Investigation on a prototype of heat pipe type solar water heater using R 718 as working fluid

A Pardede¹, H Ambarita*¹,² and T Sitepu¹

¹Department of Mechanical Engineering, Faculty of Engineering, University of Sumatera Utara, Medan, Indonesia 20155
²Sustainable Energy Research Centre, Faculty of Engineering, University of Sumatera Utara, Medan, Indonesia 20155

*E-mail: himsar@usu.ac.id

Abstract. The present work deals with experimental study on prototype heat pipe solar water heater with R718 as a working fluid. The objective is to explore the effect of the initial pressure to the performance of a heat pipe solar water heater. Three identical prototypes of the heat pipe solar water heater with collector area of 1000 mm × 500 mm have been designed and fabricated. Each solar water heater was loaded to heat the water in the tank with capacity of 5 liters of water. The refrigerant was filled to the heat pipe at three different initial pressures. They are 45 cm Hg, 40 cm Hg and 35 cm Hg, respectively. The experiments were carried out for three days. The results show that the maximum hot water temperature varies from 48.84 °C to 57.49 °C and thermal efficiency of the system starts from 20.03% to 28.30%. It was shown that initial pressure affects the performance. The higher initial pressure results in higher maximum temperature of the water in the tank. Based on the experiment results, the present solar water heater should be installed with initial pressure of 45 cm Hg.

1. Introduction

Solar energy is one of the most potential renewable energy resources. The sun emits solar irradiation with rate of $3.8 \times 10^{20}$ MW and the earth surface receives about $10.8 \times 10^{10}$ MW. This is a very big potency of energy. If only 0.1% of this energy can be converted into electricity with efficiency of 10% it results power of $10.8 \times 10^6$ MW. It is four times bigger that world electricity production. As a note, in the present the world electricity generation is only 3000 GW. In a year, solar energy that received by the earth is 3,400,000 Exajoule. The world energy consumption in the year 2008 was 474 Exajoule. This consumption can be filled by only 1 hour and 12 minutes of solar radiation. This fact reveals that solar energy is very potential to fill the energy consumption of the world in the future. This makes research on solar energy thermal has come under scrutiny in the last decades. Solar energy can be harvested in two different forms, they are solar thermal and photovoltaic. There are many applications of the solar energy thermal have been found in literature such as solar desalination [1 - 5], solar cooling [6 – 9], solar drier [10 - 12] and solar water heater [13 - 21].

This work deals with the development of solar water heater. There are many types of solar water heater have been developed by researchers [22] such as evacuated tube, simple box water heater, and heat pipe type solar water heater. In this study, the authors focus on the heat pipes solar water heater. Hossain et al. [23] have carried out the review on solar water heater collector and thermal energy performance of circulating pipe. It was revealed that the solar water heater with siphon system reaches
system characteristics efficiency of 18% higher than that of the mainstream system by decreasing heat loss from the thermos-siphon solar water heater. In this study, we focus on heat pipe type solar water heater. Studies on the heat pipe type solar water heater have been found in literature. Sitepu et al. [17] reported their investigation on a prototype of heat pipe solar water that uses R134a as a transfer fluid. The prototype was tested at Medan city of Indonesia. It was shown that temperature of the hot water raises as initial pressure of the working fluid raise up. However, the raise is not linier and there must exists the optimum initial pressure. At initial pressure of 110 psi, the maximum water temperature and maximum thermal efficiency are 45.36°C and 53.23%, respectively. It is recommended refrigerant R134a should be operated at initial pressure 110 psi. Recently, Ambarita et al. [20] reported experimental investigation on a prototype solar water heater which refrigerant R141b is used as a transfer fluid. In the study, two working fluids, R141b and R718, were compared. It was shown that at the similar working pressure, the solar water heater filled with R141b is better than R718. The solar water heater filled with refrigerant R141b at initial pressure of 30 psi shows optimum performance. It has the highest thermal efficiency which can reach 34%.

The above review studies show that in a heat pipe solar water heater, the initial pressure of the working fluid significantly affect the thermal performance of the solar water heater. Studies on the effect on the initial pressure to the performance of heat pipe solar water heater with refrigerant R141b and R134a have been explored [17, 20]. One of the potential refrigerant for heat pipe solar water heater is water or Refrigerant R718. The effect of the initial pressure to the performance of a heat pipe solar water heater with refrigerant R 718 has not been found in the literature. It is the focus on this work. The objective is to explore the effect of the initial pressure to the performance of a heat pipe solar water heater when using R718 as a transfer fluid. The results are expected to supply the necessary information on development high performance solar water heater.

2. Methods
In this study three identical prototypes of heat pipe solar water heater are designed and fabricated. This makes the experiments can be performed at the same solar irradiation when they are tested at the same day and location. The schematic diagram of the heat pipe solar water heater and data acquisition system are depicted in Figure 1.
Each prototype consists of a transfer pipe (heat pipe), water container and a flat plate type solar collector. The dimension of absorber plate is 1000 mm \( \times \) 500 mm and the thickness of the prototype is 200 mm. An insulating material consists of 100 mm of rock wall installed to the bottom and side wall of the prototype. Double glasses cover with a distance of 100 mm from the absorber plate is installed on the top of the solar collector. In each prototype, the capacity of the water container is 5 liters. It is also loaded with 5 liters of water. Data acquisition system is coupled with the solar water heater. The data acquisition unit comprises of HOBO micro station datalogger and AGILENT 34972 temperature data logger. The HOBO micro station data logger consists of 5 smart sensors. They are pyranometer smart sensor to measure solar irradiation. The air temperature and relative humidity (RH) is collected using HOBO temperature RH smart sensor. The temperature sensor and RH sensor have accuracy of 0.2°C and \( \pm 2.5\% \) RH, respectively. The wind speed during experiment is collected using HOBO wind speed smart sensor. The wind smart sensor has accuracy of \( \pm 1.1 \) m/s. On the other hand, the AGILENT coupled with 20 thermocouples. The type of thermocouples is J-type with uncertainty is 0.1°C. The measurement interval is 1 minute.

The working principle of a heat pipe solar water heater can be depicted in the following. The transfer fluid also known as refrigerant fulfilled the tube. Before the system is run, pressure within the tube is setup. Hereafter, the setup pressure known as initial pressure. In this work, initial pressure are varied. The tested initial pressure are 35 cm Hg, 40 cm Hg and 45 cm Hg. These pressures are below the atmosphere. The higher initial pressure means the more vacuum heat pipe. When it is shined to solar irradiation, the irradiation will be converted into heat and it will evaporate the working fluid. The working fluid vapor flows up to the tank. Inside the tank, the water cools the vapor of the working fluid. Thus, the vapor will be converted it into liquid. The liquid working fluid will go down back to the solar collector.

In all tests, temperature in several points and solar irradiation are recorded. These data will be used to analyze the performance. The performance of the tested water heater will be analyzed and compared
by two parameters. They are the highest temperature and thermal efficiency. The highest temperature is chosen as the maximum temperature of the water in the tank. While, the thermal efficiency is given as the ratio of useful heat in the hot water and collected energy by the absorber plate. It is given by

$$\eta = \frac{Q_u}{Q_{in}}$$

where $Q_u$ (Joule) and $Q_{in}$ [Joule] are useful energy in the hot water and total solar energy received by the solar absorber plate, respectively. The useful energy in the hot water is calculated by

$$Q_u = m_w c_w (T_w - T_i)$$

where $m_w$ (kg), $c_w$ (J/kgK), $T_w$ (°C), and $T_i$ (°C) are mass of the hot water, specific heat capacity, temperature of the water, and initial temperature, respectively. On the other hand, the solar energy received by the absorber plate is given by

$$Q_{in} = A \int I dt$$

where $A$ (m$^2$) and $I$ (W/m$^2$) are the area of the solar collector and solar irradiance, respectively.

3. Results and Discussions

The prototypes of solar water heater are exposed to the solar irradiance in Medan city of Indonesia. The location of experiment is on the top of Mechanical Engineering building in the University of Sumatera Utara USU. The experiments are carried out for three days. During the experiments temperatures and solar irradiance are measured. As a note, the inclination angle of the solar collector is fixed at 20°.

3.1. Solar Irradiation

Figure 2 shows solar irradiation and ambient temperature during the second day of experiment. The solar irradiation shown by the red circle marks and ambient temperature shown by solid blue line. The figure shows that by the noon, solar irradiation increases as time increases. After reaching the maximum value, the solar irradiation decreases with increasing time. However, in several times, solar irradiation falls down significantly due to clouds blocking. In the figure it occurs between 12 pm to 13 pm. The ambient temperature follows the trend of solar irradiation.
3.2. Characteristics of the solar water heater

Characteristics of the solar water heater are explained using temperature of the absorber plate and temperature of the water in the tank. Figure 3 shows temperature of the absorber plate and temperature of the hot water in the tank during the second day of experiment. In the figure the temperature of the absorber plate shown by dashed line. The red, black and blue dashed lines represent the water temperature in the water tank 1, water tank 2 and water tank 3, respectively. It can be seen from the figure that temperature of the absorber plate on each solar collector is almost similar. This is due to the same solar irradiation at the same day. From the beginning of the experiment until 13.00 WIB, temperature of the absorber plate increases with increasing time. The maximum temperature of the absorber plate for collector plate 1, plate 2 and plate 3 are 100.53°C, 96.66°C and 98.85°C, respectively. After reaching the maximum value, temperature of the absorber plate decreases with increasing time. In several times of the experiment, temperatures of the plates were falling down. This is because the solar irradiation was also falling down. These facts reveal that even though there are some differences, each prototype receive the same solar radiation and has the similar working temperature.

Temperature of the water within the water tank for each prototype is also shown in Figure 3. The temperature of water in Tank 1, Tank 2 and Tank 3 is shown by solid red line, black line and blue line, respectively. As expected, temperature of the water in the tank increases as time increasing. It increases gradually to reach its maximum value and after reaching the maximum value it decreases with increasing time. The maximum temperature of water in the tank 1 is 50.56°C. On the other hand, the maximum temperature of the water in the tank 2 and tank 3 is 49.08°C and 48.84°C, respectively. This fact suggests that the initial pressure of 45 cm Hg results in higher maximum temperature of the water in the tank in comparison with initial pressure of 40 cm Hg. In addition, the maximum temperature of the water in the tank of the solar water heater with initial pressure of 35 cm Hg is lower than with initial pressure of 40 cm Hg. Thus, the higher initial pressure results in the higher maximum temperature of the water in the tank.
Thermal efficiency of the solar water heater is calculated using equation (1) and the results are presented in Figure 4. It can be seen that the thermal efficiency increases suddenly in the first 15 minutes. This is because, temperature of the water in the tank is low and the solar irradiation is also low. These make the thermal efficiency is relatively high. After reaching the maximum value, thermal efficiency decreases gradually as time increasing. This is because the temperature of the water in the tank is higher and solar radiation is also increasing. The total thermal efficiency of each solar heater is calculated. The total thermal efficiency of prototype 1, prototype 2 and prototype 3 are 28.3%, 23.7% and 23.42%, respectively.

![Figure 4. Thermal efficiency the second day of experiment](image)

3.3. Effects of the initial pressure
In order to clarify the effect of initial pressure to the performance of the solar water heater, two experiments were carried out. In the experiment, all of the condition and initial pressure are similar. The different is only the solar irradiation, which is impossible to provide the similar solar irradiation in the different day. The results of all experiments are presented in Table 1. The table shows that initial pressure affects the performance of the solar water heater. The higher initial pressure results in the higher maximum temperature of the water in the tank. At the same time, the higher initial pressure results in higher thermal efficiency.

| Experiment | Initial Pressure (cm Hg) | Initial Temperature (°C) | Maximum Temperature (°C) | Thermal Efficiency |
|------------|--------------------------|--------------------------|--------------------------|--------------------|
| Day I      |                          |                          |                          |                    |
| 45         | 25.54                    | 57.49                    | 21.70%                   |
| 40         | 25.84                    | 54.81                    | 20.06%                   |
| 35         | 25.01                    | 53.00                    | 20.03%                   |
| Day II     |                          |                          |                          |                    |
| 45         | 26.31                    | 50.56                    | 28.30%                   |
| 40         | 26.08                    | 49.08                    | 23.70%                   |
| 35         | 26.87                    | 48.84                    | 23.42%                   |
4. Conclusions
In this work, the effect of the initial pressure of the heat pipe solar heater on its performance has been studied experimentally. Three identical prototypes of the heat pipe solar water heater with collector area of 1000 mm × 500 mm have been designed and fabricated. Each solar water heater was loaded to heat the water in the tank with capacity of 5 liters of water. The heat pipe was filled with R718 as refrigerant. The refrigerant was filled to the heat pipe at three different initial pressures. They are 45 cm Hg, 40 cm Hg and 35 cm Hg, respectively. The experiments were carried out for three days. The conclusions of this studies are as follows. The refrigerant R718 as a transfer fluid can deliver the heat from the solar collector plate and transfer it to the hot water. The maximum hot water temperature varies from 48.84°C to 57.49°C and thermal efficiency varies from 20.03% to 28.30%. There is a strong effect of initial pressure inside the heat pipe. Increasing initial pressure will increase maximum temperature of the hot water. It is suggested to operate the present solar water heater with initial pressure of 45 cm Hg.

Acknowledgments
The authors gratefully acknowledge that the present research is supported by Ministry of Research and Technology and Higher Education Republic of Indonesia. The support is under the research grant DRPM of Year 2018.

References
[1] Ambarita H 2016 Case Studies in Thermal Engineering 8 346 – 358
[2] Siregar R E T, Ronowikarto A D, Setyawan E Y and Ambarita H 2018 IOP Conference Series: Materials Science and Engineering 300 012059
[3] Ambarita H, Ronowikarto A D, Siregar R E T and Setyawan E Y 2018 IOP Conference Series: Materials Science and Engineering 300 012058
[4] Setyawan E Y, Napitupulu R A M, Siagian P and Ambarita H 2017 IOP Conference Series: Materials Science and Engineering 237 012012
[5] Ambarita H 2017 IOP Conference Series: Materials Science and Engineering 180 012024
[6] Ambarita H and Kawai H 2016 Case Studies in Thermal Engineering 7 36 – 46
[7] Sitorus T B, Napitupulu F H and Ambarita H 2016 International Journal of Technology 7(5) 910 – 922
[8] Sitorus T B, Ambarita H, Ariani F and Sitepu T 2018 IOP Conference Series: Materials Science and Engineering 309 012089
[9] Sitorus T B, Napitupulu F H and Ambarita H 2017 Journal of Engineering and Technological Sciences 49(5) 657 – 670
[10] Dina S F, Ambarita H, Napitupulu F H and Kawai H 2015 Case Studies in Thermal Engineering 5 32 – 40
[11] Ambarita H 2017 Journal of Physics: Conference Series 801 012093 (Development of software for estimating clear sky solar radiation in Indonesia)
[12] Siagian P, Setyawan E Y, Gultom T, Napitupulu F H and Ambarita H 2017 IOP Conference Series: Materials Science and Engineering 237 012037
[13] Ambarita H, Ronowikarto A D, Siregar R E T and Setyawan E Y 2018 Journal of Physics: Conference Series 978 012096
[14] Ambarita H, Siregar R E T, Ronowikarto A D and Setyawan E Y 2018 Journal of Physics: Conference Series 978 012097

\[
\begin{array}{cccc}
\text{Day III} & \text{45} & \text{26.69} & \text{56.21} & \text{26.38\%} \\
 & \text{40} & \text{26.43} & \text{55.07} & \text{25.64\%} \\
 & \text{35} & \text{26.16} & \text{52.91} & \text{23.89\%} \\
\end{array}
\]
[15] Tambunan D R S, Sibagariang Y P, Ambarita H, Napitupulu F H and Kawai H 2018 Journal of Physics: Conference Series 978 012099
[16] Ambarita H 2018 IOP Conference Series: Materials Science and Engineering 309 012005
[17] Sitepu T, Sembiring J and Ambarita H 2008 IOP Conference Series: Materials Science and Engineering 309 012007
[18] Ambarita H 2008 IOP Conference Series: Materials Science and Engineering 308 012028
[19] Ambarita H 2017 ARPN Journal of Engineering and Applied Sciences 12(19) 5357-5365
[20] Ambarita H and Sitepu T 2017 IOP Conference Series: Materials Science and Engineering 237 012014
[21] Sitepu T, Gunawan S, Nasution D M, Ambarita H, Siregar R E T and Ronowikarto A D 2017 IOP Conference Series: Materials Science and Engineering 180 012032
[22] Jaisankar S, Ananth J, Thulasi S, Jayasuthakar S T and Sheeba K N 2011 Renewable and Sustainable Energy Reviews 15(6), 3045-50.
[23] Hossain M S, Saidur R, Fayaz H, Rahim N A, Islam M R, Ahamed J U and Rahman M M 2011 Renewable and Sustainable Energy Reviews 15 3801-2812.