Case Studies in Thermal Engineering 7 (2016) 36–46

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Experimental study on solar-powered adsorption refrigeration cycle with activated alumina and activated carbon as adsorbent

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ARTICLE INFO

Article history:
Received 14 November 2015
Received in revised form
19 January 2016
Accepted 25 January 2016
Available online 26 January 2016

Keywords:
Solar energy
Adsorption cycle
Activated alumina
Activated carbon

ABSTRACT

Typical adsorbent applied in solar-powered adsorption refrigeration cycle is activated carbon. It is known that activated alumina shows a higher adsorption capacity when it is tested in the laboratory using a constant radiation heat flux. In this study, solar-powered adsorption refrigeration cycle with generator filled by different adsorbents has been tested by exposing to solar radiation in Medan city of Indonesia. The generator is heated using a flat-plate type solar collector with a dimension of 0.5 m × 0.5 m. Four cases experiments of solar-powered adsorption cycle were carried out, they are with generator filled by 100% activated alumina (named as 100AA), by a mixed of 75% activated alumina and 25% activated carbon (75AA), by a mixed of 25% activated alumina and 75% activated carbon (25AA), and filled by 100% activated carbon. Each case was tested for three days. The temperature and pressure history and the performance have been presented and analyzed. The results show that the average COP of 100AA, 75AA, 25AA, and 100AC is 0.054, 0.056, 0.06, and 0.074, respectively. The main conclusion can be drawn is that for Indonesian condition and flat-plate type solar collector the pair of activated carbon and methanol is the better than activated alumina.

1. Introduction

In some remote areas of Indonesia, there are many villages where electricity is presently unavailable or far from sufficient. Such areas need refrigeration machine in order to preserve foods and vaccines. Most of the refrigeration machines currently in service based on vapor compression cycle which is powered by electricity. On the other hand, Indonesian archipelagos are located around equator. Such areas receive solar radiation constantly for entirely year and long sunshine hours. According to measurements and predictions, for clear sky radiation total solar energy in Indonesian archipelagos can vary from 16 to 18 MJ/m^2 per day [1,2]. Therefore, the solar-powered refrigeration machine for harvesting the abundant solar thermal energy in order to preserve foods and vaccines is a promising application for those areas. Thus, solar-powered refrigeration machine is an interesting topic to be studied and very applicable for Indonesian remote areas.

Many researchers have been reported their works that dealt with producing cooling based on adsorption cycle powered by solar radiation. Pons and Guillminot [3] pioneered the research of solar-powered adsorption cycle to produce cooling. They designed and tested a solar-powered ice maker based on adsorption cycle. The solar collector is a flat plate type with

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http://dx.doi.org/10.1016/j.csite.2016.01.006

Nomenclature

A	altitude, km
AA	activated alumina
AC	activated carbon
a_0	a constant for atmospheric transmittance
a_1	a constant for atmospheric transmittance
B	a parameter for solar time
COP	coefficient of performance
c_p	specific heat, kJ/kg K
E	the equation of time, minute
G	solar radiation, W/m^2
H	heat of desorption, kJ/kg
I	total solar intensity, W/m^2
k	a constant for atmospheric transmittance
L	latent heat, kJ/kg
L_{st}	standard meridian for the local time zone, for Medan city 105°
L_{loc}	longitude of the experiment location, 98°
m	mass, kg
P	pressure, mbar
ST	solar time
STD	standard time
Q	energy, kJ
T	temperature, °C or K
t	time, sec
tss	time at sunset, sec
tsr	time at sunrise, sec
x	concentration of adsorbed methanol, kg/kg

Greek symbol

α	absorbance
δ	declination angle, °
ε	emissivity
τ_g	glass transmittance
τ	atmospheric transmittance, –
θ_z	azimut angle, °
φ	latitude angle, °
ω	hour angle, °

Subscripts

1, 2, 3,4	points on Clapeyron diagram
ad	adsorbent
amb	ambient
b	beam radiation
con	condenser
eva	evaporator
gen	generator
m	methanol
on	extraterrestrial
sur	surrounding
tot	total

collector area of 6 m^2. It is loaded with 130 kg activated carbon and 18 kg of methanol as refrigerant. The machine was tested by exposing to solar radiation in Orsay, France with latitude 48 °N. The solar radiation varied from 19–22 MJ/m^2/day. It was reported that their refrigeration machine can produce 30–35 kg of ice per day. Li et al. [4] carried out analysis and performance testing of a solar-powered refrigeration machine. The solar collector consists of two flat-plates with area of 1.5 m^2. The generator is loaded with activated carbon and evaporator is filled with methanol as refrigerant. Performance testing was carried out in laboratory by exposing the collector to quartz lamps as a solar simulator. By using radiation of 28–30 MJ, the refrigeration machine can produce ice of 7–10 kg ice.

Khattab [5] studied a small scale of solar-powered adsorption cycle. A prototype is designed, fabricated and tested in Cairo (30 °N). The local produced activated carbon and methanol were used. In order to enhance the heat transfer rate in the activated carbon grains are mixed with small pieces of blackened steel. Test results showed that the generator bed temperature is above 100 °C was found to be 5 h with a maximum temperature of 120 °C in winter. In summer, the corresponding values 6 h and 133 °C. The daily ice production was claimed to be 6.9 and 9.4 kg/m^2 and COP is 0.13 and 0.159 for winter and summer climate, respectively. Li et al. [6] developed a solar-powered ice maker with no valve. The used collector is flat plate type with area of 1 m^2 and it contains 19 kg activated carbon produced in China. The machine was tested by exposing directly into solar radiation of 18–22 MJ/m^2/day. The results showed that it can produce ice about 5 kg.

Literature review shows that there are several drawbacks in the solar-powered adsorption refrigeration cycle [7] and those are mainly in generator. Among the problems are: adsorption and desorption process is yet unknown perfectly, low heat transfer rate from the absorber plate into adsorbent layer, and low adsorption capacity of the adsorbent. Typical adsorbents in an adsorption refrigeration cycle can be divided into physical adsorbents and chemical adsorbents. Physical adsorbents such as activated carbon, zeolite, and silica gel. Chemical adsorbents are metal chlorides, salt and metal hydrates, and metal oxides. In order to enhance the heat transfer coefficient and adsorbent capacity, some researchers [8,9] made compound adsorbents, such as a combination of activated carbon and metal chlorides or combination silica gel and chemical adsorbent. To the present, activated carbon is the most used adsorbent for solar-powered adsorption refrigeration cycle. However, its performance is yet not satisfied and it needs improvements.

Adsorption capacity of the working pairs is one of the key on development high performance solar-powered adsorption refrigeration cycle. Shmroukh et al. [10] reported a literature review on adsorption working pair for adsorption cooling chiller. Their review based on adsorption capacity and environmental impact of both classical and modern adsorption refrigerant pairs. The results showed that maximum adsorption capacity for classical working parking pairs was 0.259 kg/kg for activated carbon methanol pair. It was suggested that further investigations are still needed to improve the performance of adsorption working pairs of adsorption refrigeration cycle as well as to develop the adsorption pairs with high sorption capacity in order to build compact, efficient, reliable, and long-life adsorption chiller. Ambarita et al. [11] performed a study on adsorption characteristics of several adsorbent–refrigerant pairs. The pairs were activated alumina and activated carbon with ammonia, methanol, and ethanol as refrigerants. The experiments were conducted using electric lamp of 1000 W to simulate solar radiation. It was concluded that the adsorption capacity of activated alumina is higher than activated carbon and the best refrigerant is methanol. The pair of activated alumina and methanol is recommended for adsorption refrigeration cycle for solar application. However, the results are not tested yet for direct solar radiation.

In this work, solar-powered refrigeration with the generator loaded by activated carbon and activated alumina as adsorbent and methanol as refrigerant will be studied experimentally. The adsorption cycle will be tested in the field by exposed with direct solar radiation in Medan city. The characteristics and the performance of the refrigeration cycle will be compared for each adsorbent type. The main objective here is to explore the best adsorbent for adsorption refrigeration cycle, if it is tested with solar radiation. As a note solar radiation is strongly affected by location. To the best knowledge of the authors, there is no study report of field tested solar-powered adsorption refrigeration cycle in Indonesia has been found in literature. The results of this study are expected to supply the necessary information in development of solar-powered adsorption refrigeration cycle in Indonesia.

2. Method and experimental apparatus

2.1. Working principle

The working principle of a solar-powered adsorption cycle can be explained by using Clapeyron diagram as shown in Fig. 1. It consists of isosteric heating, isobaric desorption, isosteric cooling, and isobaric adsorption. The cycle starts at point 1 where the refrigerant is absorbed in the adsorbent.

The total energy gained by the system during the heating period is the sum of energy from 1 to 2 (Q_{12}) and energy from 2 to 3 (Q_{23}). As a note Q_{12} is energy needed to raise the temperature of the adsorbent and refrigerant (isosteric heating) and

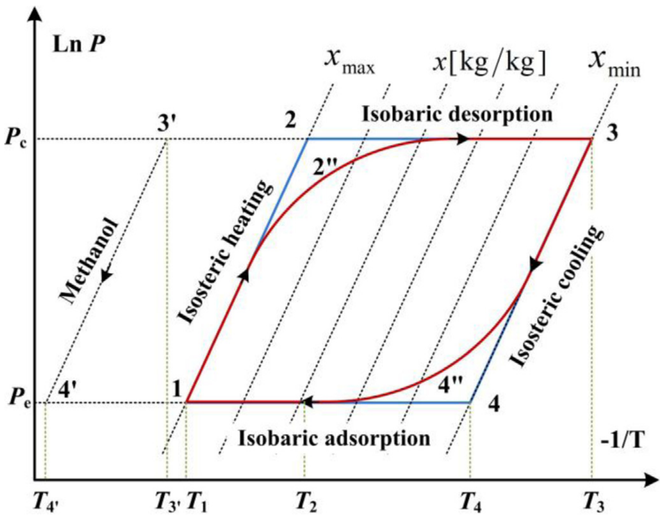

Fig. 1. The Clayperon diagram of the adsorption refrigeration cycle.

Table 1
Characteristics of methanol and adsorbent.

Parameter	Value
Specific heat at liquid methanol	$c_{p\,l}$=2534 J/kgK
Specific heat at vapor methanol	$c_{p\,v}$=1820 J/kgK
Density of liquid methanol	ρ=791 kg/m^3
Heat of evaporation of methanol	L=1102 kJ/kg
Heat adsorption of methanol	H=1400 kJ/kg
Density of activated carbon	ρ_{AC}=420 kg/m^3
Specific heat of activated carbon	c_{pAC}=920 J/kgK
Density of activated alumina	ρ_{AA}=800 kg/m^3
Specific heat of activated alumina	c_{pAA}=1000 J/kgK

Q_{23} is the energy needed for progressive heating of the adsorbent and for desorption process. These energies can be calculated using the following equations:

$$Q_{12} = (m_{ad}c_{p\ ad} + m_m c_{p\ m}) \times (T_2 - T_1) \tag{1}$$

$$Q_{23} = \left[m_{ad}c_{p\ ad} + c_{p\ m}(m_{m-1} + m_{m-3})/2 \right] \times (T_3 - T_2) + (m_{m-1} - m_{m-3})\,H \tag{2}$$

where H [kJ/kg] and c_p [kJ/kgK] are heat adsorption and specific heat capacity, respectively. The subscribe *ad* and *m* stand for adsorbent and methanol, respectively. During night or cooling period, the gross heat released during the cooling period will be the energy of vaporization of methanol, it is calculated by:

$$Q_e = (m_{m-1} - m_{m-3}) \times L \tag{3}$$

where L [kJ/kg] is the latent heat of evaporation of methanol. The characteristics of the activated carbon, activated alumina and methanol as refrigerant are given in Table 1.

The total heat collected from the solar radiation is calculated by equation:

$$Q_{rad} = \int_{tsr}^{tss} I\, dt \tag{4}$$

where *tsr* and *tss* are time at sunrise and time at sunset, respectively. Solar radiation intensity I [W/m^2] is the data collected from measurement of HOBO micro station data logger. In order to make a comparison, the theoretical one is calculated using clear sky radiation. The following equation is used to calculate the clear sky radiation [12].

$$G_{tot} = G_{on} \cos\theta_z [\tau_b + 0,271 - 0,294\tau_b] \tag{5}$$

where G_{on} is extraterrestrial radiation, θ_z is zenith angle, and τ_b is the atmospheric transmittance for beam radiation. The zenith angle is calculated by the following equation:

$$\cos\theta_z = \cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta \tag{6}$$

where φ=3°34′ is the latitude in at Medan city, δ is declination angle depend on the day measured, and ω is hour angle. The declination angle is calculated by the following equation.

$$\delta = 23,45 \sin\left(360\frac{284 + n}{365}\right) \tag{7}$$

where n is the day of the year. The hour angle is calculated by:

$$\omega = 15(STD - 12) + (ST - STD) \times \frac{15}{60} \tag{8}$$

where STD is standard time and ST is solar time. The solar time is calculated by:

$$ST = STD - 4(L_{st} - L_{loc}) + E \tag{9}$$

where L_{st} is the standard meridian for the local time zone and L_{loc} is longitude of the location. The parameter E is the equation of time and calculated by the following equation.

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B \tag{10}$$

and B is given by

$$B = (n - 1)\frac{360}{365} \tag{11}$$

The atmospheric transmittance for beam radiation is calculated by:

$$\tau_b = a_0 + a_1 \exp\left(\frac{-k}{\cos\theta_z}\right) \tag{12}$$

where

$$a_0 = r0\left(0.4237 - 0.00821(6 - A)^2\right) \tag{13}$$

$$a_1 = r1\left(0.5055 + 0.00595(6.5 - A)^2\right) \tag{14}$$

$$k = rk\left(0.2711 + 0.01858(2.5 - A)^2\right) \tag{15}$$

As suggested by Hottel [13], for Medan city the parameters in the above equations are $r0 = 0.95$, $r1 = 0.98$, and $rk = 1.02$. The altitude of the present experimental apparatus is A=0.02 km.

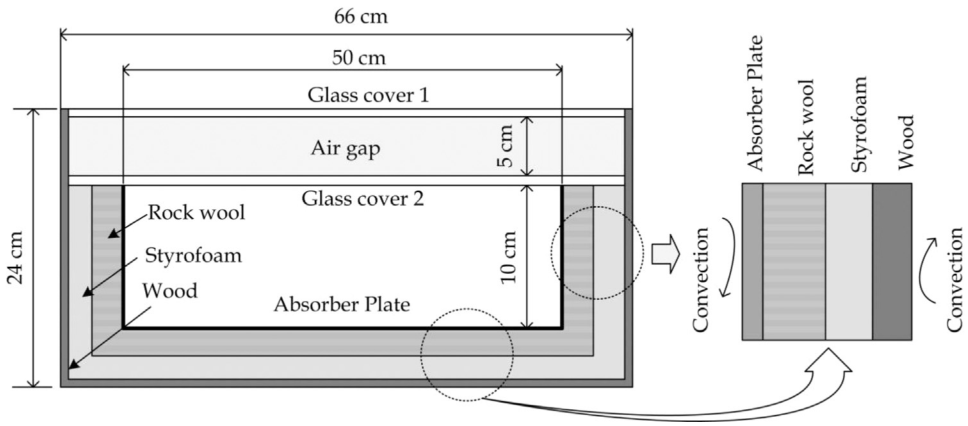

Fig. 2. Solar collector and its main dimensions.

Table 2
Characteristics of the solar collector.

Parameter	Value
Glass cover transmittance	τ=0.9
Collector absorbance	α=0.92
Thermal conductivity of the glasses	k_g=0.96 W/m K
Thickness of the glasses	d_g= 5 mm
Thermal conductivity of the absorber plate	k_{ab}=14.9 W/m K
Thickness of the absorber plate	d_{ab}= 2 mm
Thermal conductivity of the wood	k_w=0.19 W/m K
Thickness of the wood	d_w=2 cm
Thermal conductivity of the rock wool	k_{rw}=0.042 W/m K
Thickness of the rock wool	d_{rw}=4 cm
Thermal conductivity of the styrofoam	k_{st}=0.036 W/m K
Thickness of the styrofoam	d_{st}=2.5 cm

Performance of a refrigeration cycle can be evaluated by using several parameters such as refrigeration effect, cooling capacity, etc. The most common used is the Coefficient of the Performance (COP). This is a ratio of cooling load and energy input from the heat source. In this work, net solar COP is used to compare the performance of the tested refrigeration cycle. The solar COP is defined as heat released during the cooling period divided by total solar energy received by solar collector. The solar COP is calculated by:

$$COP = \frac{Q_e}{Q_{rad}} \tag{16}$$

2.2. Experimental apparatus

In order to perform the experiments, a lab scale model of solar-powered adsorption refrigeration cycle as an experimental apparatus has been designed and fabricated. The main components are solar collector, generator, condenser, and evaporator. In this study, the simplest solar collector is employed to collect the solar radiation. The type of solar collector is flat-plate with collector dimension of 0.5 m × 0.5 m and it is sloped at an angle of 30°. The main dimensions and material of the present solar collector were presented in Fig. 2. The side walls and the bottom of the solar collector are made of steel plate, rock wool, styrofoam, and wood. In order to reduce the heat losses from the top, two glasses covers are used. Physical properties and dimension of the solar collector material are presented in Table 2.

The generator placed beneath the solar collector and it is loaded with 6 kg of adsorbent. In order to reduce heat losses to atmosphere, the solar collector is covered by double glasses cover. The condenser is made of a heat exchanger where the refrigerant vapor inside the pipes and outside is a series of plate fins cooled by ambient natural convection. The evaporator is a container made of steel and water is used as a cooling load.

Data acquisition system is also installed to the experimental apparatus. Temperatures are measured by using *J*-type thermocouples with uncertainly equal to 0.1 °C. The number of thermocouple is 20, which are six thermocouples placed in collector, six in evaporator, and the rests in the condenser. Agilent 34,972, multi channel data logger is used to record

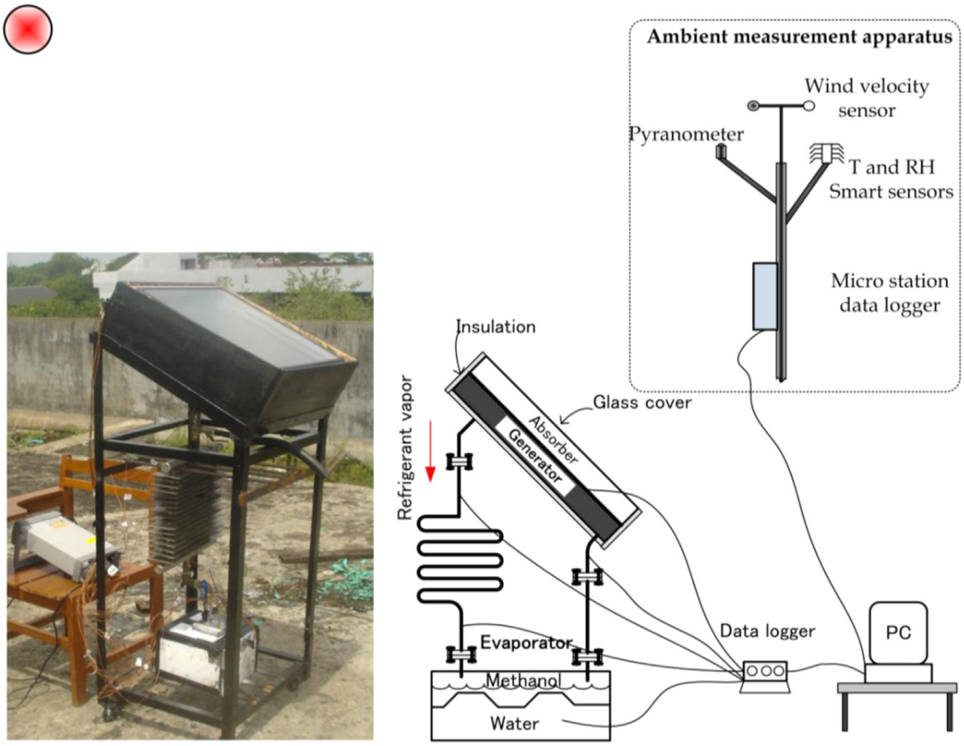

Fig. 3. Experimental apparatus and data acquisition system. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

temperatures with interval of 1 min. In order to measure the pressure inside the generator, Pace XR5 Data logger with a pressure sensor type P1600-vac-150 was used. Solar radiation is measured using HOBO pyranometer smart sensor. The ambient temperature and relative humidity (RH) is measured using HOBO temperature RH smart sensor with an accuracy of 0.2 °C and ±2.5% RH, respectively. The wind speed around the experimental apparatus is measured with HOBO wind speed smart sensor with accuracy ±1.1 m/s. The schematic diagram, data acquisition system, and photograph of the experimental apparatus are shown in Fig. 3.

2.3. Methods

After fabricated, the experimental apparatus was preliminary tested in order to make sure it is free of leakage. The apparatus was vacuumed and left for two days. After tested, the apparatus loaded by refrigerant. It is heated up to 120 °C. While the temperature is kept constant and valve for evaporator is closed, it is evacuated by using a vacuum pump for 30 min. After 30 min, the valve for evaporator is opened gradually. The vacuum pump will be stopped when the refrigerant starts to boil in the evaporator. Here, the apparatus is ready to be used.

In this study four types of adsorbents which are consist of activated alumina and activated carbon will be tested experimentally. The experiments were divided into 4 cases. For all cases all of the experimental components are the same, except the generator filled with different adsorbent. In the first case the generator was filled with activated alumina only as adsorbent and it is named as 100AA. In the second case the generator was filled with a mixed adsorbent of 75% activated alumina and 25% activated carbon, named as 75AA. In the third case the generator was filled with a mixed with 25% activated alumina and 75% activated carbon, named as 25AA. And in the last case the generator was filled with a uniform 100% Activated carbon as adsorbent, named as 100AC.

One cycle of the solar-powered adsorption cycle is 24 h. It consists of sunshine hours in daytime and off-sunshine hours in nighttime. Thus one day of experiment means daytime and nighttime. For each case, the solar-powered adsorption refrigeration was tested in the field for three days. Temperatures, pressure, evaporated methanol, solar radiation, and ambient temperature were measured and recorded using the data acquisition system.

3. Results and discussions

As mentioned in the previous section, there were four cases and each case will be tested for three days. Thus a total of 12 days of experiments were carried out. All of the experiments have been carried out during April to May 2015 at a place in

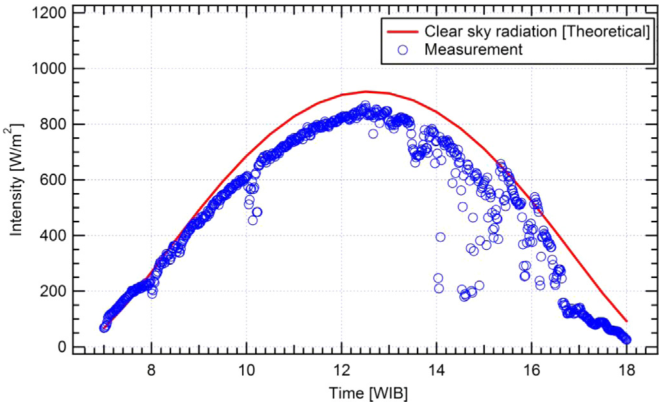

Fig. 4. Solar radiation in Medan city at April 20.

Medan city, Indonesia with geographic coordinate 3°34′ North and 98°40′ East. Every experiment starts from 8.00 a.m. local time and finishes at 6.00 a.m. in the next day. As a note local time in Medan city is WIB, stands for Indonesian West Part. The results will be presented and analyzed as follows. In the first section the characteristics of solar radiation during experiments will be presented discussed. In the second section the characteristics of the solar-powered refrigeration cycle will be compared for each case. Here only one sample will be presented. In the last section, the performance for all of the experiments will be compared. Then the conclusions will be drawn.

3.1. Characteristics of solar radiation in Medan city

Typical solar radiation in Medan city where the experiments carried out is shown in Fig. 4. The measurement was taken for April 20th, 2015. In the figure clear sky radiation calculated theoretically is also shown by red line. The figure shows that there is a bit differences between the theoretical and measured one. In the theoretical one, the maximum solar radiation is 916 W/m^2 at 12.30 WIB. On the other hand, the measured one is 868 W/m^2 at 12.30 WIB. Some measured solar irradiation way below the theoretical one. This is because of the cloud blocks the beam radiation. In general the measured solar irradiance agrees well with theoretical one. By using Eq. (4), the total solar energy during measurement is 17.64 MJ/m^2. The same method had been used to measure the total solar energy radiation during the experiments. All of the measured solar radiations are not presented as shown in Fig. 4. However, the total solar radiations for all measured days were presented in Table 3. The total solar energy radiation varied from 11 MJ/m^2 to 17 MJ/m^2 during experiments. These values will be used to calculate the solar COP in Eq. (16).

Table 3
Performance of Solar-powered adsorption refrigeration cycle.

Day	Generator Temp. [°C]		Evaporator Temp. [°C]		Pressure [mm Hg]		Ambient Temp. [°C]		Rad. [MJ/m^2]	Solar COP
	Max	Min	Max	Min	Max	Min	Max	Min		
Generator filled by 100AA										
I	98.4	23.6	25.9	11.2	144.6	51.4	34.7	23.67	13.42	0.058
II	108.1	23.6	21.3	11.3	157.9	46.6	36.2	23.62	17.64	0.059
III	87.8	24.3	22.9	11.18	144.69	39.41	34.5	24.39	11.32	0.046
								Average	14.13	0.054
Generator filled by 75AA										
I	97.0	24.3	20.8	12.7	143.66	57.9	37.18	24.14	13.43	0.054
II	107.8	24.4	17.9	10.0	151.8	51.6	38.24	24.02	17.86	0.058
III	80.9	22.4	17.9	10.0	130.6	51.06	37.39	22.18	12.24	0.056
								Average	14.51	0.056
Generator filled by 25AA										
I	95.1	24.7	21.99	13.7	144.6	51.4	36.66	24.71	12.42	0.058
II	97.6	23.4	21.2	8.2	144.7	51.4	38.47	23.01	12.86	0.069
III	95.4	23.5	22.9	11.0	144.7	51.4	35.23	23.49	12.32	0.053
								Average	12.53	0.06
Generator filled by 100AC										
I	110.1	24.2	21.3	6.03	157.9	46.4	37.45	24.2	17.42	0.085
II	77.9	21.4	22.9	9.69	150.8	51.4	36.36	21.42	11.46	0.065
III	97.9	21.3	21.9	7.3	150.9	51.4	38.04	21.38	12.02	0.071
								Average	13.63	0.074

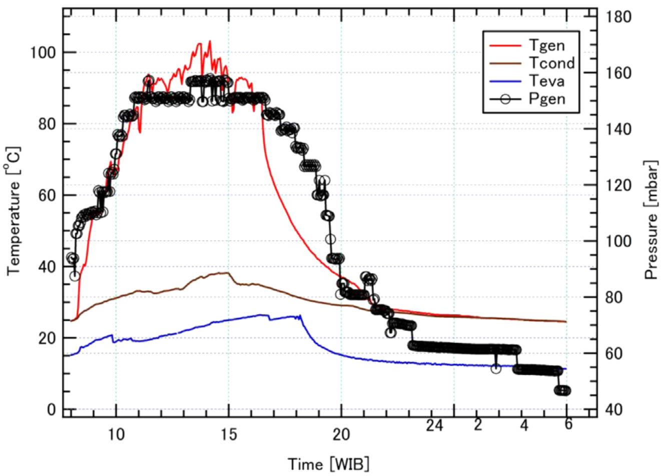

Fig. 5. Temperature and pressure history for 100AA case. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

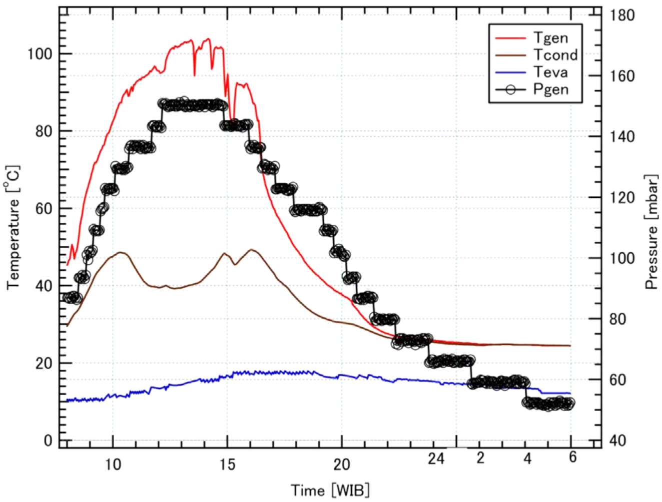

Fig. 6. Temperature and pressure history for 75AA case. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3.2. Temperature and pressure in experimental apparatus

The characteristics of the solar-powered adsorption cycle will be discussed in term of temperature and pressure. The temperature and pressure histories in the experimental apparatus during experiments are shown in the figures below. They are Figs. 5–8 for 100AA case, 75AA case, 25AA case, and 100AC case, respectively. Here, only measurements from the second day of experiments are shown in the figures. In each figure, temperature in generator, condenser, and temperature in evaporator are shown by red, brown, and blue line, respectively. The pressure in the apparatus is shown by black line with circle mark.

As explained in the previous section, an ideal adsorption cycle consists of four processes. They are isosteric heating, isobaric desorption, isosteric cooling, and the last one is isobaric desorption. Fig. 5 shows all of theses process for 100AA case. The cycle starts from 8.00 a.m.. Since the solar collector receive solar radiation, the temperature increase as time increase. The isosteric heating starts at 8.00 and it finishes at 13.30. After that, desorption occurs at a constant pressure (desorption isobaric). The figure shows that the desorption pressure is 156 mbar. The isobaric desorption finishes at 14.00. In afternoon, the solar radiation and ambient temperature decrease as time increase. Since there is no sufficient solar energy source for heating and ambient temperature also decreasing, the cycle falls into isosteric cooling. Here, the temperature and pressure in generator decrease as time increases. It can be seen that the isosteric cooling starts from 14.00 until 23.00. In the last process, the isobaric adsorption occurs at 60 mbar. Here, the refrigerant evaporates and results in cooling effect. The refrigerant vapor flows to generator and absorbed by absorbent. Then the cycle repeats for the next days. The pressure

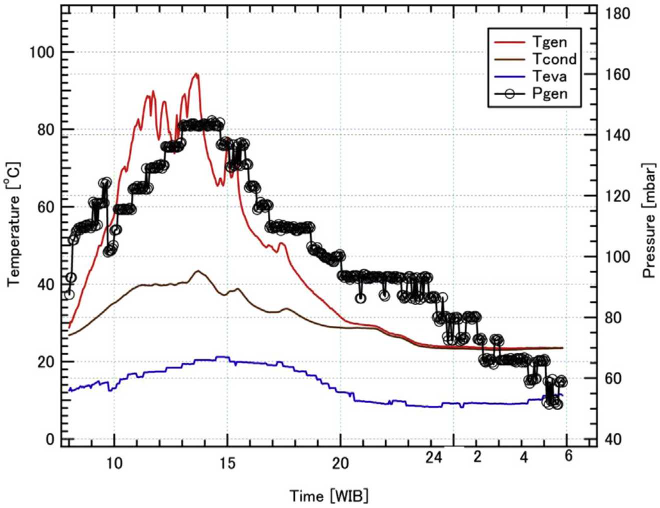

Fig. 7. Temperature and pressure history for 25AA case. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

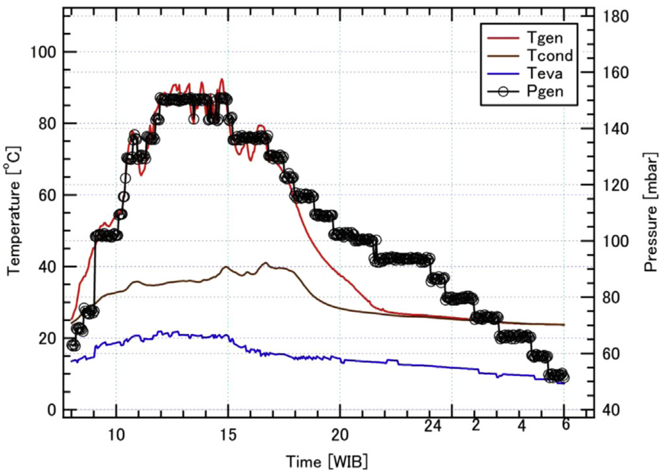

Fig. 8. Temperature and pressure history for 100AC case. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

history shows that desorption and adsorption processes occurs at pressure 156 mbar and 60 mbar, respectively. The lowest temperature can be reached in evaporator is 11.2 °C. Similar trends are shown by other cycles but with different values. The lowest temperatures in evaporator for the other cycles are 11.3 °C and 11.18 °C, respectively.

Fig. 6 shows the temperature and pressure history for 75AA case. The figure shows that the isosteric heating finishes at 12.00 and followed by isobaric desorption which finishes at 15.00 WIB. The isobaric desorption occurs also at 150 mbar. The isosteric cooling finishes at 23.00 WIB. However, the isobaric desorption occurs at several pressures. It can be seen, at 70 mbar, 60 mbar, and 50 mbar. The minimum temperature can be reached in the evaporator is 10.0 °C. The similar trends are also shown by other two cycles. The minimum temperatures in the evaporator are 10.0 °C and 12.7 °C, respectively. These are relatively lower than cycle with generator filled by 100AA adsorbent.

For adsorption cycle for generator filled by adsorbent 25AA, typical temperature and pressure history is shown in Fig. 7. The figure shows that the isosteric heating finishes at 13.00 and followed by isobaric desorption which finishes at 14.30 WIB. The isobaric desorption occurs at 145 mbar which is lower than previous cases. The isosteric cooling finishes at 20.00 WIB. The isobaric desorption also occurs at several pressures, at 90 mbar and at 70 mbar. For this cycle, the minimum temperature can be reached in evaporator is 8 °C. The similar trends are also shown by other two cycles. This is relatively lower than cycle with generator filled by 100AA and 75AA adsorbents.

Fig. 8 shows the temperature and pressure history in the experimental apparatus for generator filled by 100AC. The similar trend but different in values was also shown. The isosteric heating finish at 12.00 and followed by isobaric desorption which is finish at 15.00 WIB. The isobaric desorption occurs also at 150 mbar. The isosteric cooling finishes at 23.00 WIB. The minimum temperature can be reached in evaporator is 6 °C. The isobaric desorption also occurs at several pressures. Similar trends are also shown by other cycles but with different values. The minimum temperatures in the evaporator are 7.3 °C and 9.69 °C, respectively. These are relatively lower than previous cases.

The comparison of those figures shows that the isobaric desorption of 100AA is relatively higher than the others. On the other hand, 100AC shows the longest duration of desorption. This means the 100AC can release refrigerant more than 100AA. In addition, refrigeration effect in evaporator will be better. Ambarita et al. [11] suggested that adsorption capacity of activated alumina is higher than activated carbon and the best refrigerant is methanol. This is because the generator is heated by solar simulator with a constant intensity and higher temperature in absorber. In this study the generator is heated by solar energy which varies during day and results in a relatively low temperature in the generator. The maximum temperature that can be reached in the generator is around 100 °C. This is generally reached after 12.00 and then temperature will be decrease as solar radiation decrease with time increase. Since isobaric desorption pressure of 100AA is higher than 100AC, the amount of refrigerant released by 100AC is higher than 100AA. Thus, the cooling effect resulted by 100AC is higher than 100AA. In other word, for Indonesia condition, a solar-powered refrigeration cycle with a flat-plate type collector filled by 100AC is better than 100AA, 75AA, and 25AA.

3.3. Performance of the solar-powered adsorption cycle

The performances of all experiments are presented in Table 3. The parameters shown are the maximum and minimum temperatures on the generator surface, ambient temperature, and on the evaporator. Pressure in the experimental apparatus, total solar radiations, and solar COP are also presented in the table. It was shown that during the experiments, solar radiation was not constant. It is because affected by weather. Total daily solar radiation during experiments varied from 11.32 MJ/m^2 to 17.86 MJ/m^2. The results show that solar COP of the present solar-powered refrigeration cycle ranges between 0.046 and 0.085. In general, the COP of a solar-powered refrigeration cycle is lower than vapor compression cycle. This is because in the solar-powered refrigeration cycle, the form of energy input is heat, while in the vapor compression cycle the energy input is work through compressor. In addition, the temperature of heat source of the solar-powered adsorption cycle is very low. In this experiment, the heat source is solar energy. The solar energy is collected by solar collector and it is used to heat the generator. The heat is used to release the refrigerant from the generator. A higher temperature in generator can release more refrigerant from the adsorbent and result in more refrigerant collected in the evaporator. The more refrigerant in the evaporator means more cooling effect. Furthermore, all of the heat transfer and fluid flow mechanisms here are natural or free convection. Thus, these facts results in a low COP in comparison with vapor compression cycle.

In order to make a performance comparison, similar works found in literature will be used to validate these results. Lemmini and Errougani [14] reported a study on building and experimentation of solar powered adsorption refrigerator. The differences of their work with the present works are the type of evaporator and condenser, also the testing location. In their conclusion it was reported that COP ranges between 0.05 and 0.08 for solar radiation between 12 MJ/m^2 and 27 MJ/m^2 and daily mean temperature between 14 °C and 18 °C. In addition, Anyanwu et al. [15] reported a numerical study on solid adsorption solar refrigerator using activated carbon/methanol adsorbent/refrigerant pair. The effects of solar collector parameters such as pipe spacing, tube thickness, back insulation thickness, etc, to the solar COP have been explored. The solar COP varied from 0.02 to 0.06. This fact reveals that the present COP is within the range of results found in literature.

As a note a lower solar radiation leads to a lower generator temperature and it will influence the results. If the generators are filled with the same adsorbent, the lower solar radiation will lead to lower COP. For 100AA cases, when the total solar radiation was 11.32 MJ/m^2 the maximum temperature can be reached in generator is 87.8 °C and resulted in COP of 0.046. When the solar radiation increased to 13.42 MJ/m^2 the maximum temperature can be reached in generator is 98.4 °C and resulted in COP of 0.058. And for solar radiation of 108.1 MJ/m^2, the maximum temperature in generator is 108.9 °C and resulted in COP of 0.059. This suggests that a lower solar radiation leads to a lower COP. The same trends are also shown by other cases. The maximum temperature of ambient does not affect the performance strongly. This is because the maximum ambient temperature occurs in the desorption process. On the other hand, minimum ambient temperature will affect the performance of the adsorption cycle. A lower ambient temperature will result in a lower temperature in generator (during adsorption process). The lower temperature in the generator will lead to a lower pressure and higher adsorption capacity or higher refrigeration capacity. However, in this study the minimum ambient temperature does not vary significantly. For all cases, the minimum ambient temperature ranges between 21 °C and 24 °C. This is typical minimum ambient temperature for Medan city climate, since it is close to equator line.

There is an interesting phenomenon was captured here. For 25AA cases, total solar radiations were relatively lower in comparison with 100AA, 75AA, and 25AA. The average solar radiation for 100AA, 75AA, and 25AA are 14.13 MJ/m^2, 14.51 MJ/m^2, and 12.53 MJ/m^2, respectively. However, the COP of the refrigeration cycle with 25AA is higher than 100AA and 75AA. The average COP for 100AA, 75AA, and 25AA are 0.054, 0.056, and 0.06, respectively. This is because, the desorption temperature of activated alumina is higher than activated carbon. Even though, the solar radiation is relatively lower, since 25AA contains more activated carbon its performance is better than generator with less activated carbon.

In order to explore the effect of different adsorbent in the generator, the comparison among different cases will be made. The performance comparison for all cases will be made by using the average value of COP. The average COP for the cycle with generator filled by 100AA, 75AA, 25AA, and 100AC are 0.054, 0.056, 0.06, and 0.074, respectively. While the average solar radiation for 100AA, 75AA, 25AA, and 100AC are 14.13 MJ/m^2, 14.51 MJ/m^2, 12.53 MJ/m^2, and 13.63 MJ/m^2, respectively.

These facts reveal that even though solar radiations for 100AA and 75AA are higher than 25AA and 100AC, the COP of 25AA and 100AC are higher than 100AA and 75AA. This suggests that solar-powered refrigeration cycle with generator filled by activated carbon is better than with generator filled by activated alumina. Ambarita et al. [11] suggested that adsorption capacity of activated alumina is higher than activated carbon and the best refrigerant is methanol. That is because the generator was heated by solar simulator with a constant intensity and result in a high temperature in the generator. In this study, however, the generator is heated by solar energy which varies during day and results in a relatively lower temperature in the generator. As a result, the present solar collector heated by solar energy source can not take advantage of the high adsorption capacity of the activated alumina.

In addition, the results reveal that 100AC shows the highest average COP. The average COP and average solar radiation are 0.74 and 13.63 MJ/m^2, respectively. This suggests that solar-powered adsorption refrigeration cycle with pure activated carbon is better than activated alumina. A mixed adsorbent of activated alumina and activated carbon does not show a better COP than the pure activated carbon. Thus the mixed adsorbent of activated alumina and activated carbon is not suggested.

4. Conclusions

Experimental study on adsorption characteristics and performance of solar-powered adsorption refrigeration cycle with generator filled by activated alumina, activated carbon, and a mixed of activated alumina and activated carbon have been carried out. The experiments have been carried out by exposing the refrigeration cycle with solar radiation in Medan city of Indonesia. The generator is heated by a flat-plate type of solar collector. Every case was tested for three days. The characteristics and performance of the adsorption cycle have been analyzed. The conclusions are as follows. The maximum temperature in the generator is relatively low at around 100 °C. For all cases, the higher temperature in generator results in a better performance. Even though the adsorption capacity of activated alumina is higher than activated carbon, but for solar radiation as a heat source the pair of activated carbon is better. This is because the isobaric-desorption pressure of activated alumina is higher than activated alumina. The higher pressure needs higher temperature which will be difficult to be reached by a flat-plate type solar collector. The mixed adsorbent of activated alumina and activated carbon does not show a better COP than the pure activated carbon. Thus, for Indonesian condition and flat-plate type solar collector the pair of activated carbon and methanol is the better than activated alumina.

The COP resulted in the present study is very low. The main reasons for this include high heat losses from the solar collector and a low natural heat transfer coefficient from absorber plat into generator. In addition, the natural heat transfer is generated by density difference and gravitation. Thus a significant natural heat transfer coefficient, generally, resulted when the heat source placed in the lower part. In the present solar-powered refrigeration, solar radiation as a heat source comes from above. Solution to these drawbacks in order to improve the COP of the solar-powered adsorption refrigeration will be the next focuses in our research.

Acknowledgments

The author acknowledges the support of the Ministry of Research and Technology and Higher Education Republic of Indonesia. The support was under the Hibah-Fundamental – BOPTN of Year 2015. No. 120/SP2H/PL/Dit. Litabmas/II/2015, date February 5, 2015.

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