The performance of a solar collector on adsorption refrigerator

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Abstract. The performance of a flat plat collector on adsorption refrigerator driven by solar collector was investigated in the present work. The adsorbent used of this study were 20 kg ordinary powder activated carbon of coconut shell produced in the Sumatera Utara province of Indonesia, 5 liters of methanol as adsorbate and 6 litres of water as the medium that was cooled. The experiments were carried out under varying weather conditions with total solar radiation about 12619-17807 kJ/m\textsuperscript{2}/cycle. The experimental results show that the values of collector efficiency obtained were about 52.12\% to 53.13\%. The values of coefficient of performance obtained were in the range of 0.0365-0.0428.

1. Introduction
The National Energy Data of 2015-2050 and The International Energy Outlook 2006 suggests that Indonesia's fossil energy potential including petroleum, natural gas and coal can only last for 10 years, 31 years and 80 years from now if no reserves the new fossil energy [1, 2]. This condition again reminded the Indonesian people that a serious and systematic effort needs to be done to develop and apply renewable energy sources in order to reduce dependence on fossil fuels whose reserves are depleted. The use of renewable energy sources that are environmentally friendly also means saving the environment from the various adverse effects caused by the use of fuel oil. Several renewable and environmentally friendly renewable energy source that can be applied such as bioethanol, biodiesel, geothermal energy, micro hydro, wind energy, and solar energy. Especially for solar energy, keep in mind that every year the sun provides energy of 5.6\times1024 joules to the surface of the earth through thermal radiation [3]. Solar thermal energy has been applied in particular to drying systems of agricultural products and refrigeration systems. The existence of solar energy is potential in Indonesia where it can be seen from the position of astronomy of Indonesia on the world map. Indonesia is located on the equator, at latitude 60 North Latitude-110 South Latitude and 950 East Longitude-1410 East Longitude, and the Indonesian territory is always exposed to the sun approximately 2500 hours in a year [4,5]. It is estimated that the average of solar radiation that falls on the surface area of Indonesia is about 4.8 kWh/m\textsuperscript{2} per day [6]. One application of solar energy utilization is the adsorption refrigerator. The solar adsorption refrigerator consists of the components such as collector, condenser and evaporator. The aim at this study is to investigate the performance of solar collector in adsorption refrigerator because this equipment is the main component as absorber of solar radiation energy to drive the operating system of refrigerator.
2. Solar Collector

The solar collector is a type of heat exchanger that can convert solar radiation into thermal energy for low temperature applications such as in the adsorption refrigeration, heating systems for water and heating processes of certain industries such as drying [7]. In the solar adsorption refrigeration system, in order for the collector to work optimally at the desorption process then this component must be able to produce maximum temperature. However, when the desorption process is complete, the collector must be able to reach the minimum temperature to complete the adsorption process. In other words, during the desorption process, the losses of heat released by the collector should be as minimal as possible. But at the time of the adsorption process at night the collector must be able to release the maximum heat. The solar collector used in this research is a flat plate collector type. The main advantage of flat plate type solar collector are to utilize both solar radiation components through direct spotligting and simple distribution. The design with minimal maintenance and low cost manufacturing and generally used in solar adsorption refrigeration [8,9]. The working principle of a flat plate type solar collector is to absorb the solar energy and transfer it to the adsorbent contained in the collector. The solar radiation that falls on the partial glass cover will be immediately reflected, some will be absorbed, and some will be passed to the collector surface plate. The radiation reaching the surface of the plate will be absorbed by the collector. The heat absorbed by the collector plate is used to heat the adsorbent in the collector. Due to the heat received from the collector surface, the adsorbate or refrigerant attached to the surface of the adsorbent will be separated and flowed into the condenser to undergo a condensation process. To reduce the heat loss from the side of the wall, the collector is isolated by using the insulator materials such as wood, styrofoam and rockwool. The cross sectional solar collector used can be seen in Figure 1.

![Diagram of solar collector](image)

**Figure 1. The view section of solar collector**

Total heat losses in the solar collector component can be determined from [10]:

\[ Q_{\text{total}} = Q_{\text{wall}} + Q_{\text{bottom}} + Q_{\text{top}} + Q_{\text{radiation}} \]  

The efficiency of a flat plate type solar collector can be determined from equation [11]:

\[ \eta = \frac{Q_b}{I \cdot A} \]  

The heat energy used is obtained from the equation

\[ Q_b = F' \times (Q_{in} - Q_{total}) \]

and

\[ Q_{in} = I \cdot A \cdot \tau \cdot \alpha \]
The value of $\tau$ represents the absorptivity of the black plate 0.98, while the collector efficiency factor ($F'$) for flat plate type collector is 90% . Inside the collector is filled with adsorbents whose optimum mass ranges from 20-26 kg/m$^2$ [12]. The collector must be closed, not outer air and has a connecting pipe that becomes the passageway refrigerant in and out of the collector. According to [13] that there are four major pairs of adsorbent-adsorbents commonly used in solar adsorption refrigeration systems namely activated carbon - methanol, zeolite - water, silica gel - water and activated carbon - ammonia. The main parameter of adsorption refrigerator performance are COP (coefficient of performance ) [14,15,16]. The COP value of the adsorption cycle relies heavily on weather conditions and the efficiency of each component of the system, especially collector, condenser, and evaporator varies from 0.01 to 0.2 [17,18]. The application of this adsorption cycle refrigeration can be distinguished from / between three categories, namely for room air conditioning (8-18°C ), food refrigeration or vaccine storage (0-8°C ) and for ice freezing or coagulation purposes (<0°C ) [19 , 20,21]. The COP value of the solar adsorption refrigerator can be obtained by using the equation [21, 22].

The cooling effect (kJ) is:

$$Q_{\text{cooling}} = m_{\text{water}} \cdot C_{\text{p-water}} \cdot (T_{\text{water-max}} - T_{\text{water-min}})$$  \hspace{1cm} (6)

Solar energy received by the collector (kJ) is

$$Q_{\text{radiation}} = I_{\text{total}} \cdot A$$  \hspace{1cm} (7)

where $I_{\text{total}}$ is total radiation in one cycle obtained from pyranometer (kJ/m$^2$) and $A$ is collector area (m$^2$).

### 3. Research Methodology

#### A. Material

The adsorbent used are a powder non-commercial activated carbon of coconut shell local product of 20 kgs. The refrigerant used are 5 litres methanol pro analysis with a purity of 99%. The volume of water cool about this study was 6 litres. Table 1 shows the specifications of the flat plate type collector tested.

| Specification          | Dimension      |
|------------------------|----------------|
| Width                  | 1000 mm        |
| Length                 | 1000 mm        |
| Thickness              | 100 mm         |
| Cover glass thickness  | 3 mm           |
| Air gap                | 20 mm          |
| Isolator thickness     | wood 20 mm, styrofoam 40 mm, rockwool 50 mm |
| Plate thickness        | 2 mm           |
| Collector thickness    | 1 m$^2$        |

#### B. Experimental Scheme

Figure 2 shows the experimental scheme for experiments. The solar adsorption refrigerator consists of collector, condenser and evaporator. Collector plate is made of stainless steel with a thickness of 1
mm. The collector cross-sectional area of 1 m² with tilt angle of 30°. The cover glass consists of 2 layers having a thickness of 3 mm each. The condenser is made of stainless steel using 17 fins with a total heat transfer area of 0.68 m². The collector is cool by natural convection. The evaporator is made of stainless steel and is filled with 5 litres of methanol. The evaporator is placed in a cold chamber containing 6 litres of water and insulated from styrofoam and rockwool. To connect the collector-condenser-evaporator is used a flexible pipe with a diameter of 20 mms. The adsorption refrigerator is connected to a cole parmer data acquisition through a J-type thermocouple cable with an accuracy of ±0.4% which placed on collector, condenser, evaporator and water cool. A data logger HOBO station is used to record the weather conditions such as the intensity of solar radiation with pyrometer (±5% accuracy), air temperature with T (accuracy ±0.2°C) and humidity with RH (± 2.5% accuracy). Pace XR5 digital vacuum gauge (±2% accuracy) is mounted on the refrigerator to measure the distribution of operating pressure. All measuring processes are done every minute. A supporting tool is used vacuum pump to remove the air contained in the refrigerator because the presence of air affects the adsorption and desorption process that occurs. The independent variables observed in this study are weather conditions consisting of the intensity of solar radiation, air temperature and air humidity. The dependent variables are collector efficiency and COP.

4. Results and Discussions
A. The Weather Condition During Experiments
The energy maximum of solar radiation obtained is 17807.36 kJ/m² in the fourth cycle for the measurement conditions during experiments. Solar radiation began to be observed on pyranometer ranging between 06.00-06.25 WIB and began not observed again between 18.00-18.30 WIB during experiments. The measurement data showed that the maximum radiation time was in the second cycle of 12.47 hours/day (52%) and the minimum on the third day of 12.06 hours / day (50.27%) during experiments. The maximum radiation intensity occurring at the measurement generally occurs at 11.55 WIB - 13.44 WIB and maximum air temperature occurs at 12.13 WIB - 14.19 WIB. Figure 3 shows the characteristics of solar radiation during experiments. The measurement of weather conditions carried out for every minute. During the measurement process, a maximum radiation intensity of
1000.6 W/m$^2$ occurs in the first cycle. Table 2 shows the recapitulation data of weather conditions during experiments.

| Research time | Cycle | Average radiation (W/m$^2$) | Radiation time (hour/cycle) | Air temperature average (°C) | Average air humidity (%) |
|---------------|-------|------------------------------|-----------------------------|-----------------------------|--------------------------|
| March 2018    | 1     | 153.23                       | 12.16                       | 28.68                       | 84.09                    |
|               | 2     | 167.03                       | 12.46                       | 29.27                       | 80.99                    |
|               | 3     | 179.31                       | 12.35                       | 27.85                       | 84.26                    |

The experiments process is carried out during three cycles where one cycle is 24 hours and starting at 08.00 WIB until 08.00 WIB the next tomorrow.

**B. The Performance of Solar Collector**

The most influential component of a solar adsorption refrigerator is the collector or also called adsorber. The collector used in this study is a flat plate type that uses a cover glass. Figure 4 shows the temperature distribution on the collector during experiments. It appears that there was a temperature fluctuation on the collector surface. The maximum collector temperatures generally occur between 12.00 WIB to 14.00 WIB. This condition is also influenced by solar radiation received by the collector surface.
Based on the measurement data and calculations performed, we get the loss of heat on the top, bottom and collector walls and the efficiency of solar collector during the experiments as shown in table 3.

Table 3. The efficiency of solar collector during experiments

| Q_{wall} | Q_{bottom} | Q_{up} | Q_{radiation} | Q_{in} | Q_{used} | η_{collector} |
|----------|------------|--------|---------------|--------|---------|--------------|
| W        | W          | W      | W             | W      | W       | %            |
| 1.684    | 2.037      | 170.161| 301.299       | 1253.868| 700.818 | 53.13        |
| 1.480    | 1.897      | 163.143| 292.383       | 1188.079| 656.258 | 52.51        |
| 1.321    | 1.537      | 165.282| 302.209       | 1203.743| 660.054 | 52.12        |

The value of solar collector efficiency obtained ranged from 52.12% to 53.13% based on the experiments that have been done. It is influenced by several parameters such as solar radiation received by collector, collector surface area, and total heat loss. The cover glass used consists of two layers aimed at capturing the solar radiation while reducing the heat losses that flow into the outside air.

Based on the calculation data obtained that by using two layers of glass cover to increase collector efficiency ranges from 5% to 7%. Some heat losses are analyzed based on the calculation results, then the value of heat loss is large enough on the top side of the collector due to radiation. For certain conditions, the high temperature of the collector plate is required to heat the adsorbent contained therein, but in other cases this condition makes the value of the total heat transfer coefficient on the upper side becomes larger. Increasing the total heat transfer coefficient also increases the heat loss on the upper side of the flat plate type solar collector. Figure 5 shows the correlation of the pressure distribution on the collector with the intensity of solar radiation. It appears that changes in pressure on collectors are also influenced by the intensity of solar radiation that occur.

The measurement data shows that the average heating temperature occurs about 9 hours and 15 hours is used for cooling and adsorption process. In these experiments obtained the maximum collector temperature of 127.85°C with the maximum radiation intensity of 1000.60 W/m² which occurs in the first cycle. This study also measures the working pressure in the solar adsorption refrigeration which can be seen in table 4.
Figure 5. The correlation of pressure with solar radiation

Table 4. Working pressure during experiments

| Cycle | Total radiation (kJ/m²) | Pressure working (mbar) |
|-------|------------------------|-------------------------|
|       |                        | Maximum     | Minimum     |
| 1     | 13239                  | 896.21      | 69.11       |
| 2     | 14429                  | 899.76      | 70.32       |
| 3     | 15492                  | 912.77      | 71.27       |

In this study, the measurement of working pressure is done by using a digital vacuum manometer that can record the pressure changes during 24 hours. The measurement data indicates that the working pressure of the solar adsorption refrigerator during the experiments varies considerably. The working pressure obtained ranged from 66.33 - 935.15 millibars. The measurement data indicate that the maximum working pressure generally occurs at 12.27 WIB - 14.29 WIB, while the minimum working pressure occurs at 03.59 WIB - 06.40 WIB. This study also observed the condition of changes in water temperature as a cooled medium. The minimum water temperature that can be achieved is 1.88°C. The experimental data shows that the heating and desorption process generally takes place from 08.00 WIB to end at around 16:25 WIB - 17.10 WIB or lasts about 7 - 9 hours. The cooling and adsorption process generally takes place from 16.25 WIB - 17.10 WIB until 08.00 WIB or lasts about 12 - 15 hours.

C. The Performance of Solar Adsorption Refrigeration

To determine the characteristics of the solar adsorption refrigerator, it can be reviewed for the value of COP obtained. The COP value of the experiments can be seen in table 5.

Table 5. The COP values during experiments

| Cycle | Water temperature (°C) | COP    |
|-------|------------------------|--------|
|       | Max        | Min    |        |
| 1     | 25.70      | 3.24   | 0.0428 |
| 2     | 25.55      | 3.09   | 0.0392 |
The COP value obtained during experiments is about 0.0365-0.0428. It appears that the COP value obtained corresponds to the range of COP values generated by a solar adsorption refrigerator according to 0.01-0.2 [15]. In general, the COP value of solar adsorption refrigerator is lower than the vapor compression cycle system. This is because the energy source of the adsorption refrigerator is solar energy whereas the vapor compression cycles uses electrical energy to drive the compressor. The energy heats source of the adsorption refrigerator, especially those driven by solar power, generally has a temperature below 150°C and the radiation intensity is not constant. The solar energy is stored by the collector and used to heat the adsorbent in order to release the refrigerant from the adsorbent during the desorption process. The greater the heat energy the adsorbent receives the higher the adsorbent temperature and the more refrigerant of methanol released by the adsorbent so that the amount of methanol stored in the evaporator will be more numerous.

The more of methanol contained in the evaporator, the cooling effect will increase. In addition, the cooling of collector surface occurs by natural convection and influenced by weather conditions. It should be noted, in the solar adsorption refrigerator that the rate of heat transfer and mass that occurs in the adsorber is low enough that it takes a long time for a cycle. This is the condition that makes the COP value of solar adsorption refrigeration is lower than the vapor compression system that drives by electrically. Based on the analysis of experimental data, it is found that the main parameters affecting the performance characteristics of the solar adsorption refrigerator tested are solar radiation received by the collector, the length of one cycle and the performance of the collector. First, the fluctuations in solar radiation are influenced by conditions of the sky such as bright, cloudy and rainy bright. The solar radiation received by the collector surface generally makes the maximum collector temperature below 150°C and this affects the ability of the adsorbent to release methanol during the desorption process. Secondly, the existence of unwanted gasses is closely related to the vacuum process. According to [23] that generally the adsorption refrigerator using methanol refrigerant has normal operational pressure ranging from 20-200 mbar. The operational pressure of the adsorption refrigerator tested was 66.33-935.15 mbar. Third, regarding the performance of collectors where the heat losses during the radiation process needs to be minimized which can be caused by collector wall insulation. In other conditions there is a need for improvement in the collector cooling process that occurs naturally in order to increase collector efficiency. During the cooling process the collector temperature is required as low as possible so that the adsorbent can absorb the entire methanol during the desorption process.

D. Correlation of weather with collector efficiency

Table 6 shows the weather conditions for calculating collector. The maximum collector efficiency is obtained 53.13% when the maximum radiation of 1000.6 W/m². Based on the statistical function used, the correlation between weather parameters with the efficiency of the flat plate type collector is tested.

| Cycle | Maximum radiation (W/m²) | Air temperature (°C) | Air humidity (%) | Collector efficiency (%) |
|-------|--------------------------|----------------------|------------------|--------------------------|
| 1     | 1000,60                  | 34,62                | 58,60            | 53,13                    |
| 2     | 948,10                   | 34,55                | 62,30            | 52,51                    |
| 3     | 960,60                   | 33,39                | 61,10            | 52,12                    |

Table 7 shows that there is a significant correlation between collector efficiency to solar radiation of 0.723. In addition, we also calculate the effects of weather on collector efficiency by using multiple
regression analysis. It is obtained the coefficient of determination ($R^2$) of 0.94 which indicate that the effect of weather conditions on collector efficiency is 94%.

Table 7. Correlation of weather parameter with collector efficiency

| Parameter | $I_{max}$ | $T_u$ | $\phi_u$ | $\eta_c$ |
|-----------|-----------|-------|----------|----------|
| $I_{max}$ | 1         |       |          |          |
| $T_u$     | 0.152     | 1     |          |          |
| $\phi_u$  | -0.643    | -0.730| 1        | -0.916   |
| $\eta_c$  | 0.723     | 0.796 | 1        |          |

where $I_{max}$ is maximum radiation, $T_u$ is air temperature, $\phi_u$ is air humidity and $\eta_c$ is collector efficiency.

5. Conclusions

This research has been successfully assembled flat plate type collector for solar adsorption refrigerator and tested its performance. Based on the experimental data obtained that the performance of the flat plate type collector greatly affects the operating system of solar adsorption refrigerator. Similarly, the performance of flat plate type collectors used is strongly influenced by weather conditions during experiments. The performance or efficiency of flat plate type solar collectors obtained during experiments varies considerably. The value of collector efficiency is influenced by several parameters such as solar radiation received by collector, collector surface area, and total heat loss. The value of the efficiency of the solar collector obtained during experiments ranged from 52.12% to 53.13%. The results of the statistical study state that the effect of weather conditions on collector efficiency is 94%. The COP values obtained of the solar adsorption refrigerator is about 0.0365-0.0428.

Acknowledgments

The authors wish to acknowledge the financial support that provided by DRPM DIKTI project in 2018.

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