Experimental study on a prototype of heat pipe solar water heater using refrigerant R134a as a transfer fluid

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Abstract. A prototype of a solar water heater by using refrigerant as a heat transfer fluid is investigated experimentally. The objective is to explore the characteristics and the performance of the prototype. To make heat transfer from the collector to the heated fluid effectively, refrigerant R134a is used as a transfer. In the experiments, the initial pressure inside the heat pipe is varied. The prototype is exposed to solar irradiation in a location in Medan city for three days of the experiment. Solar collector temperatures, solar radiation, water temperature, and ambient temperature are measured. The efficiency of the system is analyzed. The results show that temperature of the hot water increases as the initial pressure of the working fluid increase. However, the increasing is not linear, and there must exist an optimum initial pressure. For the case with the refrigerant pressure of 110 psi, the maximum hot water temperature and maximum thermal efficiency are 45.36°C and 53.23%, respectively. The main conclusion can be drawn here is that solar water heater by using refrigerant R134a should be operated at initial pressure 110 psi.

1. Introduction

Global warming is the increasing average temperature of the atmosphere. This is caused by all activities in the globe that emit Greenhouse Gases (GHGs). To avoid the human being from the catastrophe, many countries have committed in reducing the GHG emissions. According to Intergovernmental Panel on Climate Change (IPCC), the GHG emissions can be divided into four sectors. They are Energy, Industrial Process and Product Use (IPPU), Agriculture, Forestry, and other Land Use, and Waste sectors [1]. In the energy sector emissions resulted by all activities in burning fossil fuel to provide heat and power. One of the activities that use heat is the water heater. The water heater typically powered by fossil fuels and electricity. The subsectors that need water heater includes hotels, hospital, restaurant and residential. Indonesia has released two different targets in reducing its GHG emission [2, 3]. To reach the target, one of the potential mitigation actions is using alternative energy to provide solar water heater. The promising alternative energy resource to provide water heater is solar energy. Because it is clean and sustainable. Thus, studies on solar water have received much attention from researchers.

Hossain et al. [4] have reported their review on solar water heater collector and thermal energy performance of circulating pipe. The study found that the solar water heater with siphon system achieves system characteristics efficiency of 18% higher than that of the conventional system by reducing heat loss from the thermos-siphon solar water heater. There are many types of solar water heaters found in literature, such as an evacuated tube, simple box water heater, and heat pipe type solar water heater. In this study, we focus on the heat pipe type solar water heater. Jaisankar et al. [5] reported their study on a comprehensive review on the solar water heater. The conclusions are as follows. More researches may be initiated in thermosyphon solar water heaters to improve the performance. Research work in parallel flow will improve and will give a new insight into thermal performance, variation in flow velocity of the working fluid in the riser tubes can be made uniform.
using variable headers, and the convective heat loss from glass cover may be reduced using a suitable aero profile design that will prevent the movement of air over glass surface.

The above reviews show that there several types of solar water heater. The solar water heater using two-phase transfer fluid has received more attention due to high performance. Here, a working fluid (or transfer fluid) is employed to transfer the solar heat from solar collector to the hot water. Chen et al. [6] reported an experimental work on the long-term thermal performance of two-phase thermosyphon solar water heater. They proposed a new system in the study. The results show that the proposed system achieved system characteristics efficiency 18% higher than that of the conventional systems is reducing heat loss for the two-phase thermosyphon solar water heater. Chun et al. [7] reported an experimental study on employing heat pipe for solar water heater. The result shows interesting performance data stemming from the difference in working fluids, the presence of wick, and other various design parameters associated with the collection and utilization of solar energy. Arab et al. [8] proposed vibrated heat pipe solar water heater. In the experimental work, it was shown that the best performance of the proposed model resulted by pipe filled with 70% transfer fluid. This model is stable and shows longer durability. The comparison of thermosyphon and vibrated heat pipe solar water heater are made. The average temperatures of hot water resulted by thermosyphon and vibrated heat pipe type is 35.5°C and 34.5°C, respectively. Studies of the performance of different fluid in heat pipe type solar water heater are found in the literature. Esen and Esen [9] studied experimentally the performance of heat pipe solar water heater using different refrigerant as transfer fluid. The refrigerants are R410a, R407C, and R134a. The results showed that higher performance is shown by R410a. Josep and Yakasai [10] reported the performance comparison of R12, R134a, and ethanol as a transfer fluid in the heat pipe type solar water heater. The results revealed that R134a show a better efficiency and higher hot water temperature.

Those reviewed literature showed that transfer fluid plays an important role in the performance of heat pipe solar water heater. It is suggested to employ R134a due to high performance. In this study, we investigate the effect of the internal pressure of the heat pipe when the refrigerant R134a is used as a transfer fluid. The system will be tested by exposing to solar irradiation in Medan city of Indonesia. The objective is to find the optimum operating condition of the heat pipe solar water heater using R134a as a transfer fluid. The results are expected to supply the necessary information on development high-performance solar water heater.

2. Methods
In order to perform the experiments, three identical prototype heat pipe solar water heaters are designed and fabricated. The main reason to fabricate three solar water heaters is to make that all equipment are tested under the same solar irradiation at the same day. As a note, typically the solar irradiation is different every day due to weather condition. Figure 1 shows the schematic diagram of the experimental setup. The solar water heater consists of a flat plate type solar collector, heat pipe, and hot water tank. The collector area of each solar water heater is 1000 mm × 500 mm. The thickness is 200 mm. To reduce heat loss to the surrounding a double-glasses cover and rockwool insulation are used. The insulation of 100 mm thickness is used in the bottom and side walls. The distance of glass cover to plat absorber is 100 mm. The heat pipe is placed on the absorber plate with a distance of 100 mm. Several parts of the heat pipe are passed through a water tank. The water tank with a volume of 5 liters is placed beneath the top part of the solar collector. In order to perform experiment, a data acquisition system is used. The system consists of HOBO micro station data logger and temperature measurement system. There are 20 thermocouples are used to measure temperatures. The sensors are made of J-type thermocouples with uncertainty equal to 0.1°C. A datalogger (Agilent 34972) consists of 20 thermocouple channels are used to record temperatures with interval of 1 minute. The solar radiation is measured using HOBO pyranometer smart sensor. The ambient temperature and relative humidity (RH) is measured using HOBO temperature RH smart sensor with an accuracy of 0.2°C and ±2.5% RH, respectively. The wind speed around the experimental apparatus is measured with HOBO wind speed smart sensor with an accuracy ±1.1 m/s.
The working mechanism of a heat pipe solar water heater is explained as follows. The refrigerant as a transfer fluid filled the pipe. Before the system is tested, the pressure of inside the pipe is regulated. Hereafter, the pressure named as initial pressure. In this study, three different initial pressure will be investigated, they are 90 psi, 100 psi, and 110 psi below the atmosphere. When it is exposed to solar irradiation, the received heat will evaporate the refrigerant. The refrigerant vapor flows up to the hot water tank. In the tank, the water cooled the refrigerant vapor and converted it into liquid refrigerant. The liquid refrigerant will flow down and cycle repeats. In the experiments, temperatures and solar irradiation are measured, and the performance is analyzed. The performance of the present water heater will be compared using two parameters; they are maximum temperature and thermal efficiency. The maximum temperature is defined as the highest temperature of the water in the hot water tank. On the other hand, the thermal efficiency is defined as the ratio of useful heat in hot water and solar energy collected by the absorber plate. The thermal efficiency is calculated using the below equation.

$$\eta = \frac{Q_u}{Q_{in}} \quad (1)$$

where $Q_u$ [Joule] and $Q_{in}$ [Joule] are useful energy in hot water and total solar energy incident to the solar absorber plate, respectively. These parameters can be calculated using the following equations.

$$Q_u = m_w c_w (T_u - T_i) \quad (2)$$
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. While the solar energy incident is given by

\[
Q_i = A \int I dt
\]  

where \( A \) (m²) and \( I \) (W/m²) are the area of the solar collector and solar irradiance, respectively.

3. Results and Discussions

The solar water heaters have been exposed to the solar irradiance in Medan city of Indonesia for three different days. Temperatures and solar irradiance are measured. The results will be discussed in terms of characteristics, maximum temperature comparison, and thermal efficiency.

3.1. Characteristics of the solar water heater

![Figure 2. Temperature history of solar water heater during experiment](image)

The characteristic of the solar water heater is presented using temperature history of a solar water heater during the experiment. In the experiment, there are nine different temperature histories have been measured. Figure 2 shows temperature history of the solar water heater for day one at an initial pressure of 90 psi. The measured solar irradiation of day one is started from 8:30 local time. The initial solar irradiation was 161.9 W/m², and the maximum solar irradiation was 620 W/m² captured at 14:00 local time. Total solar energy radiation for the Day 1 of the experiment was 1.204 MJ.

The figure shows that temperature of absorber plate increases with increasing the time until reaching its maximum value of 104°C at 12:34 local time. After this, the temperature of the absorber plate decreases with increasing time. As expected, the temperature of the plate absorber can reach the temperature above 100°C due to the effectiveness of insulation and glass cover. The temperature of the glass cover shows the similar trend with the temperature of plate absorber but with different maximum value. The maximum temperature of glass cover was 74.6°C at the same time 12:35 local time. During
the experiment, the temperature of the glass cover is lower than the temperature of the absorber plate. This is because heat loss from the absorber plate to ambient through the glass cover is still significant. The solar energy collected by solar collector will be used to heat water in the tank, and the temperature of the water will increase. This fact shown in the figure. It can be seen that the temperature of the water increases with increasing time. In this case, it starts from 25.4°C and reaching its maximum value of 36.47°C. Thus, the total energy utilized by the solar collector was 0.186 MJ. By using equation (1) thermal efficiency of the system is 23.25%.

Figure 3. Efect of initial pressure to the maximum hot water temperature

As mentioned in the method, in every experiment three solar water heaters are exposed at the same time. In this experiment, the other solar water heaters are filled with the same refrigerant but different initial pressure. Figure 3 shows temperature history of the hot water heater at initial pressure 90 psi, 100 psi, and 110 psi. It can be seen clearly that, there is a strong effect of initial pressure inside the heat pipe to the performance of the system. The maximum temperatures of the hot water for initial pressure 90 psi, 100 psi, and 110 psi are 36.47°C, 40.55°C, and 42.87°C, respectively. This is because when the initial pressure far below the atmosphere, temperature evaporation will be lower. In other word, the amount of refrigerant that evaporated will be higher. It leads to higher solar energy can be transferred to the hot water tank. The increasing of initial pressure is not linier to increasing maximum temperature. Increasing initial pressure 10 psi from 90 to 100 psi will increase maximum temperature 4.08°C. However, increasing the same initial pressure of 10 psi from 100 psi to 110 psi, maximum temperature will increase only 2.32°C. This reveal that there must exist an optimum initial pressure for maximum performance.

3.2. Effects of the initial pressure
In order to make a clear effect of initial pressure to the performance of the solar water heater, additional two similar experiments were performed. In the experiment, all of the condition and initial pressure are the same. The different is only the solar irradiation, which is impossible to provide the
similar solar irradiation in the different day. Table 1 shows the performance of the solar water heater during three days of experiment. It can be seen clearly that there a clear effect of initial pressure to the performance of the solar water heater. The table shows that maximum temperature during experiments varies from 36.47°C to 45.36°C. The maximum temperature of the hot water for day 1, day 2, and day 3 of experiments are 42.87°C, 45.36°C, and 44.42°C, respectively. These maximum values are shown by the same initial pressure of 110 psi. The fact that additional initial pressure from 90 psi to 100 psi is more effective than additional initial pressure from 100 psi to 110 psi is also shown in the table.

Table 1 Effects of the initial pressure on the performance of solar water heater filled with R134a

| Experiment | Initial Pressure (psi) | Initial Temperature (°C) | Maximum Temperature (°C) | Thermal Efficiency |
|------------|------------------------|--------------------------|--------------------------|-------------------|
| Day I      | 90                     | 25.54                    | 36.47                    | 23.25%            |
|            | 100                    | 25.84                    | 40.55                    | 42.36%            |
|            | 110                    | 25.01                    | 42.87                    | 53.23%            |
| Day II     | 90                     | 27.31                    | 38.48                    | 21.86%            |
|            | 100                    | 27.08                    | 44.35                    | 40.24%            |
|            | 110                    | 27.87                    | 45.36                    | 45.42%            |
| Day III    | 90                     | 26.69                    | 37.93                    | 20.13%            |
|            | 100                    | 26.43                    | 42.28                    | 34.34%            |
|            | 110                    | 26.16                    | 44.42                    | 43.98%            |

Thermal efficiency of the solar water heater is also shown in Table 1. As a note, the thermal efficiency is calculated using equation 1. Thus, the thermal efficiency is affected by incident solar energy and maximum temperature of the hot water. In other words, the highest maximum temperature of hot water is not directly the gives the highest thermal efficiency. The present results are comparable with the results reported by Esen and Esen [9]. In their work, by exposing the solar water heater in Elazığ Turkey, for refrigerant R134a the maximum temperature of the hot water varies from 28°C to 50°C while the thermal efficiency varies from 48% to 60%. There are discrepancies of the present result and results reported by Esen and Esen [9]. This is because different of whether condition and different operational method. In their work, the hot water is replaced several times during experiment. In this work, it is without water replacement. As shown in the table the highest maximum temperature of hot water was captured in the Day 2 of experiment it is 45.36°C. In this case the thermal efficiency is 45.42%. On the other hand, the highest thermal efficiency was captured in Day 1, it is 53.23%. In this case, the maximum hot water temperature is 42.87°C.

4. Conclusions
In this work, a prototype heat pipe type solar water heater filled with R134a as a transfer fluid has been designed and tested by exposing under solar irradiation in Medan city of Indonesia. After exposing for three days of experiments, the conclusions are as follows. The refrigerant R134a 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 36.47°C to 45.36°C and thermal efficiency varies from 20.13% to 53.23%. 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 110 psi.
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References
[1] IPCC, 2006, Guidelines for National Greenhouse Gas Inventories.
[2] Gov. of Indonesia PresidentialY Decree No No 61 Year 2011, National Action Plan For ReducingGreenhouse Gas Emissions.
[3] Gov. of Indonesia, 2016, First Nationally Determined Contribution Republic of Indonesia.
[4] 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.
[5] Jaisankar S, Ananth J, Thulasi S, Jayasuthakar S T and Sheeba K N 2011 Renewable and Sustainable Energy Reviews 15(6), 3045-50.
[6] Chen B R, Chang Y W, Lee W S and Chen S L 2009 Solar Energy 83, 1048-1055
[7] Chun W, Kang Y H, Kwak H Y and Lee Y S 1999 Applied Thermal Engineering 19, 807-17
[8] Arab M, Soltanieh M and Shafii M B, 2012 Experimental Thermal and Fluid Science 42, 6-15
[9] Esen M and Esen H, 2005 Solar Energy 79, 459 - 468
[10] Eneburekhan J and Yakasai U T, 2008 Desalination 243, 208-217