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by Bambang Ariantara -

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Thermal Performance of Evacuated Tube Heat Pipe Solar Collector

Nandy Putra[a)], M. R. Kristian[b)], R. David[c)], K. Haliansyah[d)], and Bambang Ariantara[e)]

Heat Transfer Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia Kampus Baru UI, Depok, West Java 16424 Indonesia

[a)]nandyputra@eng.ui.ac.id
[b)]mikael.robertusr@gmail.com
[c)]roland.david@windowslive.com
[d)]kristoferhaliansyah@yahoo.com
[e)]bambang.ariantara@gmail.com

Abstract. The high fossil energy consumption not only causes the scarcity of energy but also raises problems of global warming. Increasing needs of fossil fuel could be reduced through the utilization of solar energy by using solar collectors. Indonesia has the abundant potential for solar energy, but non-renewable energy sources still dominate energy consumption. With heat pipe as passive heat transfer device, evacuated tube solar collector is expected to heat up water for industrial and home usage without external power supply needed to circulate water inside the solar collector. This research was conducted to determine the performance of heat pipe-based evacuated tube solar collector as solar water heater experimentally. The experiments were carried out using stainless steel screen mesh as a wick material, and water and Al2O3-water 0.1% nanofluid as working fluid, and applying inclination angles of 0°, 15°, 30°, and 45°. To analyze the heat absorbed and transferred by the prototype, water at 30°C was circulated through the condenser. A 150 Watt halogen lamp was used as sun simulator, and the prototype was covered by an insulation box to obtain a steady state condition with a minimum affection of ambient changes. Experimental results show that the usage of Al_2O_3-water 0.1% nanofluid at 30° inclination angle provides the highest thermal performance, which gives efficiency as high as 0.196 and thermal resistance as low as 5.32 °C/W. The use of nanofluid as working fluid enhances thermal performance due to high thermal conductivity of the working fluid. The increase of the inclination angle plays a role in the drainage of the condensate to the evaporator that leads to higher thermal performance until the optimal inclination angle is reached.

INTRODUCTION

The use of non-renewable energy source must be reduced, not only because the energy supply become rare and not much, but also because the global issues, such as global warming, which caused by CO_2 production as resulted from combustion of fuels. [1]. However, reducing the consumption of non-renewable energy is not easy to be engineered and to be applied. One wise solution is to increase the use of renewable energy sources such as solar, wind, geothermal, ocean energy and biomass [2, 3]. Although this is not easy, it is expected to contribute to the reduction of non-renewable energy consumption.

In big cities, energy consumption in building applications is a significant contributor. Substituting the needs of non-renewable energy in building application seems to be a promising way since it reaches 20% to 40% of total energy consumption [4]. Geographically, Indonesia, a tropical country, spans crossed the equator line from 6o° North Latitude to 11° South Latitude and 95° to 141° East Longitude. With abundant energy from the sun in the form of heat, Indonesia receives high daily thermal radiation up to 4.8 kWh/m^2/day [5], but 96% of its energy usage comes from non-renewable sources [6]. Indonesia could utilize this great potential of solar energy by applying solar collectors as the solar water heaters in building applications.

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Solar collector has two types, one is flat plate solar collectors, and the other is evacuated tube solar collectors. Compared to the flat plate solar collectors, evacuated tube solar collectors is more efficient in low thermal insulation due to vacuum condition inside the tube [7-9], yet several problem needs to be solved to optimize the thermal performance. An evacuated tube solar collector absorbs heat from the sun through water flow inside vacuum tubes. This method has several disadvantages, namely extra cost and extra energy to flow the water inside vacuum tubes, limited heat transfer due to the low specific heat of water, pipe corrosion, the freeze of water at night, and backflow circulation at night due to the low ambient temperature [10]. Using heat pipe as a heat transfer passive device is an expected solution to overcome those disadvantages. Commonly, heat pipes use copper or aluminum tubes that filled with porous media called wick inside the pipe, covering the inner wall of the tube at a specific thickness. They are filled with working fluid, and sometimes it is vacuumed to ease evaporation of the working fluid. Heat pipes are divided into three section: evaporator, adiabatic, and condenser. Heat pipes can be applied with the certain inclination angle. By absorbing the heat at the evaporator, working fluid shall be boiled. Water vapor will move, pass through the adiabatic section, and reach the condenser. Heat will be released at the condenser, and working fluid will be condensed. It will be pumped back to the evaporator by capillary action provided by the wick [11]. As passive heat transfer device, a heat pipe uses no external energy supply to circulate the working fluid, moreover, it transfers a large quantity of heat by utilizing the latent heat of evaporation [10]. Selecting a proper working fluid will prevent the liquid change into solid state at night.

Heat pipe usage in solar collector has been studied by several researchers [11-14]. The thermal performance of a heat pipe is affected and limited by several factors such as the entrainment, capillary, sonic, velocity, and boiling limitation. Also, gravity could affect the performance of a heat pipe. A solar collector absorbs heat in a definite heat flux, which depend on the surface area. The more the inclination angle is, the less surface area that absorbs heat, however, heat pipe thermal performance will be better due to gravity effect. On the other hand, several researchers found that there is an optimum inclination angle for the usage of the heat pipe [15, 16]. It is when the condensate is overflown and cooled the liquid in the evaporator and disturb the boiling process.

Nowadays, nanoparticles are used to be suspended to enhance the thermal conductivity of base fluid [15, 17, 18]. Increasing volumetric concentration of nanofluid, and increasing the size of nanoparticle increase the thermal performance of a heat pipe [19]. By using screen mesh as the wick, Putra et al. [20] used Al_2O_3, TiO_2, ZnO, distilled water, and ethylene glycol as working fluid in his research at the usage of a heat pipe for cooling system application. They found a parallel result with Shung-Wen Kang et al. [19] that more concentration provides better heat transfer phenomenon. Putra [20] also found that by using nanofluid, a thin layer appeared at the pore of screen mesh wick. The thin layer was provided by nanoparticle suspended in base fluid. This layer, reduce pore size, leading to better capillary structure and better thermal performance as a result.

The amount of heat transferred to the water that flow in the water manifold is a measure of a solar collector performance. Since the quantity of heat is proportional to the temperature change, the thermal performance of the prototype could be indicated by the temperature difference between the water inlet and the water outlet. The heat transfer done by the heat pipe is influenced by their thermal resistance. The thermal resistance of a heat pipe is defined as the heat transferred at the certain temperature difference between the evaporator and the condenser. Low thermal resistance will provide a high thermal performance of prototype, resulting in high heat transfer along the system. This research was conducted to determine the performance of a heat pipe-based evacuated tube solar collector as the solar water heater with water and nanofluid as working fluids at various inclination angles experimentally.

METHODOLOGY

The solar water heater used in this experiment consists of solar collectors and a water manifold. Solar collectors with evacuated tubes were used due to the thermal performance stability and higher thermal performance as discussed in the previous section. A solar collector was constructed by four components, which are a vacuum tubes, a tube support, heat pipes, and thermal insulation. Six vacuum tubes were constructed. Each tube was made of borosilicate glass with a tube connector to connect one tube to another. The tube connectors were made of silicon. One of the vacuum tubes was equipped with vacuum valve to facilitate the vacuum process of all tubes using a vacuum pump. Every tube has a sealing cap and installed on the tube support. The heat pipes were made of copper tubes with 300 mm length, 8 mm O.D., and 1 mm thickness. They were filled with working fluid with 60% filling ratio. The evaporators of the heat pipes are located inside the tubes. Two layers of stainless steel screen mesh were used as the capillary wick. Before the filling with working fluid, the heat pipes were evacuated to be vacuumed. To facilitate the vacuum and filling process one end of each heat pipe was equipped with a valve while the other was edged and welded.

Each heat pipe has the evaporator section of 170 mm length, the adiabatic section of 30 mm length, and the condenser of 100 mm length. Polyurethane was used to insulate the adiabatic section. Figure 1 shows the prototype of the solar collector.

FIGURE 1. Prototype of solar collector

Water manifold plays an important role, i.e. to collect the heat released from the condenser sections. It is a storage where cold water flows and be heated. Water manifold was made of acrylic and manufactured to form a box with six holes for heat pipes and two holes for water inlet and water outlet as shown in Fig. 2. Each of six holes for the heat pipes was equipped with a flange to ease the assembling process. The water inlet and outlet holes were connected to a Circulating Thermostatic Bath (CTB) and a flow meter. The CTB was used to supply a constant water temperature at 30°C to the water manifold while the flow meter was used to measure the water flow rate.

FIGURE 2. Water manifold

The thermal radiation of the sun was simulated by a 150 W halogen lamp. An insulation box was made covering the vacuum tube and adiabatic section of the heat pipes to eliminate the heat loss to the surrounding. The insulation box was made of styrofoam with 28 mm thickness, 260 mm length, 160 mm width, and 228 mm height. Furthermore, the inner side of the box was covered with aluminum foil. The top side of the insulation box was made of plywood, which also used as a mechanical support to keep the position of the halogen lamp steady.

This experiment used water and nanofluid as working fluids. The nanoparticle volume fraction can be obtain using Eq. (1).

$$\%\,volume\ fraction = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{m_f}{\rho_f}} \quad (1)$$

where m_p is nanoparticle mass, m_f is base fluid mass, ρ_p is nanoparticle density, and ρ_f is base fluid density. Some nanoparticle and distilled water were mixed manually and then mixed using ultrasonic processor within 30 minutes. Several hours was taken to examine if there was any agglomeration or sedimentation of the nanoparticle.

The experiment was conducted in the laboratory with a variation on the type of working fluid and the inclination angle of the prototype. The variation of the type of working fluid was conducted by applying distilled water, and Al_2O_3-water nanofluid with 0.1% volumetric concentration and the variation of inclination angle was conducted with 0°, 15°, 30°, and 45°. K-type thermocouples with 0.2 mm diameter were used to measure the temperature at several measurement points as shown in Fig. 3. A computer-based data acquisition system was used to record the temperature measurement data.

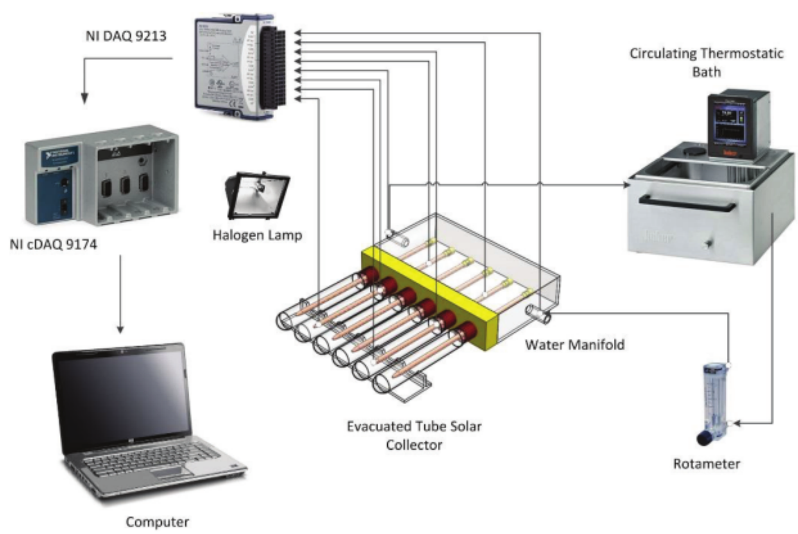

FIGURE 3. Experimental setup

RESULT AND DISCUSSION

Each experiment was carried out until the system reaches a steady state. Figure 4 visualizes the temperature measurement of the prototype with varied inclination angle with water as working fluid. It is seen that the evaporator temperature increased rapidly as the experiment started. It decreased as time goes by until the system began to steady after 6000 seconds. The condenser temperature increased slowly until the steady state condition was reached. The highest evaporator temperature was reached at the inclination angle of 0°, followed by 45°, 15°, and 30°. The evaporator temperature decreased with the inclination angle, but after 30°, it increased. The parallel result was found by Ping-Yang Wang et al. [15] who used screen mesh as the capillary wick, and nanofluid as working fluid. They applied the inclination angle at 0°, 30°, 45°, 60°, and 90°, and found that the optimum inclination angle is 45°. Another parallel result was found by Yi-Hsuan Hung et al. [16] whose research was to evaluate the thermal performance of heat pipe with nanofluid as working fluid. They conducted experimentation with inclination angle within 10°, 40°, 70°, and 90° and found that thermal performance increase with inclination angle until the optimum point was reached at 40° and decreased at the further increase of the inclination angle. They stated that increasing inclination angle will allow gravity to enhance the liquid flow from the condenser to the evaporator. However, excessive gravity effect will allow too much condensate to flow from condenser to evaporator that will decrease evaporation at evaporator as a result of the cooling phenomenon at evaporator by excessive condensate.

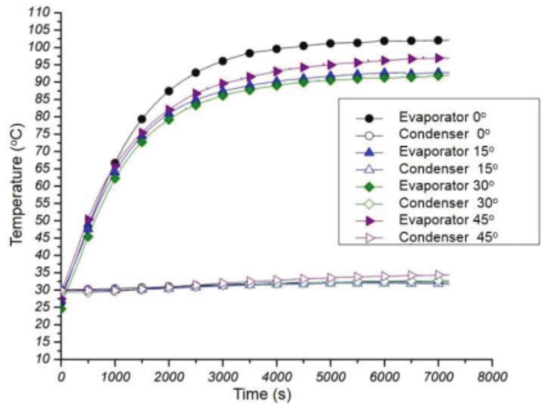

FIGURE 4. Measured temperature at prototype using water as heat pipe working fluid

Similar characteristic of the graph was found at the experiment with nanofluid as working fluid. The highest evaporator temperature was reached at 0° inclination angle, followed by 45°, 15°, and 30°, which mean that the optimum inclination angle was at 30°. Compared to the usage of the prototype at 0°, the usage of the prototype at 30° could reduce the temperature of the evaporator by 10.4°C and 11.2°C with water and nanofluid as working fluid respectively. At inclination angle of 15°, the evaporator temperature could be reduced by 9.3°C and 7.3°C with distilled water and nanofluid as working fluid respectively.

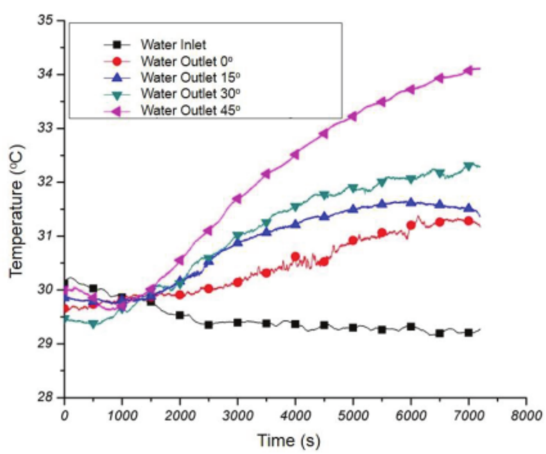

FIGURE 5. Measured temperature at water manifold using water as heat pipe working fluid

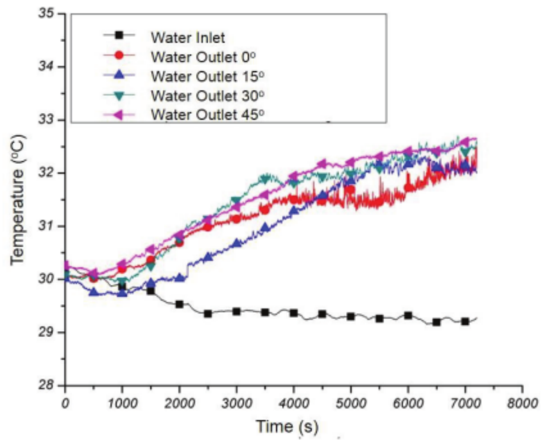

FIGURE 6. Measured temperature at water manifold using nanofluid as heat pipe working fluid

Thermal performance of the prototype has obtained through the calculation of the heat transferred, indicated by the temperature difference between the water inlet and water outlet of water manifold. Figure 5 and 6 show the temperature of the water inlet and water outlet of water manifold at the different inclination angle with water and nanofluid as heat pipe working fluid respectively. As seen from Fig. 5 and Fig. 6 that at 45°, the temperature of water inlet remains constant at the varied inclination angle, the temperature of water outlet when the prototype was set at 45° was the highest among all.

Figure 7 shows the temperature difference between the evaporator and the condenser with water as working fluid at the different inclination angle. By applying temperature difference data and heat transfer rate in Eq. 2, the thermal resistance of heat pipes was obtained and visualized in Fig. 8 for both water and nanofluid as working fluid.

$$R_T = \frac{T_e - T_c}{Q} \quad (2)$$

In Eq. (2), R_T is thermal resistance, T_e is evaporator temperature, T_c is condenser temperature, and Q is the heat transfer rate. From Fig. 7, it is seen that the highest temperature difference occurred at the inclination angle of 0°, followed by 45°, 15°, and 30°. This temperature difference was calculated by data obtained from Fig 4. Therefore, the explanation for the occurred phenomenon is the same as discussed in previous section, e.g. the heat transfer of the heat pipe is affected by gravity. The characteristic of the temperature difference between evaporator and condenser with nanofluid as working fluid is similar to the one with water as working fluid shown in Fig. 7 as the evaporator and condenser temperature has similar characteristic according to Fig. 4.

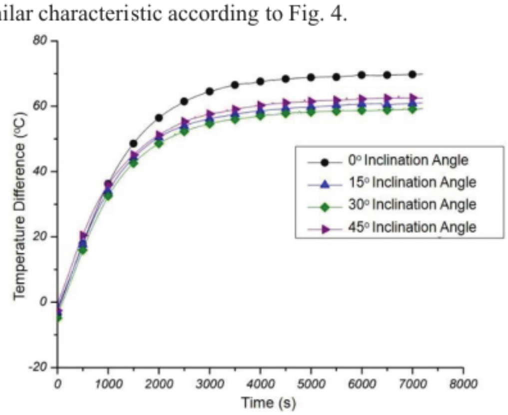

FIGURE 7. Temperature difference of heat pipes with water as working fluid

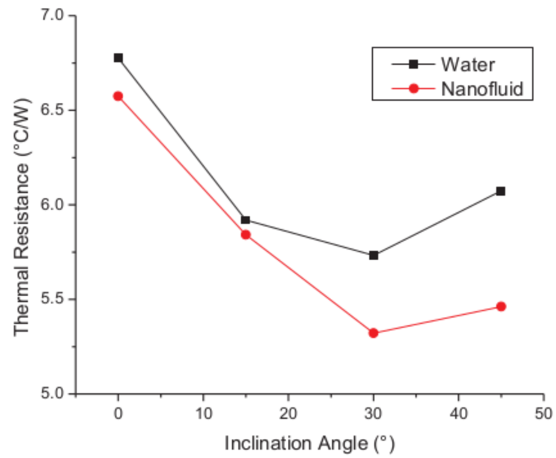

FIGURE 8. Thermal resistance of heat pipes

Anomaly was found when Fig. 5 and Fig. 6 is reexamined at 30°, where the heat pipes at their highest thermal performance could not elevate the water temperature at water manifold as high as at 45°. It is predicted that this anomaly probably caused by higher ambient temperature while collecting the data. The thermal resistance of heat pipe with nanofluid has no significant difference between 30° and 45° inclination angle. Therefore, a little ambient temperature difference will do play a role at the increasing temperature of water manifold due to less thermal insulation at water manifold, creating heat flow from ambient to the system as a result. It can be seen from Fig. 6 that the temperature at water outlet difference between 30° and 45° is not significant. A significant difference of temperature difference between 30° and 45° can be clearly seen from Fig. 5. A remarkable difference of mean ambient temperature was noted while collecting the data. The ambient temperature with 30° inclination angle was 24°C. Meanwhile, it was 26°C at 45° inclination angle.

Referring to Fig. 7 and Fig. 8, the lowest thermal resistance, which indicate the highest thermal performance of heat pipes, was obtained at 30° inclination angle with both of nanofluids and water usage. This result is parallel to the temperature difference data. Thermal resistance difference at 45° and 30° using nanofluid is less significant than using water. Using nanofluid as working fluid will escalate the thermal performance of heat pipes as it stabilize, and intensify bubble growth, increase base fluid thermal conductivity, and enhance boiling phenomenon. Increasing thermal performance was indicated by the less thermal resistance of heat pipe that used nanofluid compared to water at any inclination angle. Zhen Hua Liu et al. [18] state that there are four reasons. The first, the thermal conductivity of base fluid will be increased as nanoparticle had higher thermal conductivity and suspended homogeneously at base fluid. The second, nanofluid can reduce the contact angle between the solid phase substances and liquid phase substances inside a heat pipe that could spread the working fluid homogeneously inside heat pipe and amplify the capillarity. The third is that nanoparticle agglomerated at the inner wall of the tube, form a thin layer that could rise the wettability of the wall and maximize the capillary force of the inner wall. The last is that turbulent effect caused by Brown random movement could increase the heat transfer of the fluid itself due to the increase of heat transfer coefficient.

Thermal efficiency, which, in this case, is defined by a ratio of the heat received by water at water manifold to the heat exposed to the prototype of a solar collector as formulated by Eq. 3.

$$\varepsilon = \frac{Q_W}{Q_L} \tag{3}$$

where ε is the efficiency of the prototype, Q_W is heat received by water, and Q_L is heat exposed to the prototype. The efficiency of the prototype with water as working fluid at 0°, 15°, 30°, and 45° is 0.12, 0.14, 0.18, and 0.29 respectively. The efficiency of the prototype with nanofluid as working fluid at 0°, 15°, 30°, and 45° is 0.17, 0.18, 0.196, and 0.198 respectively. The efficiency has the parallel result to the performance of the prototype and the performance of the heat pipe. Anomaly at 45°, which was caused by the high ambient temperature was discussed in the previous section.

CONCLUSION

The performance of heat pipe-based evacuated tube solar collector has been determined experimentally with water and nanofluid as working fluid at 0°, 15°, 30°, and 45° inclination angles. It can be concluded that:

1. The inclination angle plays an important role in defining the thermal performance of a heat pipe-based evacuated tube solar collector. The optimum inclination angle is 30° for both using water and nanofluid as working fluid. Lower inclination angle would decrease gravity effect, creating a disturbed flow of liquid and vapor as a result. More inclination angle would cause too much gravity force, leading to the cooling phenomenon at evaporator by condensate and less evaporation will occur.
2. By using nanofluid, thermal performance of the heat pipe and solar collector can be enhanced, providing better heat transfer as a result. Nanoparticles suspended in the base fluid will escalate the thermal performance of heat pipes as it stabilize and intensify bubble growth, increase base fluid thermal conductivity, and enhance boiling phenomenon.
3. The highest thermal performance was obtained with nanofluid as working fluid at 30° inclination angle, providing thermal efficiency as high as 0,196 and thermal resistance as low as 5.32 °C/W.

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