PERFORMANCE ANALYSES OF SOLAR ADSORPTION REFRIGERATION SYSTEM USING INDONESIAN ACTIVATED CARBON AND METHANOL AS WORKING PAIR

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Abstract

This study aimed to analyse the performance of a solar adsorption refrigerator using granular activated carbon of coconut shell made in Indonesia and methanol as working pair. The experiments carried out with varying weather conditions. The type of collector were the flat plate with an area of 0.25 m^2. In this research, the maximum value of the COP obtained is 0.1276 when daily global irradiance is 3.918 kWh/m^2 and the minimum value obtained is 0.0830 when daily global irradiance is 2.681 kWh/m^2. The maximum value of SCP obtained is 0.0189 kW/kg and the minimum value obtained is 0.0185 kW/kg. The best adsorption result was the cooling process of water from temperature of 27.90°C to 4.09°C, where the heat extracted from water in the cold box to lower its temperature about 450.01 kJ.

Key words: solar adsorption refrigerator, Indonesian activated carbon, performance analyses.

INTRODUCTION

Indonesia has abundant potential of solar energy because its location is on the equator line between 6°N and 11°N latitudes and in between 95 °E and 141°E longitudes. Most of the Indonesian area gets enough radiation with the average of the solar radiation intensity falling on the surface of the earth Indonesia is 4 kWh/m^2. Based on clear sky conditions that total solar energy in Indonesian archipelagos can range from 16000 to 18000 kJ/m^2/day, according to measurements and predictions (HANDAYANI, 2012; AMBARITA, 2016). One of solar energy utilization for refrigeration system is adsorption refrigerator. The solar powered solid adsorption refrigeration system is the most promising technology with low cost, simple manufacture, maintenance requirements and environmentally friendly. Keep in mind that, researches about solar adsorption refrigerator are still rarein Indonesia. The main objective of this research is to obtain performance of adsorption refrigerator driven by solar energy. This study use granular activated carbon of coconut shell made in local as an adsorbent because the ability to absorb methanol is 300 ml/kg (AMBARITA, 2014). As noted, the activated carbon and methanol seem to be the suitable pair in terms of higher COP and less expensive than other pairs so far in a solid adsorption refrigeration cycle (CRITOPH, 1988).

There are four main working pairs commonly used in solar adsorption refrigerator, namely activated carbon - methanol, zeolite - water, silica gel - water and activated carbon - ammonia (IOAN ET AL., 2015). The application of adsorption refrigeration cycle can be divided into three categories for the room air conditioner (8°C-15°C), for refrigeration of food and vaccine storage (0°C-8°C) and for the purpose of freezing ice and condensation (< 0°C) (FAN, 2007). The physical adsorbents commonly used in adsorption refrigerator are activated carbon, silica gel and zeolite (ANYANWU, 2003). There are two main parameters to evaluate the performance of adsorption refrigeration namely the coefficient of performance (COP) and specific cooling power (SCP). The amount of cooling achieved by a refrigerator per unit of heat supplied is usually given by the COP. The COP valueof the intermittent adsorption refrigerator varies from 0.15 to 0.35 with heat source temperature 60°C-165°C (ZEYGHAMI ET AL., 2015). The COP value of adsorption refrigerator driven by solar energy can be obtained using the equation (JI ET AL., 2014; PARASH ET AL., 2016):

$$COP = \frac{(Q_{cool} - Q_{c-e})}{\int i_{(t)}\, dt} \quad (1)$$

Where i(t) is solar radiation intensity (W/m^2). The cooling effect can be expressed as:

$$Q_{cool} = \Delta x \cdot m_a \cdot L \quad (2)$$

and

$$\Delta x = x_{bd} - x_{ad} \quad (3)$$

where m_a is adsorbent mass inside the collector, 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 refrigerant liquid from condensing temperature to evaporation temperature can be written as:

$$Q_{c-e} = \int m_a \; \Delta x \; C_{pm} \; dt \qquad (4)$$

where C_{pm} is the specific heat of the refrigerant. Meanwhile, the specific cooling power is the cooling capacity for each kilogram of adsorbent mass can be calculated from equation (WANG ET AL., 2009):

$$SCP = \frac{W_L}{m_a} \qquad (5)$$

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

$$W_L = \frac{(m_i \times L_w) + (m_i \times c_{pw} \times T_{wa}) - (m_i \times cp_i \times T_i)}{t_c} \qquad (6)$$

where m_i is ice mass (kg), L_w is latent heat of water (kJ/kg), T_{wa} is water temperature (°C), $T_i$is ice temperature (°C), $t_c$is cycle time (second), cp_i is the specific heat of ice (kJ/kg°C) and $cp_w$is the specific heat of water (kJ/kg°C).Thus the aim of this study is to analyse the performance of a solar adsorption refrigerator using granular activated carbon of coconut shell made in Indonesia and methanol as working pair.

MATERIALS AND METHODS

The adsorbent used in this study was ordinary granular activated carbon of coconut shell produced in Sumatera Utara province of Indonesia with grain size 1-3 mm of 6.5 kg shown in Fig. 1. Methanol as refrigerant of 3 litres and water as a medium that was cooled of 4.5 litres.

Fig. 1. – Granular activated carbon of Indonesia

The prototype of solar adsorption refrigerator has been fabricated and used in experiments. The refrigerator consists of three main components, namely collector, condenser and evaporator. The collector was made of stainless steel with plate thickness 2 mm. Two plain glasses cover with thickness of 3 mm separated by a 2 cm air gap were used as transparent covers to prevent the heat loss from the top. The collector contains 6.5 kg of adsorbent then mixed with 15 of the bolts of stainless steel. The bolts of stainless steel with diameter 0.016 m and length 0.05 m, which was aimed to allow a good transfer of heat in the adsorbent. The collector area of 0.25 m^2 and oriented Eastward with tilt angle of 30°. The flat plate collector type was used in this research because easily manufactured and they were commonly used in solar adsorption refrigeration systems (UMAIR ET AL., 2014; SOTERIS, 2009). The collector was isolated using insulating materials, namely wood (20 mm), styrofoam (30 mm), and rockwool (40 mm) as shown in the Fig. 2.

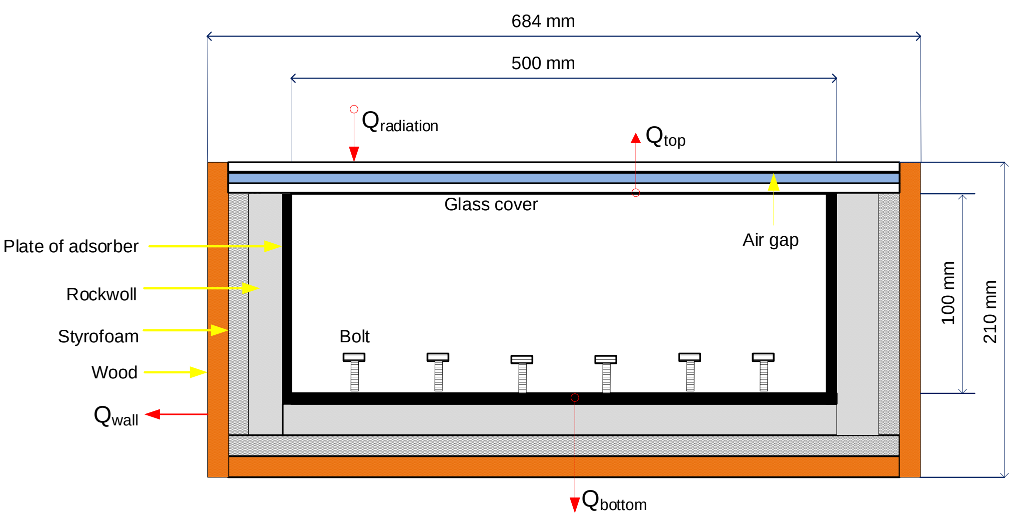


Fig. 2. – The cross section of collector

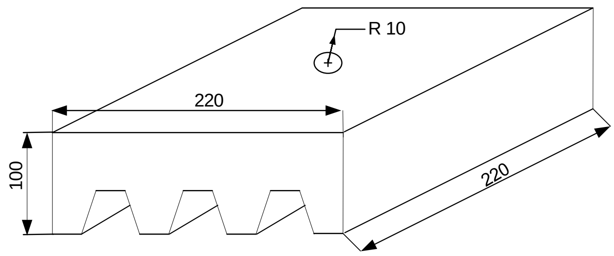
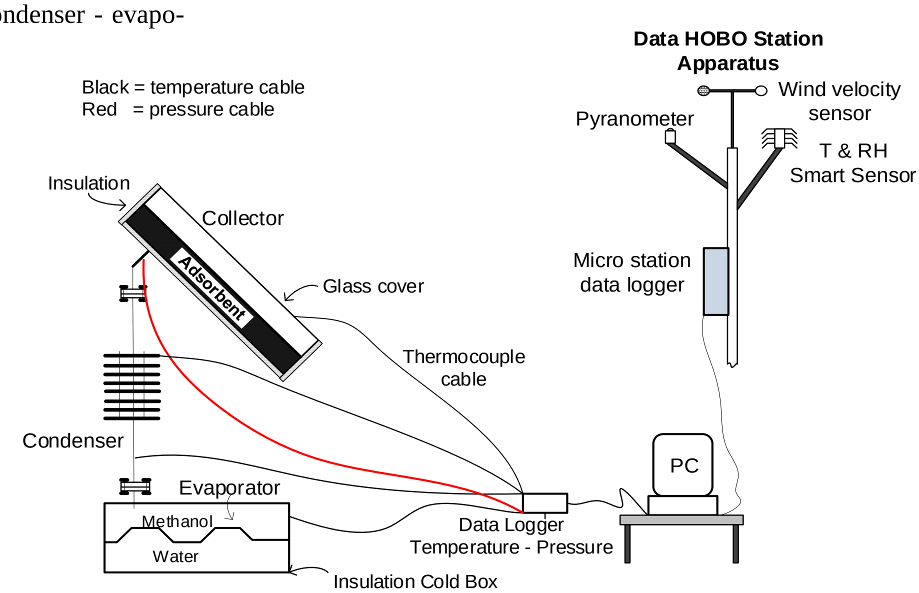


Fig. 3. – Sketch of the evaporator (mm)

The evaporator with heat exchange area of 0.19 m^2 which filled refrigerant of 3 litres was immersed in a cold box. The cold box was filled with water of 4.5 litres and isolated with styrofoam and rockwool. The connections of the collector - condenser - evaporator were flexible tubes with a diameter of 20 mm. The photograph of solar adsorption refrigerator and schematic of refrigerator with measurement systems as shown Fig. 4.



(a) (b)

Fig. 4. – (a) Photograph of refrigerator; (b) schematic of refrigerator with measurement systems

The solar adsorption refrigerator was connected to a data acquisition system, Agilent 3497A through the thermocouples which were placed on the components refrigerator. 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 speed. A Pace XR5 type P1600-vac-150 data logger with an accuracy ±2% installed on the solar adsorption refrigerator to measure the operating pressure that occurs in solar refrigerator. The measurements were made every one minute. The experimental procedure can be described as follows. Collector heating process until desorption was done by using solar energy and lasts about 9 hours from 08.00 WIB - 17.00 WIB local time. As a note, western Indonesian time or WIB is used in Medan city for local time. When heating-desorption process was completed, then conducted vacuum process around 30 minutes. This process aims to remove the air containing water vapor still present in the adsorbent. The next stage was the filling of liquid refrigerant into the evaporator through a channel that has been made. Furthermore the adsorption process occurred starting from the afternoon. The experiments of solar refrigerator performance were carried out from 08.00 WIB until 08.00 WIB the next day during seven experiments. The experiments had been carried out on location in Medan city, Indonesia in May 2016 with geographic coordinate 3°35’ North - 98°40’ East and altitude about 37.5 meters above sea level.

RESULTS AND DISCUSSION

Tab. 1 shows the weather condition during experiments. The maximum value of solar radiation total during the experiments is 3.918 kWh /m^2 of the fourth experiment and the minimum value occurred on the third experiment is 2.681 kWh /m^2. It also shows the solar radiation time in one experiment ranged from 12.10 - 12.31 hours/day. Solar radiation began to appear from 06.22 WIB until 06.25 WIB during experiments. The distinction of solar radiation total was influenced by the state of the sky such as clear, cloudy and rain with bright.

Tab. 1. – The weather condition during experiments

May 2016 Date	Experiment	Mean Ambient Temperature (°C)	Mean Relative Humidity (%)	Mean Wind Speed (m/s)	Solar Radiation Time (hours/ day)	Solar Radiation Total (kWh/m^2)
1 - 2	1	28.76	83.45	1.06	12.15	2.746
2 - 3	2	28.29	86.44	0.47	12.30	3.042
3 - 4	3	28.10	89.05	0.29	12.13	2.681
4 - 5	4	29.10	82.78	1.17	12.28	3.918
5 - 6	5	30.08	81.09	1.02	12.17	3.874
6 - 7	6	28.06	86.56	0.53	12.31	3.036
7 - 8	7	28.76	83.63	1.69	12.10	3.095

Fig. 5 shows the fluctuations of solar radiation intensity during 24 hours in which the maximum radiation occurs on the second experiment 988.10 W/m^2 at 12.10 WIB. Based on experimental data, that the maximum solar radiation generally occurs at 11.54 WIB - 13.25 WIB and maximum air temperature at 12.41 WIB - 14.45 WIB.

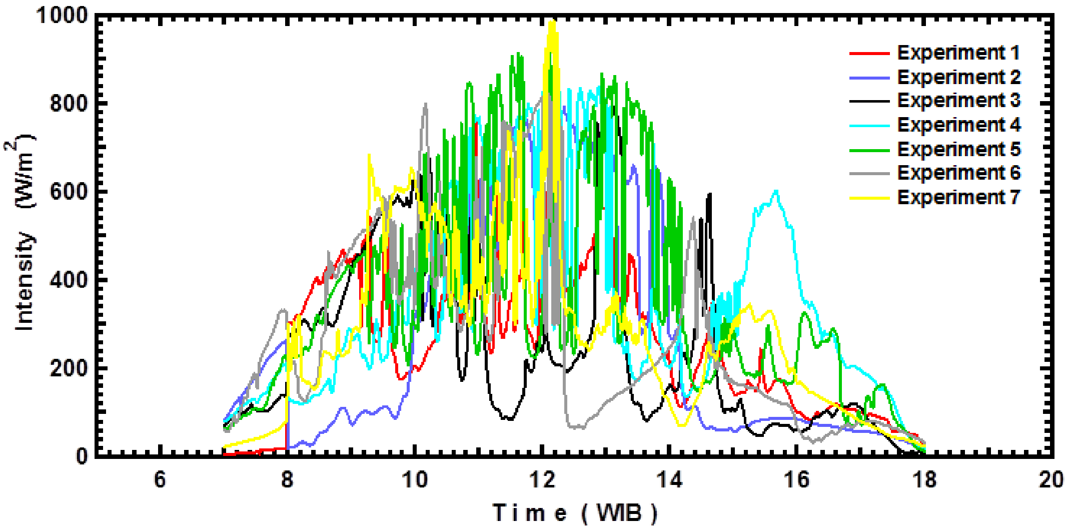


Fig. 5. – Solar radiation during experiments

Fig. 6 shows the typical intensity of solar radiation measurement and theoretical on the fourth experiment. It was used the assumption of clear sky conditions on theoretical calculations. The maximum solar radiation is 930.9 W/m^2 at 12.00 WIB in theoretical calculation and the maximum solar radiation measurement is 841.9 W/m^2 on fourth experiment.

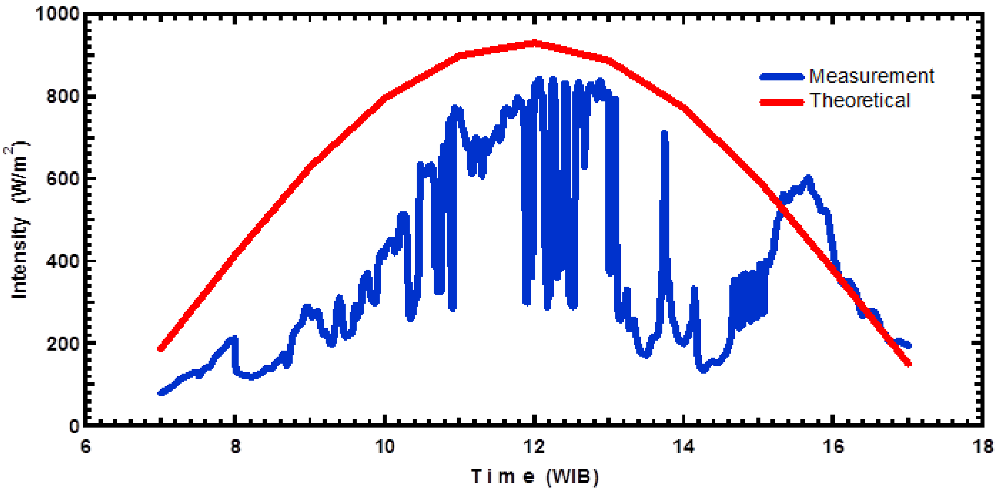


Fig. 6. – Intensity measurement and theoretical on the fourth experiment

The measurement solar radiation way below the theoretical calculation because of the cloud obstruct the beam radiation. In general, the measurement solar radiation agrees well with theoretical calculation. Fig. 7 shows the effect of solar radiation intensity on the component temperature of the first experiment. The experimental data demonstrate that the generation time lasts about nine hours through the day and the cooling process up to adsorption process lasts about fifteen hours. The variations in the collector temperature followed the solar radiation pattern which depends on the solar radiation level. The maximum collector temperature can be achieved was 100.63°C when desorption. From this experiment also show that the higher the solar radiation total will lead to lower the evaporator temperature and this due to the increasing of desorbed refrigerant from adsorbent. This experiment was also carried out measurements of operating pressure that occur in the solar adsorption refrigerator. The measurement results showed the operating pressure of refrigerator varied from 0.0521 bar to 0.3314 bar.

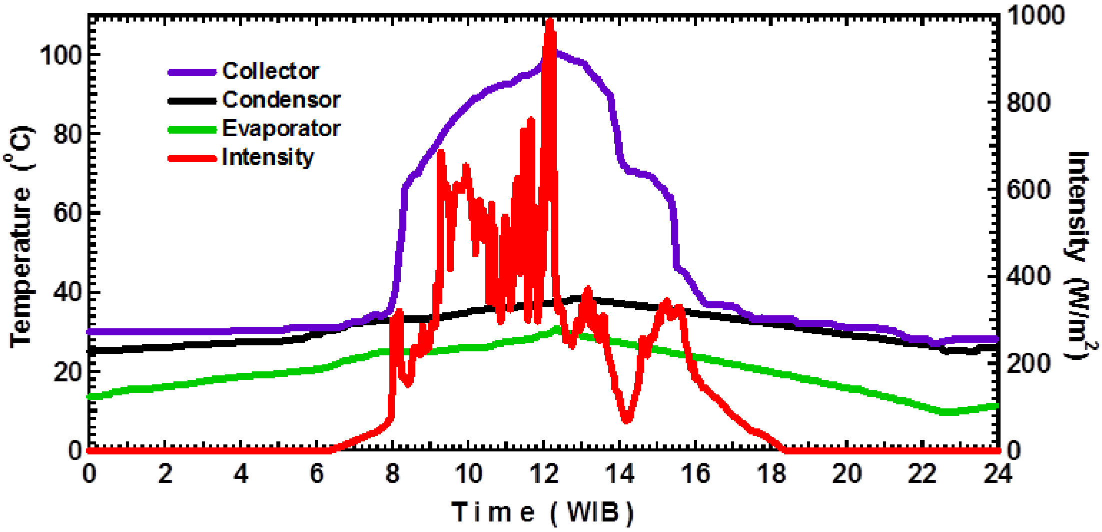


Fig. 7. – The effect of intensity of solar radiation on the component temperature

To analyze the working process of this solar adsorption refrigerator was used pressure - temperature diagram. Fig. 8 shows the actual P-T diagram of seventh experiment, which was representing the working process of solar adsorption refrigerator. The heating process starts from point A at 08.00 WIB local time where the adsorbent was at a low temperature and low pressure. The A-B process was a heating process that followed desorption process B-C takes place on the noon in which the collector receives heat energy so that the collector temperature increases and followed by pressure increasing. The desorption process makes the collector temperature increase until it reaches maximum temperature of 100.63°C when solar radiation maximum was 988.10 W/m^2 at 12.10 WIB local time and followed by pressure increasing to 0.3314 bar that causes refrigerant vapor. In the condenser, the refrigerant vapor was changed to liquid and heat was dissipated to the surroundings. The condensate flows by gravity into the evaporator. During the cooling process C - D and followed 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 25.08°C at 02.00 WIB and followed by decreasing of pressure that causes refrigerant vapor. In order to evaporate, the refrigerant adsorbs heat from the water around the evaporator as much as the latent heat of vaporization of refrigerant. The cycle was said to be intermittent because the adsorption process happens only during the night.

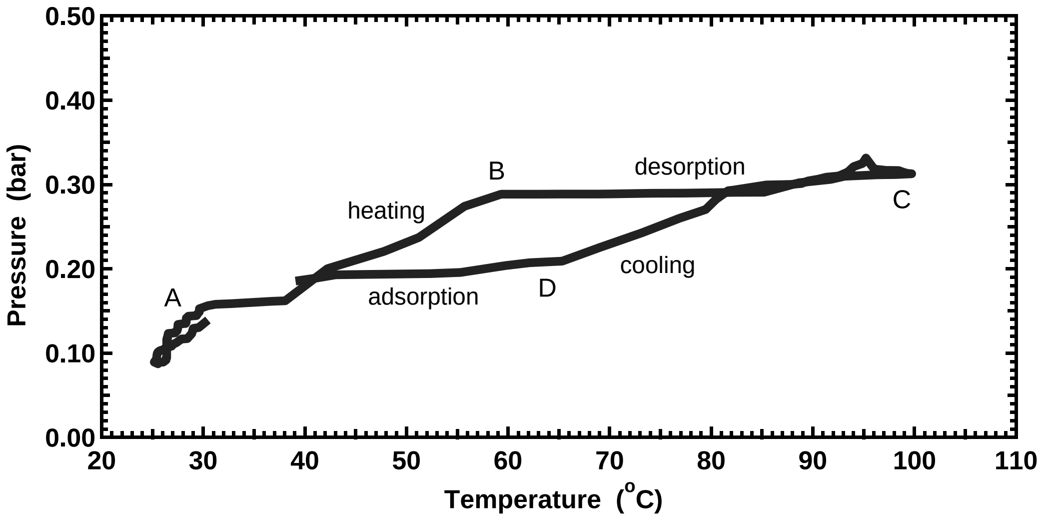


Fig. 8. – The actual P - T diagram of seventh experiment

Tab. 3. – The water temperature and the cooling produced during experiments

Experiment	The actual cooling produced (kJ)	Water temperature (°C)	
		Max	Min
1	302.97	25.76	14.73
2	349.84	26.28	12.77
3	294.84	25.44	14.84
4	547.34	27.90	4.09
5	503.87	27.76	6.10
6	336.23	25.94	13.15
7	399.17	27.16	11.04

Tab. 3 shows conditions of water temperature and the actual cooling produced during experiments.

The minimum water temperature that can be achieved in these experiments during the adsorption process is 4.09°C-14.84°C with a heat source of temperature range 81.02-100.63°C. The total incident global solar energy to the collector area ranging 2412.61 kJ-3525.86 kJ and the actual useful cooling produced was the heat extracted from water in the cold box to lower its temperature of about 200.34 kJ-450.01 kJ during experiments.

Fig. 9 shows the values of COP and SCP obtained during experiments. It appears that the fluctuating value of the COP was always followed by the value of SCP. From the experimental data on this solar refrigerator showed the coefficient of performance to be in the range 0.0830-0.1276 when the solar energy total lies between 9.65 MJ/m^{2}and 14.10 MJ/m^2. The cooling capacity for each kilogram of adsorbent mass or SCP obtained ranging 0.0185 kW/kg - 0.0189 kW/kg. Based on the analysis carried out, the main parameters that affect the performance of a solar adsorption refrigerator were solar radiation total, collector performance and the process of vacuum. The heat received by the collector was eventuality not optimum and also required improving the cooling of the collector. As noted, the solar adsorption refrigerator that uses methanol have normal operating pressure ranges from 0.02 bar-0.2 bar (ERIC, 1998; WANG ET AL., 2009; ZEYGHAMI ET AL., 2015). And the operating pressure of the refrigerator under test was obtained about 0.0521 bar-0.3314 bar. This condition means that the operating pressure of adsorption refrigerator being tested has not fulfilled as expected. This was mainly caused by a vacuum process that is still not optimal, which resulting the presence of unwanted gases in refrigerator.

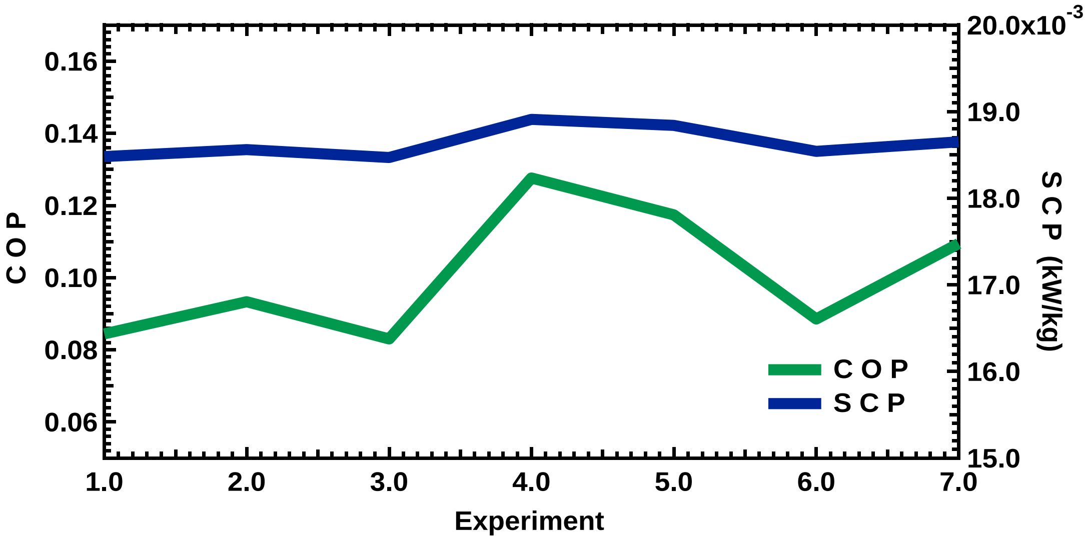


Fig. 9. – The valuesof COPandSCPobtained during experiments

The presence of unwanted gases affects the cycle of thermodynamics, and operating pressure of refrigerator (HANDAYANI, 2012; AMBARITA, 2016). As we know, the average micropore size of the adsorbent was able of adsorbing not only refrigerant, but also unwanted gases such as leaked air. It was thought that the unwanted gases occupy a part of the adsobent microporous surface otherwise available for refrigerant. The presence of unwanted gases that have much higher saturated pressure than refrigerant at the same temperature would destroy the vacuum and diminish the performance of the solar adsorption refrigerator (ERIC, 1998; PARASH ET AL., 2016). The refrigerant adsorbed by adsorbent is less than without the presence of unwanted gases. The unwanted gases desorbed earlier than the refrigerant, making more adsorbent microporesavailable for adsorption of refrigerant during the heating process. The operating pressure would keep increasing as the collector temperature increased because the unwanted gases could not be condensed. Consequently, when there were unwanted gases in the system, a higher maximum collector temperature would be needed to generate the same amount of refrigerant as without the presence of unwanted gases. The desorbed refrigerant would be less than before if the maximum collector temperature was the same.

Tab. 4 shows the collector efficiency, which obtained during experiments. The maximum collector efficiency obtained was 51.46% when maximum solar radiation was 998.10 W/m^2. With statistical function was obtained correlation of weather conditions on the collector efficiency.

Tab. 4. – Collector efficiency during experiments

Experiment	Maximum Solar Radiation (W/m^2)	Ambient Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)	Collector Efficiency
1	770.60	31.94	69.9	1.53	0.3464
2	793.10	33.13	68.3	1.62	0.4075
3	791.90	34.89	65.3	1.51	0.3932
4	841.90	35.10	63.0	1.33	0.4788
5	948.10	33.97	66.8	0.92	0.4903
6	824.40	32.79	67.4	1.57	0.4196
7	988.10	34.47	61.2	1.07	0.5146

Tab. 5. – Correlation of weather parameters on efficiency collector

Data	Maximum radiation	Ambient temperature	Relative humidity	Wind speed	Collector efficiency
Maximum radiation	1				
Ambient temperature	0.418	1			
Relative humidity	-0.649	-0.837	1		
Wind speed	-0.917	-0.443	0.521	1	
Collector efficiency	0.903	0.642	-0.788	-0.818	1

Tab. 5 shows that there was a significant correlation between collector efficiency to solar radiation intensity 0.903. In addition, also examined the effect of weather on the collector efficiency by using multiple regression analysis. And obtained the coefficient of determination (R^2) is 0.905, it means that the effect of weather conditions on the collector efficiency about 90,5%. Tab. 6 shows the correlation of the daily global irradiance received by collector against the minimum temperature of water and the value of the COP. It was obvious that the correlation of daily global irradiance against with the minimum temperature of water in the cold box and the value of COP namely -0.986 and 0.880 respectively. It states that the greater the daily global irradiance received by the collector, the lower the temperature of the cold water produced and the greater the COP value obtained.

Tab. 6. – Correlation of daily global irradiance on the water temperature and COP

Parameter	Minimum water temperature	Daily global irradiance	COP
Minimum water temperature	1		
Daily global irradiance	-0.986	1	
COP	-0.939	0.880	1

CONCLUSIONS

The performance of adsorption refrigeration driven by solar energy with granular activated carbon-methanol as working pair has been studied. The performance is influenced by the main parameter, namely solar radiation total, collector efficiency, and vacuum process. Experimental results showed that the working pair system can deliver evaporator temperature of about 2.81°C-13.61°C. It is clear that granular activated carbon of coconut shell produced in Sumatera Utara province of Indonesia with methanol as working pair can produce the cooling effect in a solar adsorption refrigerator with a heat source of temperature range of 81.02°C and 100.63°C.

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REFERENCES

1. AMBARITA, H.: The adsorption capacity of activated carbon and activated alumina as adsorbent against refrigerants in adsorption cycle. Proceedings of the National Seminar, Mechanical Engineering - University of Indonesia (SNTTM XIII), Jakarta, 15 - 16 October, 2014.
2. AMBARITA, H., KAWAI, H.: Experimental study on solar-powered adsorption refrigeration cycle with activated alumina and activated carbon as adsorbent. Case Studies in Thermal Engineering vol 7, 2016: 36 - 46.
3. ANYANWU, E.E.: Review of solid adsorption solar refrigerator I: an overview of the refrigeration cycle. Energy Conversion and Management vol 44, 2003: 301-312.
4. CRITOPH, E.R.: Performance limitations of adsorption cycles for solar cooling. Solar Energy vol 41, 1988: 21 - 31.
5. ERIC, H., J.: A Study of Thermal Decomposition of Methanol In Solar Powered Adsorption Refrigeration Systems. Solar Energy vol. 62, No. 5, 1998: 325-329.
6. FAN, Y.: Review of solar adsorption technologies - Development and Applications. Renewable and Sustainable Energy Reviews vol 11, 2007: 1758 – 1775.
7. HANDAYANI, A. N.: Potency of Solar Energy Applications in Indonesia. International Journal of Renewable Energy Development vol 1 (2), 2012: 33-38.
8. IOAN, S., CALIN, S.: General review of solar-powered closed sorption refrigeration system". Energy Conversion and Management vol 105, 2015: 403 - 422.
9. JI, X., LI, M., FAN, J., ZHANG, P., LUO, B., WANG, L.: Structure optimization and performance experiments of a solar-powered finned-tube adsorption refrigeration system. Applied Energy vol 113, 2014: 1293-1300.
10. PARASH, G., PRASHANT, B., ARVIND, M., AMEENUR, S. R. : Adsorption refrigeration technology - An overview of theory and its solar energy applications. Renewable and Sustainable Energy Reviews vol 53, 2016: 1389-1410.
11. SOTERIS, K.: Solar Energy Engineering Proccess and Systems. 1st ed., Cyprus University of Technology 2009.
12. UMAIR, M., AKISAWA, A., UEDA, Y.: Performance Evaluation of a Solar Adsorption Refrigeration System with a Wing Type Compound Parabolic Concentrator. Energies vol 7, 2014: 1448-1466.
13. WANG, W. L., WANG., WANG, Z.R., OLIVEIRA G.R.: A review on adsorption working pairs for refrigeration. Renewable and Sustainable Energy Reviews vol 13, 2009: 421-432.
14. ZEYGHAMI, M., YOGI GOSWAMI, D., STEFANAKOS, E.: A review of solar thermo-mechanical refrigeration and cooling methods. Renewable and Sustainable Energy Reviews vol 51, 2015: 1428-1445.

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