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EXPERIMENTAL STUDY OF SOLAR REFRIGERATOR SYSTEM USING ACTIVATED ALUMINA AND METHANOL ADSORPTION PAIR

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ABSTRACT

This study investigates the performance of a solar adsorption refrigerator using activated alumina and methanol adsorption pair. The experiments were carried out for 24-hour. The refrigeration was completed during seven cycles with varying weather conditions. A flat plate type collector was used with an area of 0.25 m^2 and tilt angle of 30^o. Theoretical calculations show that, the maximum collector efficiency is 47.15% when the maximum solar radiation obtained is 936.9 W/m^2. In this research, the maximum value of the COP is 0.0991 when the total solar energy is 16.485 MJ/m^2 and the minimum value obtained is 0.0919 when the total solar energy is 7.609 MJ/m^2. The experiment results show that the adsorption pair system can deliver an evaporator temperature of about 9.92°C and the cooling load can be achieved by a heat source with a temperature range of 83.95°C and 95.39^{o}C.

Keywords: Activated alumina and methanol; Refrigerator performance; Solar energy

1. INTRODUCTION

In 1886 Boltzmann, one of the fathers of modern physical chemistry, wrote that the struggle for life is not a struggle for basic elements or energy, but a struggle for the availability of energy transferred from the hot sun to the cold earth. The sun sends 5.6×10^{24} joules of energy to the earth through thermal solar energy every year (Hanjalic et al., 2008) while the total energy consumption of the world is about 1.84×10^{13} W (Ioan et al., 2015). Direct thermal solar energy has been used since the early days of agriculture, particularly for drying produce and refrigeration systems. Indonesia has a great potential for solar energy because it lies on the equator between 6° North latitude and 11° North latitudes and between 95° East longitude and 141° East longitudes. Most locations in Indonesia receive abundant solar energy throughout the year. The average daily solar radiation is 14.5 MJ/m^2 and the total annual sunshine duration is about 2,500 hours (Rumbayan et al., 2012). One application of solar energy utilization for refrigeration system is a solar adsorption refrigerator. It could be argued that research on solar adsorption refrigerator are still rare in Indonesia. The purpose of this study was to determine the performance of an adsorption refrigerator driven by solar energy. This experiment uses activated alumina as an adsorbent because its ability to absorb methanol is good enough, namely 350 ml/kg adsorbent (Himsar, 2014). To the best of our knowledge, no similar research using adsorbent of activated alumina (type X Na86) in a solar adsorption refrigerator has been conducted.

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1.1. Intensity of Solar Radiation

The intensity of solar radiation is the amount of energy received by a surface per unit area per unit time. The characteristics of solar radiation intensity are always changing with time. The amount of total solar radiation energy can be calculated by the equation (Duffie, 2006):

$$Q_{rad} = \int_{tsr}^{tss} I \, dt \tag{1}$$

where I is solar radiation intensity (W/m^2), t_{ss} is time at sunset and t_{sr} is time at sunrise. By knowing the astronomical position and altitude of an area, the amount of solar radiation intensity at a given time can be predicted by considering the direct radiation and the diffuse radiation. Beam radiation or direct radiation is radiation that is transmitted directly from the atmosphere to the earth's surface and can be written as:

$$I_b = I_{on} \tau_b \cos \theta_z \tag{2}$$

where I_b is beam radiation (W/m^2), I_{on} is radiation received by the earth's atmosphere (W/m^2), τ_b is the fraction of radiation transmitted to the earth and θ_z is the azimuth angle. The diffuse radiation (W/m^2) that is reflected radiation in all directions can be used, which can be calculated by:

$$I_d = I_{on} \cos \theta_z (0.271 - 0.294 \tau_b) \tag{3}$$

The intensity of solar radiation is the sum of the direct radiation and diffuse radiation that can be expressed by:

$$I = I_b + I_d \tag{4}$$

or

$$I = I_{on} \cos \theta_z (0.706 \tau_b + 0.271) \tag{5}$$

Besides being influenced by the astronomical position and location, the intensity of solar radiation is also affected by the altitude of the earth's surface, the thickness of the clouds, topography and the seasons.

1.2. Performance of Solar Adsorption Refrigerator

In comparison with mechanical vapor compression systems, adsorption refrigerator systems have the benefits of energy saving if powered by waste heat or solar energy, and controlled by simpler, noiseless, non-corrosive, and environmentally friendly means, with lower operation costs. Four main adsorbent-adsorbate pairs are commonly used in solar adsorption refrigerator: activated carbon-methanol, zeolite-water, silica gel-water and activated carbon-ammonia (Spahis et al., 2007). For its application, the adsorption refrigeration cycle can be divided into three categories, for freezing ice and condensation (<0°C), refrigeration of food and vaccine storage (0°C–8^{o}C) and for air conditioning (8^{o}C–15^{o}C) (Fan, 2007). The physical adsorbents commonly used in adsorption refrigerator are activated carbon, silica gel and zeolite (Anyanwu, 2003). Two main parameters can be used to evaluate the performance of adsorption refrigeration: the coefficient of performance (COP) and specific cooling power (SCP). The COP value of the intermittent adsorption refrigerator varies from 0.01 to 0.2 depending on the collector efficiency (Alghoul et al., 2007; Anyanwu, 2004). The coefficient of performance is defined as the ratio of the total heat extracted by evaporation of the desorbed mass of the methanol (kJ) to the total incident global irradiance from sunrise to sunset can be written as in equation (Li et al., 2005; Parash et al., 2016):

$$COP = \frac{(Q_{ref} - Q_{c-e})}{\int i_{(t)}\, dt} \tag{6}$$

where ∫ i(t) dt is total incident global irradiance . The refrigeration effect can be written as:

$$Q_{ref} = \Delta x \,.\, m_a \,.\, L \tag{7}$$

and

$$\Delta x = x_{bd} - x_{ad} \tag{8}$$

where m_a is adsorbent mass inside the adsorber, L is the latent heat of vaporization, x_{bd} is the adsorption capacity before desorption and x_{ad} is the adsorption capacity after desorption. The energy used to cool down the methanol liquid from condensing temperature to evaporation temperature can be expressed as:

$$Q_{c-e} = \int m_a\ \Delta x\ C_{pm}\ dt \tag{9}$$

where C_{pm} is the specific heat of methanol. Meanwhile, the specific cooling power is the cooling capacity for each kilogram of adsorbent mass can be calculated from equation (Wang et al., 2009):

$$SCP = \frac{W_L}{m_a} \tag{10}$$

where m_a is adsorbent mass inside the adsorber (kg). And the cooling power (kW) is

$$W_L = \frac{(m_i\ x\ L_w) + (m_i\ x\ c_{pw}\ x\ T_{wa}) - (m_i\ x\ cp_i\ x\ T_i)}{t_c} \tag{11}$$

where m_i is ice mass (kg), L_w is latent heat of water (kJ/kg), T_{wa} is water temperature (^oC), T_i is ice temperature (^oC), t_c is cycle time (second), cp_i is the specific heat of ice (kJ/kg^oC) and cp_w is the specific heat of water (kJ/kg^oC).

1.3. Collector Efficiency

The collector efficiency is defined as the ratio between the useful heat gain over some specified time period to the incident solar energy over the same time period. Flat plate collectors were used in this research because they are easily manufactured and they are commonly used in solar adsorption refrigeration systems (Umair et al., 2014). The total mass of adsorbent needed in the collector for each 1-m^2 of collector area is about 20-26 kg (Pons & Guilleminot, 1986). The collector was isolated by using insulating materials, such as wood, styrofoam, and rockwool as shown in the Figure 1.

The collector efficiency can be expressed as (Duffie, 2006 ; Kalogirou, 2009):

$$\eta_c = \frac{Q_{radiation}}{I\ .\ A} \tag{12}$$

where A is the collector area (m^2). The heat radiation during sunshine hours can be written as:

$$Q_{radiation} = F' \quad x \quad (Q_{in} - Q_{total}) \tag{13}$$

where F' is factor of collector efficiency, which is assumed to be 0.9. The heat input received by the collector is defined as:

$$Q_{in} = I \ . \ A \ . \ \tau \ . \ \alpha \tag{14}$$

where τ is absorptivity of the adsorber plate and α is the transmissivity of the glass cover. The total heat loss from the collector is calculated by using the following equation:

$$Q_{total} = Q_{wall} + Q_{bottom} + Q_{top} \tag{15}$$

where Q_{wall} is heat lost from the wall (watt), Q_{bottom} is heat lost from the bottom of the collector (watt) and Q_{top} is heat lost from the top of the collector (watt).

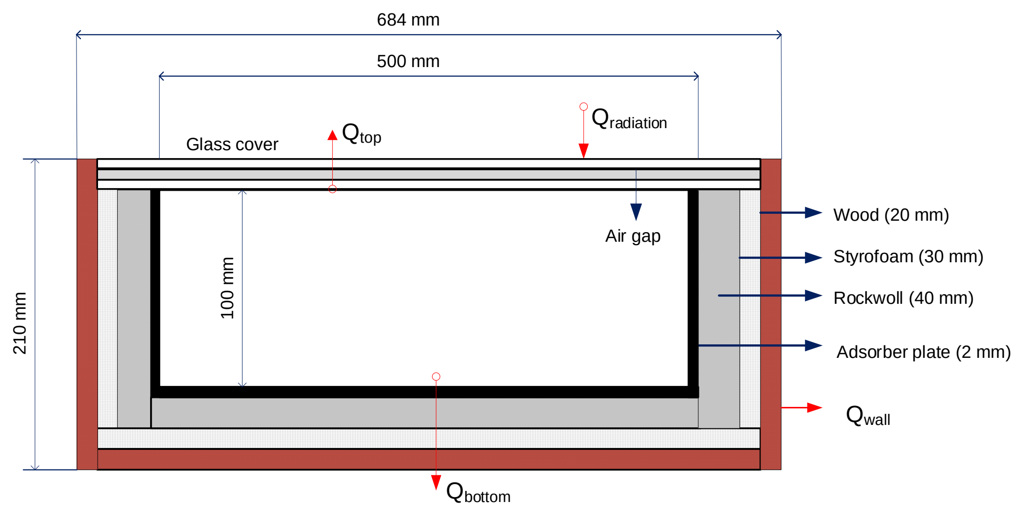

Figure 1 The cross section of collector

2. EXPERIMENT

2.1. Place and Time

The experiments were carried out during eight consecutive days from February 13 to February 20, 2015, at the Solar Energy Laboratory, University of Sumatera Utara in Medan city, Indonesia, with geographical coordinates 3°35' North latitude, 98°40' East longitude, and altitude of about 37.5 meters above sea level.

2.2. Materials

The materials used for this study included activated alumina (*type of molecular sieve* 13X - Na86 [(AlO_2) 86 (SiO_2) 106]• 264H_2O) of 6.5 kg. The type X of activated alumina has a larger, elliptical-shaped internal cavity of 13 angstroms in diameter with a pore diameter of approximately 8 angstroms for the sodium form. Three liters of methanol with a purity of 99% was used as the refrigerant and a medium 4.5 liters of water was cooled.

2.3. Experimental Scheme

The designed adsorption refrigerator consists of collector, condenser and evaporator as shown in Figure 2. The collector is made from stainless steel with plate thickness 1 mm. Two plain window glasses with thickness of 3 mm separated by a 2 cm air gap are used as transparent covers to prevent heat loss from the top. The collector area is 0.25 m^2 with tilt angle of 30° and contains 6.5 kg of activated alumina, which is spread between 12 fins. The fins are rectangular, measuring 0.5 m long and 0.05 m wide, which is optimal to allow a good transfer of heat in the activated alumina. The condenser is made from stainless steel with 17 fins and total heat exchange area of 0.68 m^2. The collector and condenser are cooled by natural convection air. The evaporator is made from stainless steel and filled with 3 liters of methanol and then placed inside a cold chamber. The cold chamber is filled with 4.5 liters of water and isolated with styrofoam and rockwool. The connections of the collector-condenser-evaporator are flexible tubes with a diameter of 20 mm.

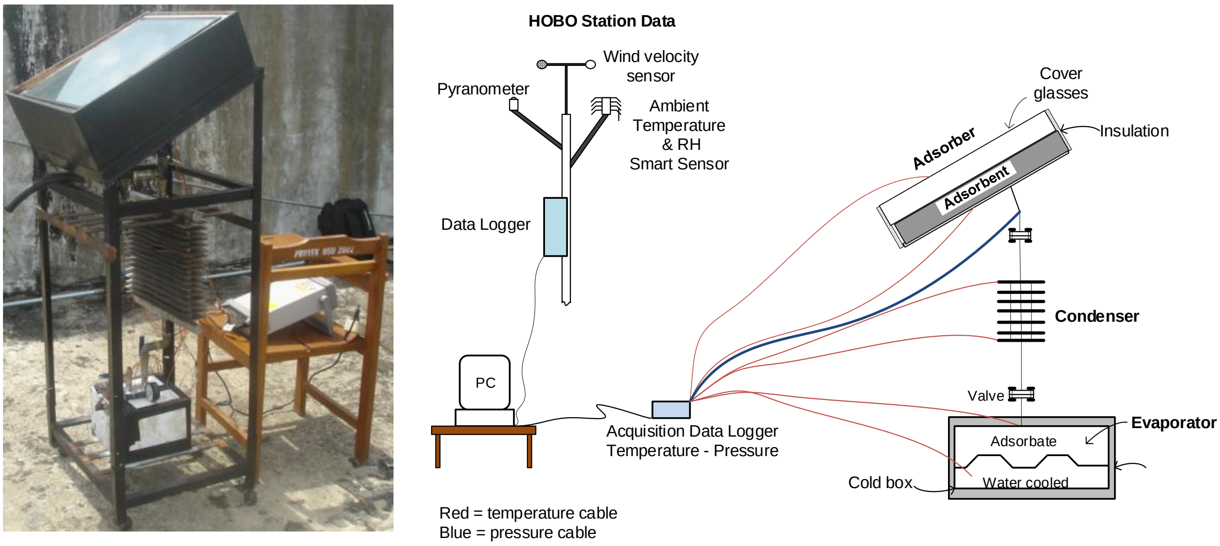

Figure 2 Photograph of solar adsorption refrigerator and experimental scheme

The solar adsorption refrigerator is connected to a data acquisition system Agilent 3497A through the thermocouples. Eight thermocouples were used in the experiments, three for the collector, two for the condenser and three is located inside the evaporator. Temperatures were measured using J type thermocouples with an accuracy of 0.4%. A HOBO micro station data logger was used to record weather conditions such as solar radiation intensity, ambient temperature, relative humidity and wind velocity. A vacuum pressure gauge data logger was installed on the solar adsorption refrigerator to measure the operating pressure of the solar refrigerator. The measurements were made every one minute. Briefly, the experimental procedure can be described as follows. Collector heating process until desorption was done by using solar energy and the process lasted about 9 hours from 08:00 until 17:00 local time. After the heating-desorption process was completed, vacuum process was conducted for around 30 minutes. This process was aimed at removing the air containing water vapor still present in the adsorbent. The next process was the filling of liquid refrigerant into the evaporator through a channel that had been specifically made. Furthermore the adsorption started in from the afternoon. The experiments of solar refrigerator performance were carried out from 08:00 until 08:00 the following day during seven experiments.

3. RESULTS AND DISCUSSION

The experiments of solar refrigerator performance were carried out from 08:00 local time and ended at 08:00 the next day after the refrigeration was completed. The experiments process went through seven cycles, or eight days. Table 1 shows that the maximum value of total solar radiation during the experiments is 4.579 kWh/m^2/day in the first cycle and the minimum value of 2.114 kWh/m^2/day occurred on the sixth cycle. Table 1 also shows the solar radiation time during experiments from 10.90 to 12.18 hours. Solar radiation began to appear from 06:20 until 18:25 during the experiments.

Table 1 Weather condition during experiments

Experiments Date Feb 2015	Cycle	Mean Ambient Temperature (°C)	Mean Relative Humidity (%)	Mean Wind Speed (m/s)	Solar Radiation Time (hours/day)	Total Solar Radiation (kWh/m²/day)
13–14	1	30.15	76.25	1.11	12.18	4.579
14–15	2	29.72	77.34	1.04	12.12	4.304
15–16	3	28.78	77.87	1.67	11.85	4.213
16–17	4	23.91	92.31	0.25	11.90	2.650
17–18	5	27.21	86.73	0.39	10.90	3.382
18–19	6	23.11	94.10	0.11	11.90	2.114
19–20	7	28.56	83.10	0.42	12.02	3.568

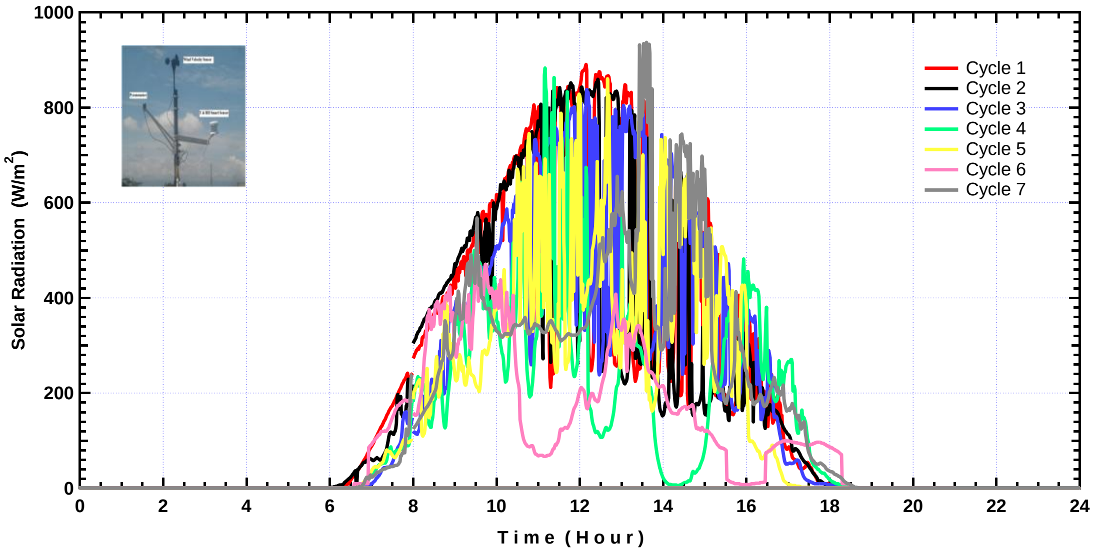

Figure 3 Solar radiation intensity during experiments

Figure 3 shows the fluctuations of solar radiation intensity during 24 hours. From the experimental data, it can be seen the maximum radiation occurs on the seventh cycle measuring 936.90 W/m^2 at 13:45 when the sky was clear. In this experiment, the maximum collector temperature of 95.39°C was achieved at the seventh cycle of the desorption process.

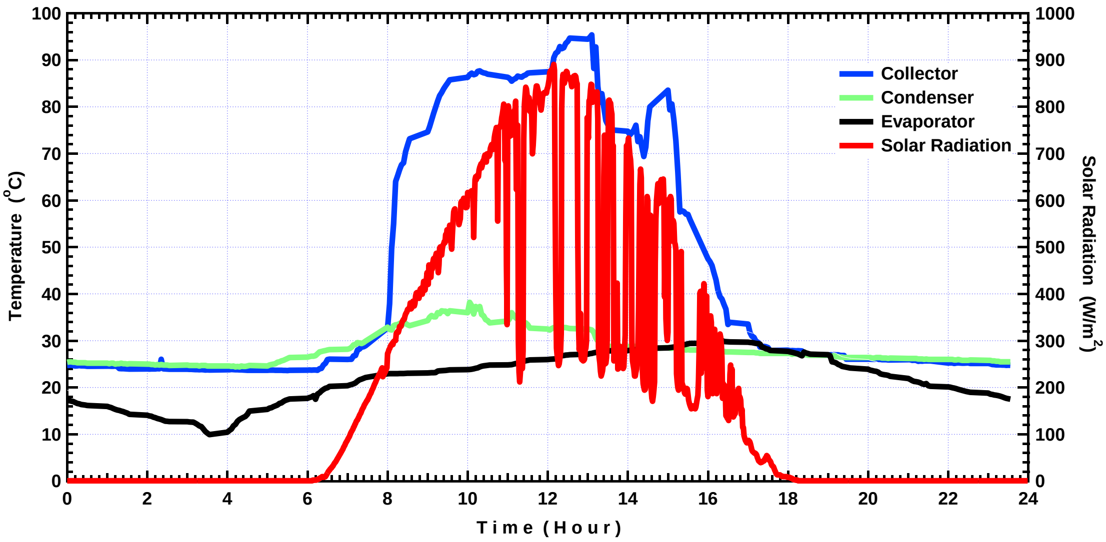

Figure 4 Effect of solar radiation on the component temperature

Figure 4 shows the effect of solar radiation on the component temperature in the first cycle. The experimental data show that the heating process up to desorption or generation time lasts about 9 hours throughout the day, while the cooling process to adsorption process lasts about 15 hours. The variations in the collector temperature followed the solar radiation pattern, and consequently depended on the solar radiation level. During this heating process the pressure increased progressively due to methanol generation. As the heating and desorption process ceased after 9 hours, the temperature fell quickly by natural cooling, and the temperature re-increased slightly after a while due to the heat of adsorption. After the progress of the adsorption process side by side with the methanol evaporation in the evaporator, the temperature started to fall until it reached a minimum value. This experiment showed that the higher the total solar radiation, the lower the evaporator temperature, and this is due to the increasing in the desorbed methanol from the adsorbent. Table 2 shows the collector efficiency during experiments where the maximum value is obtained 47.15% when solar radiation is at the maximum 936.9 W/m^2. With statistical function, the correlation of weather conditions is obtained on the collector efficiency.

Table 2 Collector efficiency during experiments

Cycle	Solar Radiation Maximum (W/m^2)	Ambient Temperature (°C)	Relative Humidity (%)	Wind Velocity (m/s)	Collector Efficiency (%)
1	890.60	34.53	63.32	1.55	46.07
2	859.40	34.33	63.90	1.43	43.79
3	838.10	34.28	64.01	1.05	43.15
4	883.10	34.49	63.61	1.40	45.22
5	860.60	34.48	63.78	1.43	44.08
6	730.60	30.67	66.02	1.68	40.03
7	936.90	34.85	61.69	0.87	47.15

There is a significant correlation between collector efficiency and solar radiation intensity at 0.984. In addition, the effect of weather on the collector efficiency was also examined, by using multiple regression analysis. The coefficient of determination (R^2) is 0.987, which means that the effect of weather conditions on the collector efficiency about 98.7%.

These experiments also carried out measurements of operating pressure that occured in the solar adsorption refrigerator. The measurement results showed the operating pressure variations from the desorption to the adsorption process ranged from 0.0782 bar to 0.3326 bar. The operating pressure of the solar refrigerator is shown in Table 3.

Table 3 Conditions of operating pressure and evaporator temperature

Cycle	Total Energy Solar (MJ/m^2/day)	Operating Pressure (bar)		Evaporator Temperature (^{o}C)	
		Max	Min	Max	Min
1	16.485	0.3326	0.0874	31.77	9.92
2	15.495	0.2885	0.1057	31.06	10.95
3	15.168	0.2895	0.0864	30.05	11.21
4	9.542	0.3161	0.0924	26.62	13.85
5	12.175	0.2991	0.1094	28.96	12.63
6	7.609	0.3185	0.0782	24.98	15.67
7	12.843	0.2907	0.0841	29.07	11.93

The minimum water temperature that can be achieved during adsorption is 12.01°C and the maximum water temperature is 33.61^{o}C. The experimental data show that the minimum water temperatures occur between 04:00 and 05:00. The experiment results also showed that the activated alumina-methanol adsorption system can deliver an evaporation temperature to about 9.92°C and a heat source with a temperature range of 83.95 to 95.39^{o}C, which is widely available in solar energy sources.

The experimental data on this solar refrigerator shows the coefficient of performance to be in the range of 0.0991 and 0.0919 when the total solar energy lies between 7.609 MJ/m^2 and 16.485 MJ/m^2. The experimental data also shows that the greater total solar energy received by the collector the greater the COP value generated. The total incident of global solar energy to the collector area ranges of 1902.36 kJ and 4121.22 kJ, and the actual useful cooling produced was the heat extracted from the water in the cold chamber to lower its temperature range of 174.83 kJ and 408.24 kJ during the experiments. Meanwhile, the maximum value of the cooling capacity for each kilogram of adsorbent mass or SCP obtained was 0.0188 kW/kg on the first cycle and the minimum value obtained was 0.0184 kW/kg on the sixth cycle.

Based on the analysis carried out, the performance of a solar adsorption refrigerator depends on certain parameters such as total solar radiation, collector performance and the presence of unwanted gases. The daily fluctuations of total solar radiation are influenced by the state of the sky: for example, whether it is clear, cloudy, or raining. The collector performance can be affected by the heat in the collector area, which determines the eventuality of a less than optimum, insulation system and cooling process during adsorption. In general, a solar adsorption refrigerator that uses methanol has a normal operating pressure ranging from 0.02 bar to 0.2 bar (Eric, 1998), while the operating pressure of an adsorption refrigerator under test is approximately in the range of 0.0782 bar and 0.3326 bar. From this condition, it can be stated that the vacuum pressure of adsorption refrigerator being tested has not performed as expected. This is due to the fact that the vacuum process is still not optimal, which result in the presence of unwanted gases in the refrigerator. The presence of unwanted gases affects the cycle of thermodynamics, and the operating pressure of the solar refrigerator. As it is known, the average size of microporous adsorbents is about 20 Angstroms, which is quite capable of absorbing not only methanol but also unwanted gases such as air infiltration. It is estimated that unwanted gas occupies part of a micro surface adsorbent that should be occupied by methanol. The presence of unwanted gases has a higher saturation pressure than methanol at the same temperature, which would damage the vacuum process and reduce the performance of solar adsorption refrigerator (Eric, 1998). Therefore, the amount of methanol that is absorbed by the adsorbent is diminished by the presence of unwanted gases. Unwanted gases adsorbed earlier than methanol, which makes microporous adsorbents are becoming more available for the adsorption of methanol during the heating process. In addition, the operating pressure of the refrigerator will continue to increase due to the increase in collector temperature caused by unwanted gases that cannot be condensed. As a result, when there is unwanted gas in the refrigerator, the maximum collector temperature is required. If the maximum collector temperature remains the same, then the amount of adsorbed methanol will be reduced from the previous amount.

The working system of the solar adsorption refrigerator can be explained using a Clapeyron diagram. Figure 5 shows the actual Clapeyron diagram of the first cycle, which represent the operational systems of solar adsorption refrigerators.

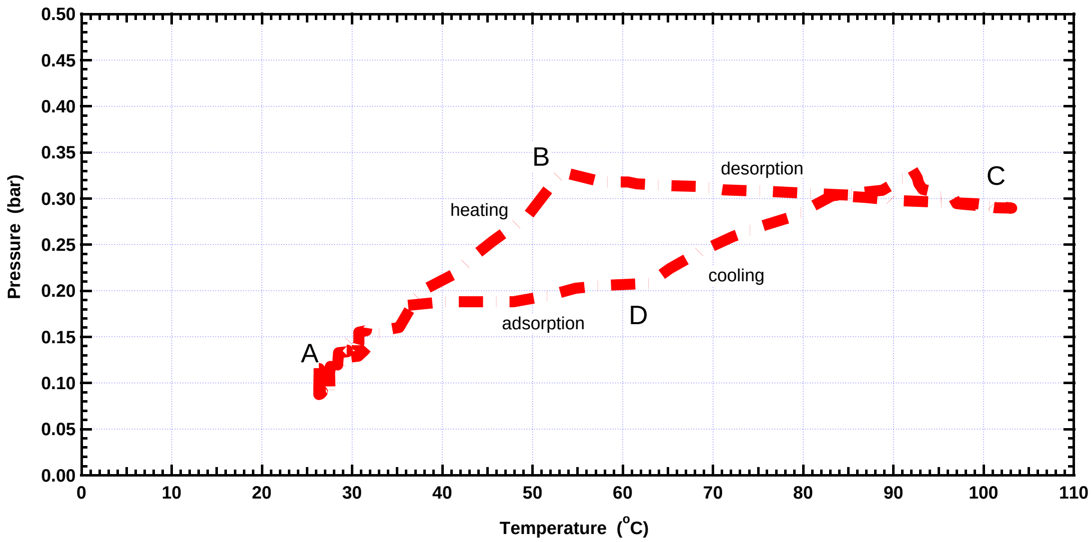

Figure 5 The actual Clapeyron diagram of first cycle

The heating process began from point A at 8:00 local time when the adsorbent was at a low temperature and low pressure. The A-B process is a heating process that follows the desorption process B-C and takes place at around noon; the collector receives heat energy so that the collector temperature increases and the pressure increases. The desorption process causes the collector temperature to increase until it reaches the maximum temperature of 94.23°C and pressure of 0.3326 bar, and when the pressure increases, it causes methanol vapor. In the condenser, the methanol vapor is turned into liquid and the heat is dissipated to the surroundings. The condensate flows by gravity into the evaporator. During the cooling process C-D and following adsorption process D-A, the collector is cooled to near ambient temperature, thus reducing the pressure of the entire system. Because the collector continues to release heat during the process of natural convection, the collector undergoes decreasing temperature until it reaches the minimum temperature of 26.32°C and is followed by a decreasing of pressure that causes methanol vapor. In order to evaporate, methanol absorbs as much heat from the water around the evaporator as the latent heat from the evaporation of methanol. The cycle is said to be intermittent because the adsorption process only happens during the night.

4. CONCLUSION

The purpose of this paper was to study the performance of solar adsorption refrigeration with activated alumina and methanol adsorption pair. The main parameters that affect the performance are total solar radiation, collector performance and the presence of unwanted gases. The experimental results show that the maximum collector efficiency is 47.15% when the intensity of maximum solar radiation is 936.9 W/m^2. The coefficient of determination 0.93 is obtained from the multiple regression analysis, which means that the effect of weather conditions on collector efficiency is 93%. In this research, the maximum value of the COP is 0.0991 when the total solar radiation is 4,579 kWh/m^2. The minimum value of the COP obtained is 0.0919 when the total solar radiation is 2.114 kWh/m^2. This solar adsorption refrigerator can achieve a minimum water temperature of between 12.01°C and 17.77°C and an evaporator temperature of between 9.92°C and 15.67°C under the condition of about 7.609-16.485 MJ/m^2 solar insolation. The main conclusion that can be drawn here is that by using this adsorption pair, a cooling effect can be produced in a solar adsorption refrigerator.

5. ACKNOWLEDGEMENT

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