A Study on Adsorption Refrigerator Driven by Solar Collector Using Indonesian Activated Carbon

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Abstract. In the present work, the performance of an adsorption refrigerator driven by a solar collector was investigated. The adsorbent used in this study was 6.5 kg ordinary granular activated carbon of coconut shell produced in the Sumatera Utara province of Indonesia, 3 liters of methanol as adsorbate and 4.5 litres of water as the medium that was cooled. The experiments were carried out under varying weather conditions during seven cycles with total solar radiation about 2.681-3.918 kWh/m^2/cycle. In this study, the values of the coefficient of performance (COP) obtained were about 0.0827-0.1271. The values of specific cooling power (SCP) obtained were in the range of 0.01839-0.01883 kW/kg. The experimental results show that the adsorption refrigerator system can deliver an evaporator temperature of about 2.81-13.61°C.

Keywords: *coconut shell activated carbon; Indonesian activated carbon; refrigerator performance; solar adsorption refrigerator; solar collector.*

1 Introduction

Most of Indonesian gets plenty of solar radiation. The average solar radiation intensity falling on earth surface in Indonesia is 4 kWh/m^2 [1]. Based on clear sky conditions the total solar energy in the Indonesian archipelagos can range from 16000 to 18000 kJ/m^{2}day, according to measurements and predictions [2]. The adsorption refrigerator is a solar energy application for refrigeration systems. In general, the advantages of a solar powered solid adsorption refrigeration system are simple manufacturing, absence of moving parts, no maintenance requirements, no crystallization or corrosion problems, and environmental friendliness. It is a good alternative refrigeration method that can have great benefits in a considerable number of fields of human life, notably in remote areas without electricity network [3, 4]. Few researches on solar adsorption refrigerators have been conducted in Indonesia. The main purpose of the present study was to obtain the performance of an adsorption refrigerator driven by a solar collector. This research used granular activated carbon of coconut shell made locally as an adsorbent because its ability to absorb

Received January 11th, 2017, 1st Revision May 21st, 2017, 2nd Revision August 23rd, 2017, Accepted for publication November 30th, 2017.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2017.49.5.7

methanol is 300 ml/kg [5]. As noted, the activated carbon and methanol seem to be a suitable pair in terms of higher coefficient of performance (COP) and being less expensive than other pairs so far applied in the solid adsorption refrigeration cycle [6]. There are four main working pairs commonly used in solar adsorption refrigerators, namely activated carbon-methanol, zeolite-water, silica gel-water and activated carbon-ammonia [7]. The application of adsorption refrigeration can be divided into three categories: (1) for room air conditioning (8-15 °C), (2) for refrigeration of food and vaccine storage (0-8 °C), and (3) for the purpose of freezing ice and condensation (< 0 °C) [8]. The physical adsorbents commonly used in adsorption refrigerators are activated carbon, silica gel and zeolite [9]. Two main parameters are used to evaluate the performance of adsorption refrigeration, namely the COP and the 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 value of an intermittent adsorption refrigerator varies from 0.15 to 0.35 with heat source temperature at 60-165 °C [10]. The COP value of an adsorption refrigerator driven by a solar collector can be obtained using the following Eq. (1) [11, 12]:

$$COP = \frac{Q_{cool}}{Q_{solar}} \tag{1}$$

where Q_{cool} (kJ) is the cooling effect that can be expressed in Eq. (2) as follows:

$$Q_{cool} = m_w . c_{pw} . (T_{w-max} - T_{w-min}) \tag{2}$$

The solar energy received by the collector (kJ) is shown in Eq. (3) as follows:

$$Q_{solar} = I_t . A_c \tag{3}$$

where m_w is water mass (kg), c_{pw} is the specific heat of the water (kJ/kg^{o}C), T_{w-max} is maximum water temperature (^{o}C), T_{w-min} is minimum water temperature (^{o}C), I_t is the total solar radiation (kJ/m^2) and A_c is the collector area (m^2). Meanwhile, the specific cooling power, i.e. the cooling capacity for each kilogram of adsorbent mass, can be calculated in Eq. (4) as follows [13]:

$$SCP = \frac{W_L}{m_a} \tag{4}$$

where m_a is the adsorbent mass inside the collector (kg). The cooling power (kW) is described in Eq. (5) as follows:

$$W_L = \frac{(m_w . L_w) + (m_w . c_{pw} . T_{w-max}) - (m_w . c_{pw} . T_{w-min})}{t_c} \tag{5}$$

where L_w is the latent water heat (kJ/kg), and t_c is the cycle time (seconds).

2 Experimental Setup

A solar adsorption refrigerator was fabricated and used in this research. The main components of the refrigerator were: a collector, a condenser and an evaporator. The collector was made of stainless steel with a plate thickness of 2 mm. Two plain glasses covered with a thickness of 3 mm separated by a 2 cm air gap were used as transparent covers to prevent heat loss from the top. The adsorbent used in this research was 6.5 kg of ordinary granular activated carbon of coconut shell produced in the Sumatera Utara province, Indonesia with a grain size of 1-3 mm, as shown in Figure 1. Methanol with purity 99% as adsorbate (3 liters) and water as a medium that was cooled (4.5 liters).

Figure 1 Photograph of Indonesian granular activated carbon.

The collector contained 6.5 kg of adsorbent along with 15 stainless steel bolts. The stainless steel bolts had a diameter of 0.016 m and a length of 0.05 m, and were aimed at allowing a good transfer of heat in the adsorbent.

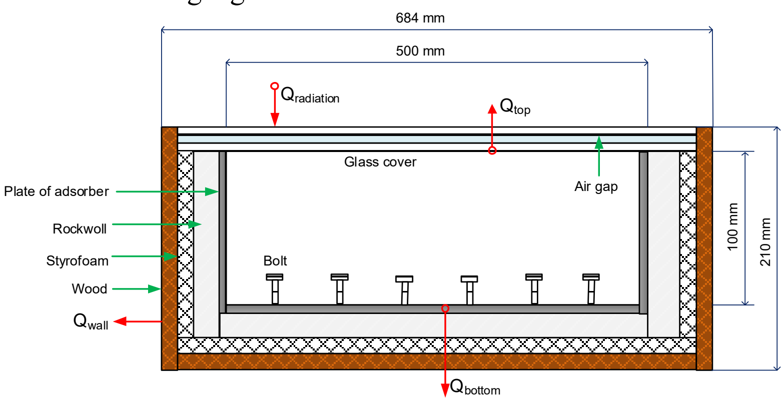

Figure 2 Section view of the collector.

The collector area was 0.25 m^2 and it was oriented eastward with a tilt angle of 30°. A flat plate collector type was used in this research because it can be easily manufactured and is commonly used in solar adsorption refrigeration systems [14, 15]. The collector was isolated using insulating materials, namely wood (20 mm), styrofoam (30 mm), and rockwool (40 mm), as shown in Figure 2. The condenser was made of stainless steel and had 17 fins and a total heat exchange area of 0.68 m^2. The collector and condenser were cooled by natural air convection. The evaporator was made from stainless steel and the heat exchange surface was designed as a series of four trapezoidal cells, the purpose of which was to enhance the heat transfer effect, as shown in Figure 3.

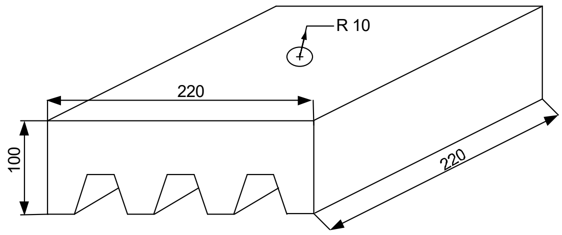

Figure 3 Sketch of the evaporator used (mm).

The evaporator with a heat exchange area of 0.19 m^2 filled with 3 liters of adsorbate was immersed in a cold box. The cold box was filled with 4.5 litres of water and isolated with styrofoam and rockwool. The connections of the collector-condenser-evaporator were flexible tubes with a diameter of 20 mm. A photograph of the solar adsorption refrigerator is shown in Figure 4.

Figure 4 Photograph of solar adsorption refrigerator.

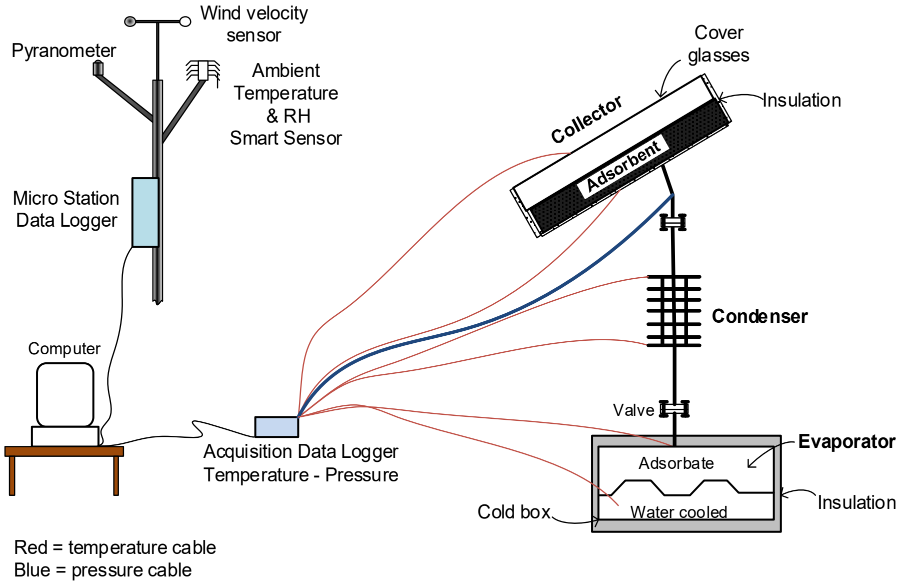

Figure 5 Scheme of experimental setup.

A scheme of the experimental setup is shown in Figure 5. The refrigerator was connected to a data acquisition system (Agilent 3497A) through thermocouples placed on the refrigerator components. 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.

The ambient temperature and relative humidity (RH) were measured using a HOBO temperature RH smart sensor with an accuracy of 0.2 °C and ±2.5% RH, respectively. The wind speed around the experimental apparatus was measured with a HOBO wind speed smart sensor with an accuracy of ±1.1 m/s and a pyranometer with an accuracy of ±5%. A Pace XR5 type P1600-vac150 data logger with an accuracy of ±2% was installed on the refrigerator to measure the operating pressure in the refrigerator. Adsorber or collector heating until desorption was done by using solar energy and lasted about 9 hours from 08.00-17.00 WIB local time. As a note, western Indonesian time or WIB (Waktu Indonesia Barat) is used in Medan city as local time.

The solar adsorption refrigerator was preliminary tested in order to make sure it was free of leakage after fabrication. The refrigerator was vacuumed and left for two days. The next stage was the filling of liquid methanol into the evaporator through a pipe. It was heated up to 120 °C. While the temperature was kept constant and evaporator valve was closed, it was evacuated using a vacuum pump for 30 minutes. The evaporator valve was opened gradually after 30 minutes. The vacuum pump was stopped when the methanol in the evaporator started to boil. At that instant, the adsorption refrigerator was ready for use. Furthermore, adsorption occurred starting from the afternoon. The experiments of solar refrigerator performance were carried out from 08.00 to 08.00 WIB the next day in seven experiments. The experiments were carried out on location in Medan city, Indonesia in May 2016 with geographic coordinates 3°35' North - 98°40' East and an altitude of about 37.5 meters above sea level.

3 Results and Discussions

Table 1 shows the weather conditions during the experiments. The maximum value of total solar radiation during the experiments was 3.918 kWh/m^2, occurring during the fourth cycle and the minimum value was 2.681 kWh/m^2, occurring during the third cylce. It also shows that the solar radiation time in one cycle ranged from 12.10-12.31 hours per day. Solar radiation began to appear from 06.22 to 06.25 WIB during the experiments. The differences in total solar radiation were influenced by the state of the sky, such as clear, cloudy, or rain with bright sunlight.

Table 1 Weather conditions during experiments.

May 2016 Date	Cycle	Average ambient temperature (°C)	Average relative humidity (%)	Average wind speed (m/s)	Solar radiation time (hours)	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

Figure 6 shows the fluctuation of solar radiation intensity during 24 hours in which the maximum radiation occurred during the second cycle: 988.10 W/m^2 at 12.10 WIB. Based on the experimental data, the maximum solar radiation generally occurs at 11.54-13.25 WIB and the maximum air temperature at 12.41-14.45 WIB.

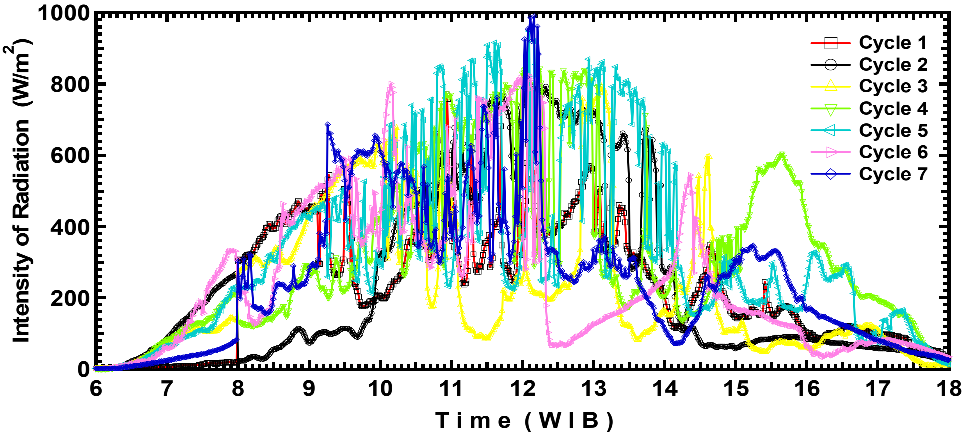

Figure 6 Solar radiation during seven cycles.

Figure 7 shows the typical and theoretical intensity of solar radiation during the fourth cycle.

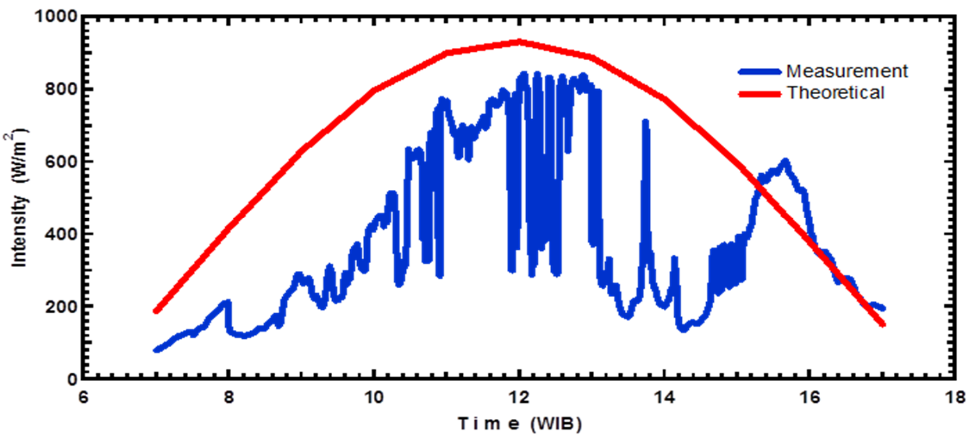

Figure 7 Intensity measurement and theoretical intensity during the fourth cycle.

The assumption of clear sky conditions was used for the theoretical calculations. The maximum solar radiation was 930.9 W/m2 at 12.00 WIB in the theoretical calculations while the maximum solar radiation measurement was 841.9 W/m2, occurring during the fourth cycle. The measurement of solar radiation was far below the theoretical calculation because of clouds obstructing the solar radiation. In general, the solar radiation measurements agreed well with the theoretical calculations. Figure 8 shows the effect of solar radiation intensity on the component temperature for the seventh cycle. The experimental data demonstrate that generation time was about nine hours through the day and the refrigeration process from cooling to adsorption lasted about fifteen hours. The variations in collector temperature followed the solar radiation pattern, which depends on the solar radiation level.

The heating process that followed the desorption process made the collector temperature increase until it reached the maximum temperature of 100.63 °C. The experiment also showed that a higher total solar radiation will lead to a lower evaporator temperature, which is due to the increase of desorbed adsorbate from the adsorbent. During the experiment also measurements were carried out of the operating pressure that occurred in the solar adsorption refrigerator. The results show that the operating pressure in the refrigerator varied from 0.0521 to 0.3314 bar.

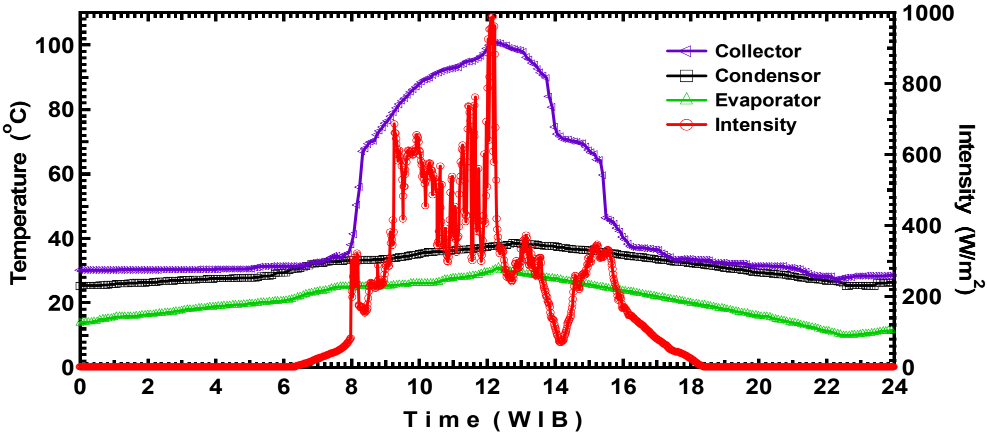

Figure 8 Effect of solar radiation on the component temperature.

Figure 9 shows the actual P-T diagram of the seventh cycle, which represents the working process of the solar adsorption refrigerator. The heating process starts from point A at 08.00 WIB local time where the adsorbent was at low temperature and low pressure. The A-B process is the heating process that follows the desorption process B-C, taking place in the afternoon, where the collector receives heat energy so that the collector temperature increases, followed by a pressure increase.

The desorption process made the collector temperature increase until it reached the maximum temperature of 100.63 °C, when the solar radiation maximum was 988.10 W/m^2 at 12.10 WIB local time, followed by pressure increasing to 0.3314 bar, causing adsorbate evaporation.

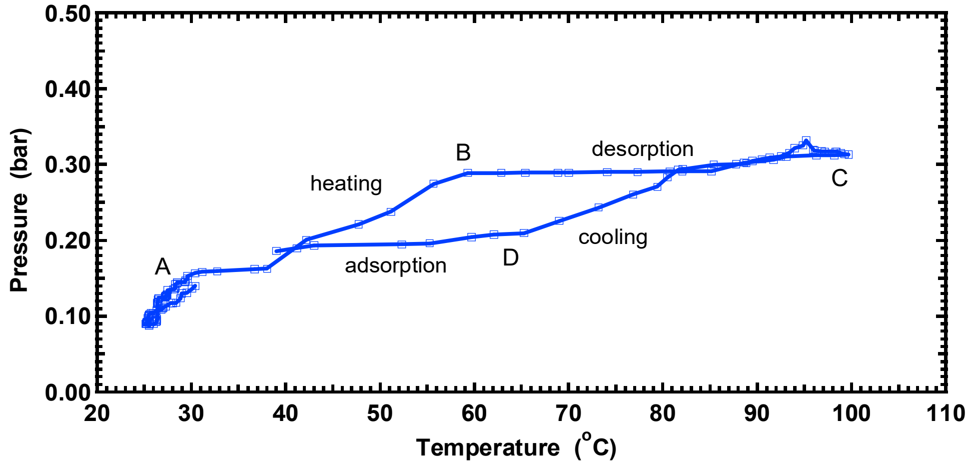

Figure 9 The actual P-T diagram for the seventh cycle.

During the cooling process C-D and the 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 underwent a decrease in temperature until it reached the minimum temperature of 25.08 °C at 02.00 WIB, followed by a pressure decrease causing adsorbate evaporation. In order to evaporate, the adsorbate adsorbs heat from the water around the evaporator as much as the latent heat of the adsorbate vapor. The cycle is intermittent because the adsorption process happens only during the night.

Table 2 shows the water temperature and evaporator temperature during the experiments. The evaporator temperature that could be achieved during these experiments in the adsorption process was 2.81-13.61 °C with the temperature of the heat source ranging 81.02-100.63 °C. The total global solar energy incident on the collector area ranged from 0.6702-0.9794 kWh during the experiments.

Table 3 shows the values of COP and SCP obtained during the experiments. It appears that the fluctuating value of the COP was always followed by the value of SCP. The experimental data on this solar refrigerator show the COP to be in the range of 0.0827-0.1271, while the solar energy total was between 2.681 and 3.917 kWh/m^2.

Table 2 Water temperature and evaporator temperature during experiments.

Cycle	Evaporator temperature (°C)		Water temperature (°C)	
	Max	Min	Max	Min
1	24.50	13.50	25.76	14.73
2	25.03	11.54	26.28	12.77
3	24.19	13.61	25.44	14.84
4	26.82	2.81	27.90	4.09
5	26.52	4.89	27.76	6.10
6	24.69	11.92	25.94	13.15
7	25.91	9.82	27.16	11.04

Table 3 Values of COP and SCP obtained during experiments.

Cycle	COP values	SCP values (kW/kg)
1	0.0840	0.01840
2	0.0929	0.01848
3	0.0827	0.01839
4	0.1271	0.01883
5	0.1169	0.01876
6	0.0881	0.01846
7	0.1089	0.01857

The cooling capacity for each kilogram of adsorbent mass or SCP obtained ranged from 0.01839-0.01883 kW/kg. Based on the analysis carried out, the main parameters that affected the performance of the solar adsorption refrigerator were: total solar radiation, collector performance, and the vacuum process. The heat received by the collector was eventually not optimum and also required improving the cooling of the collector. As noted, a solar adsorption refrigerator using methanol has normal operating pressure ranging from 0.02-0.2 bar [16]. The operating pressure of the refrigerator under testing was obtained at about 0.0521-0.3314 bar. This condition means that the operating pressure of the adsorption refrigerator being tested was not fulfilled as expected. This was mainly caused by the vacuum process still not being optimal, which resulted 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 refrigerator. As is known, the average micropore size of the adsorbent is capable of adsorbing not only adsorbate, but also unwanted gases such as leaked air. It is assumed that the unwanted gases occupy part of the microporous surface of the adsorbent otherwise available for adsorption. The presence of unwanted gases that have much higher saturated pressure than the adsorbate at the same temperature will destroy the vacuum and diminish the performance of the solar adsorption refrigerator [16]. Less adsorbate is adsorbed by the adsorbent than without the presence of unwanted gases.

If the unwanted gases are desorbed before the adsorbate, more adsorbent micropores become available for adsorption of adsorbate during the heating process. The operating pressure will keep increasing as the collector temperature increases because the unwanted gases cannot be condensed. Consequently, when there are unwanted gases in the system, a higher maximum collector temperature is needed to generate the same amount of adsorbate as without the presence of unwanted gases. The amount of desorbed adsorbate will be smaller than before if the maximum collector temperature is the same. Table 4 shows the collector efficiency obtained during the experiments. The maximum collector efficiency obtained was 51.46% when maximum solar radiation was 998.10 W/m^2.

Table 4 Values of collector efficiency during seven cycles.

Cycle	Maximum solar radiation (W/m^2)	Ambient temperature (°C)	Wind speed (m/s)	Collector efficiency
1	770.60	31.94	1.53	0.3464
2	793.10	33.13	1.62	0.4075
3	791.90	34.89	1.51	0.3932
4	841.90	35.10	1.33	0.4788
5	948.10	33.97	0.92	0.4903
6	824.40	32.79	1.57	0.4196
7	988.10	34.47	1.07	0.5146

Table 5 shows that there was a significant correlation between collector efficiency and solar radiation intensity 0.903. In addition, also the effect of the weather on the collector efficiency was examined by using multiple regression analysis. The coefficient of determination (R^2) was 0.9046, which means that the effect of weather conditions on collector efficiency was about 90.46%.

Table 5 Correlation of weather parameters on efficiency collector.

Data	Maximum radiation	Ambient temperature	Wind speed	Collector efficiency
Maximum radiation (W/m^2)	1			
Ambient temperature (°C)	0.418	1		
Wind speed (m/s)	-0.917	-0.443	1	
Collector efficiency	0.903	0.642	-0.818	1

Table 6 shows the correlation between the total solar radiation received by the collector against collector efficiency and the COP value. It is obvious that the correlation of solar radiation was totaled against collector efficiency and COP, namely 0.711 and 0.933 respectively. It shows that the total solar radiation received by the collector had significant influence on collector efficiency and COP value obtained.

Table 6 Correlation of total solar radiation total on collector efficiency and COP.

Parameter	Solar radiation total	Collector efficiency	COP
Total solar radiation (kWh/m^2)	1		
Collector efficiency	0.711	1	
COP	0.933	0.841	1

4 Conclusions

An experimental investigation was carried out to analyse the performance of an adsorption refrigerator driven by a solar collector using Indonesian granular activated carbon. According to the experimental data, the performance was mainly influenced by: total solar radiation, collector efficiency, and the vacuum process. In this research, the maximum COP value obtained was 0.1276 and the minimum value obtained was 0.0830. The maximum SCP value obtained was 0.0189 kW/kg and the minimum value obtained was 0.0185 kW/kg. The experimental results also showed that the working pair system could deliver an evaporator temperature of about 2.81-13.61°C. It was found that the granular activated carbon from coconut shell produced in Sumatera Utara province of Indonesia with methanol as a working pair could produce a cooling effect in a solar adsorption refrigerator with a temperature heat source ranging between 81 and 100 °C.

Acknowledgements

The authors wish to acknowledge Professor Hideki Kawai from the Department of Mechanical Systems of Engineering, Muroran Institute of Technology, Japan for his helpful comments during the research.

Nomenclature

A	=	collector area (m^2)
c_{pw}	=	specific water heat (kJ/kg °C)
COP	=	coefficient of performance
I_t	=	total solar radiation (kJ/m^2)
L_w	=	latent water (kJ/kg)
m_a	=	adsorbent mass inside the collector (kg)
m_w	=	water mass (kg)
Q_{cool}	=	cooling effect (kJ)
Q_{solar}	=	solar energy received by collector (kJ)
SCP	=	specific cooling power (W/kg)
T_c	=	cycle time (seconds)
$T_{w\text{-}max}$	=	maximum water temperature (°C)
$T_{w\text{-}min}$	=	minimum water temperature (°C)

W_L = cooling power (kW)

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