in the evaporator with circular fins which can increase heat absorption by 39.46% and flat fins can increase heat absorption by 29.30% compared to heat pipes without fins.

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