Int. J. of Thermal & Environmental Engineering
Volume 15, No. 2 (2017) 143-150

Study on Adsorption Refrigeration System Using Activated Carbon-Ethanol as Working Pair

I. Made Astina[a], *, Ren Sokha[b], Prihadi S. Darmanto[a]

[a] *Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia*
[b] *Department of Industrial and Mechanical Engineering, Institute of Technology of Cambodia, Phnom Penh, Cambodia*

Abstract

The adsorption refrigeration system is an alternative refrigeration system powered by thermal source so that it is possible to use waste heat and solar energy. This paper reports the experiment of the ethanol-activated carbon (AC) as the adsorbate-adsorbent pair. Experimental work was conducted with two adsorption beds as thermal compressor. Ethanol-AC pair can be operated with the heat source temperatures 90ºC and 100ºC for different heat sink temperature 20ºC, 25ºC and 30ºC, respectively. The experimental result shows when temperature of the hot water 100ºC and the cooling water temperature 30ºC, the system give the higher coefficient of performance (COP) than another testing operation condition. Additionally, the COP of the system is varying a long operating in average 0.19 due to manually intermittent operation of both adsorption beds. The maximum adsorption capacity is 0.302 kg/kg·AC while the desorption temperature, desorption pressure and heating time of the adsorption bed are 85ºC, 85.52 kPa and 80 minutes, respectively, and the cooling capacity is 23.61 kJ for a operating cycle. The experimental result proved that the ethanol-AC is suitable pair with the adsorption system for cooling application. It can be operated at low temperature driven heat source, and has an environmentally friendly behavior and the working pair is easy to be found in the commercial market.

Keywords: *Adsorption, Activated Carbon, Ethanol, Cooling Capacity, Coefficient of Performance.*

1. Introduction

A revolution in cooling technology occurred with the discovery of synthetic refrigerants which is famously called as Freon in 1932 greatly increase the coefficient of performance (COP) of vapor compression refrigeration systems. Since two decades ago the synthetic refrigerants have two environmental issues i.e. ozone depletion and global warming. The substances such as CFCs, HCFCs and HFCs used as the working fluid in most vapor compression systems have been found to be responsible for ozone layer depletion as well as contributing to global warming. Vapor compression systems driven by compressors consume huge amount of electrical energy. More electrical energy used means more fossil fuel burned to drive power plant due to major electrical power plant is fossil fueled power plant. It also indirectly contributes on global warming. Because of the negative effects, the CFCs are banned by the Montreal Protocol and HCFCs will stop to be produced in 2015 [1]. Previously the researcher stated that the refrigerant HFCs don't impact to the environment but later the researcher found that the HFCs will increase the greenhouse gas according to the Kyoto Protocol [1]. However, since the vapor compression refrigeration systems were applied in wide spread area, many researchers concern on finding high efficiency alternative refrigerants. One of those works is reported in a paper [2] which concerns on finding replacement of R12 by HC and HFC. The energy sustainable and friendly environment concerns have again drawn researchers' attention to the need for reliable, pollution free and low energy cost refrigeration systems. Among refrigeration systems, sorption systems have possibilities to use waste heat and thermal solar energy as heat source. Adsorption refrigeration is solid sorption thermally driven refrigeration system, which can be powered by solar energy as well as waste heat. It may reduce carbon dioxide emission from fossil fuel combustion in power plants. Another advantage for the adsorption systems compared to conventional vapor compression systems is friendly working fluid to be used. Adsorption systems mainly use a natural working fluid such as water, ammonia, methanol and ethanol, which have zero ozone depletion potential [3].

* Corresponding author
E-mail: astina@ftmd.itb.ac.id

DOI: 10.5383/ijtee.15.02.010

Wang and Oliviera [4] reported adsorption refrigeration as an efficient way to make good use of waste heat and solar energy and stated that the COP is usually around 0.2 to 0.6 for silica gel-water. In some commercially produced machine, the COP can be up 0.7. The other researcher Habib et al. [5] modeled a novel combined cycle integrating an activated carbon (AC)-R507A adsorption refrigeration cycle as the bottoming cycle and AC-R134a adsorption refrigeration cycle as the topping cycle and deliver refrigeration load at as low as -10^{o}C at the bottoming cycle.

Recently, many researchers have done the experiment of the adsorption system with different natural working fluids and adsorbents to seek for the suitable pair that performs high COP. Water was widespread to be investigated to get high COP. However, operating temperature of evaporator has to be very vacuum. Three types of working adsorbate and adsorbent, respectively, are favored for pairing for use in solid adsorption solar refrigeration technology: ammonia, methanol and water for adsorbate and activated carbon, silica-gel and zeolite for adsorbent [6]. Saha et al [7] reported experimental work by measuring adsorption rate of AC fiber for ethanol. The mass uptake of ethanol on AC fiber was studied under a controlled pressure and temperature environment and it is measured by a thermogravimetric analyzer.

The recent technology which is available in commercial market uses a working pair of zeolite-water. More detail review of adsorption refrigeration technology was reported in reference [8]. The concept of the heat recovery was introduced in the development to improve the COP of the adsorption system. Recently, some researchers utilize multi-salt and multi-hydride to intensify the heat recovery efficiency in chemical adsorption. Heat recovery is an effective way to enhance COP of the adsorption system.

Therefore finding suitable working pair of adsorption refrigeration is very important to be conducted. Based on available material in local commercial market, this paper reports the experimental work of adsorption refrigeration cycle that employed AC-ethanol pair by using heat source 100^{o}C and 90^{o}C to run the system. Numerical work based on CFD method is also included to complete the analysis of this research.

2. Thermodynamic of Adsorption System

Thermodynamic aspect of adsorption system plays important role on performance of the refrigeration system. Characteristics of absorbent and absorbate will significantly contribute heat and mass transfer processes in thermodynamic cycle. This section will describes on AC and ethanol as working pair, their working principle and thermodynamic evaluation of the adsorption refrigeration system.

2.1 Working Pair

The selection of adsorbent/adsorbate depends on certain desirable characteristics of their constituents, including the affinity for each other [6]. Among natural refrigerants/ adsorbates such as ammonia and water, ethanol is interesting to be applied due to friendly environment neither effect on global warmming and ozone deplection potentials. Ethanol is a volatile, colorless liquid that has a slight odor. It burns with a smokeless blue flame that is not always visible in normal light. The physical properties of ethanol stem primarily from the presence of its hydroxyl group and the shortness of its carbon chain. Ethanol's hydroxyl group is able to participate in hydrogen bonding, rendering it more viscous and less volatile than less polar organic compounds of similar molecular weight, such as propane. It has the boiling point 78.24^{o}C. Other properties of the pure ethanol are represented in Table. The ethanol used in the experiment has 96% purity v/v as available product in domestic market as given shown in Fig. 1(a).

Table 1. Chemical and physical properties of ethanol

Properties	Value	Unit
Normal boiling point	78.24	^{o}C
Tripple point	-114.15	^{o}C
Density	785.47	kg/m^3
Molecular weight	46.068	kg/kmol
Critical temperature	240.75	^{o}C
Critical pressure	6.148	MPa

AC used in this experiment is made from coconut shell. It has a highly porous, amorphous solid consisting of micro-crystalline with a graphite lattice. The AC is reactivity with oxygen at moderate temperatures over 300°C. Fig. 1(b) shows the AC used in this research. It has a granular form and commonly used in water filtering.

Manufacturing process of AC can be groupped in two steps i.e. carbonization and activation. The carbonization process includes drying and then heating to separate products, including tars and other hydrocarbons from the raw material, as well as to drive off any gases generated. The process is completed by heating the material over 400°C in an oxygen-free atmosphere that cannot sustain combustion. The AC in granular form is produced by Brataco Ltd, Indonesia. This AC is initially purposed for water filter.

(a) (b)

Fig. 1. Working pair: (a) AC granular and (b) alcohol bottle

2.2. Working Principle

The schematic of the adsorption refrigeration is illustrated in Fig. 2. Inside the adsorption bed is filled with the adsorbent to adsorb the adsorbate/refrigerant. Six valves are used in the system for controlling desorption and adsorption processes so that each adsorption bed works intermittently. Valve V1, V2, V5 and V6 are opened for desorption process and valve V1, V2, V3, and V4 are opened for adsorption process. When desorption process is undergoing in adsorption bed 1, the released gaseous refrigerant has to flow to condenser and otherwise adsorption process in the bed 1, evaporated refrigerant from evaporator flows to adsorption bed 1. Each bed will run each process intermittently with different process so that the cooling effect undergoing in evaporator.

The system has two beds which each bed gets heating and cooling processes intermittently. In operating condition for the adsorption bed 1 is in saturated refrigerant and the adsorption bed 2 is in vacuum condition and also the condenser and the evaporator has refrigerant with operating level, the system can be run by heating the bed 1 and cooling the bed 2. At the beginning of the desorption process in the bed 1, the V1 and V6 are opened and V4 and V5 are closed, therefore, the saturated vapor of refrigerant will flow to the condenser and condenses inside. The condensed liquid flows through the expansion valve to the evaporator and the liquid inside evaporator adsorbs heat from the environment so that it evaporates. V2 and V3 are then opened to allow the bed 2 to adsorb the vapor from the evaporator. At the end of adsorption process the cycle is complete and the next cycle started by inversing the above process i.e. the bed 2 is heated.

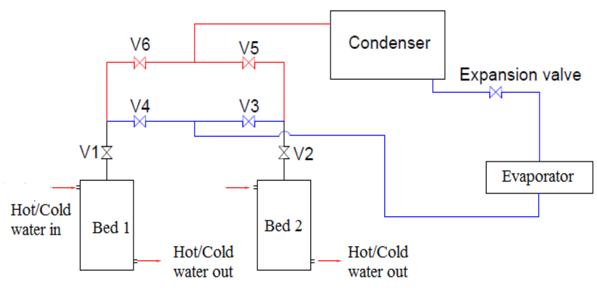

Fig. 2. Schematic of Adsorption System

Working principle of adsorption system can be illustrated in the Clapeyron diagram as shown in Fig. 3. On the Clapeyron diagram, there are four thermodynamic steps and two loops. Heating and pressurization process (1-2): hot water is used as the thermal source. For process (1-2), the pump is run to pump the hot water for heating the adsorption bed. After a few minutes the adsorbent temperature increases and pressure also increases from evaporation pressure (P_e) up to condensation pressure (P_c) as shown in Fig. 3. The next process is desorption (2-3) and condensation process (2-c). During process (2-3), there are heating for the adsorption bed and desorption of refrigerant from absorbent inside bed and release the refrigerant vapor. At a certain time the process (2-3) is connected with the condensation process (2-c) and the refrigerant vapor changes to be liquid phase in the condenser.

Cooling and depressurization process (3-4) need cold water as the cooling source to cool the bed. For process (3-4), cold water is pumped to cool the adsorption bed, therefore after a few minutes the adsorbent temperature decreases and pressure also decreases from condensation pressure (P_c) to evaporation pressure (P_e). The adsorbent can adsorb the low pressure refrigerant vapor from the evaporator.

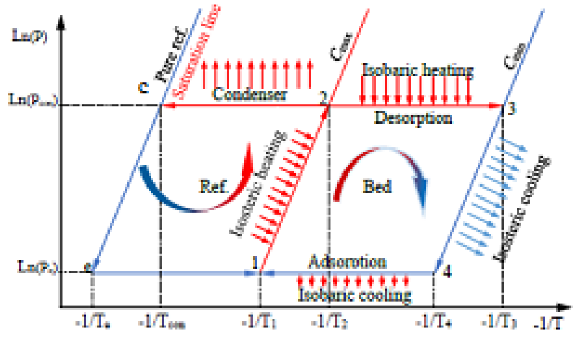

Fig. 3. Clapeyron Diagram for Adsorption Cycle

Cooling adsorption process (4-1) and evaporation process (e-1) undergo simultaneously. The process (4-1) undergoes inside cooling and adsorption. For this case, the adsorption bed is still cooled and adsorbs the refrigerant vapor. At a certain time the process (4-1) is connected with the evaporation process (e-1) and the liquid refrigerant is vaporized in the evaporator.

2.3. Dubinin's Theory

The Dubinin is the theorem of filing volume of micro-porous is applied to evaluate the adsorption isotherms to develop the capillary structure micro-porous of carbonaceous solid. This theory is represented by Dubinin-Astakhov (D-A) equation as written in Eq. (1).

$$C = C_0 \exp\left(-\frac{A}{\beta E_0}\right)^n \tag{1}$$

The term βE_0 is equal to E, where E_0 and E are characterizing the adsorption energies for a standard and a chosen adsorption, respectively. Therefore Eq. (1) can be written in Eq. (2).

$$C = C_0 \exp\left(-\frac{A}{E}\right)^n \tag{2}$$

Other relation of adsorption isotherms is given in Dubinin-Radushkevich (D-R) equation as expressed in Eq. (3). It is used to represent the D-A equation and to fit the experimental data. D-R equation could be expressed as function of T_{adb} and T_s as written in Eq. (4).

$$W = W_0 \exp\left(-D\left[T \ln\left(\frac{P_{ab}}{P_s}\right)\right]^n\right) \tag{3}$$

$$C = C_0 \exp\left\{-k\left[\left(\frac{T_{ab}}{T_s} - 1\right)\right]^n\right\} \tag{4}$$

2.4. Adsorption Bed Heat Input

Heat input into adsorption bed (Q) is the energy absorbed from the hot water 100°C to heat the bed at the isosteric heating process and isobaric heating process (desorption process). Based on the first law of thermodynamics, the energy that is needed to heat absorption bed can be evaluated in Eq. (5).

$$\dot{Q}_{input} = \dot{m}_{hw} \, c_{p,w} \, (T_{hw,in} - T_{hw,out}) \qquad (5)$$

2.5. Evaporator Heat

Heat absorbed from the water as evaporator load can be estimated by using Eq. (6). It gives total energy absorbed as long as the cooling process.

$$Q_{eva} = m_{w,eva} \, c_{p,w} \, (T_{w,i} - T_{h,f}) \qquad (6)$$

2.6. Coefficient of Performance

Since the system is intermittent, colling rate in evaporator is not exactly constants. The rate will have fluctuation along one cycle time. Therefore, cooling coefficient of performance (COP) is calculated in accordance with energy base for a cycle time. The COP can be defined as a ratio of the cooling capacity (Q_{eva}) and heat input (Q_{input}) into the system. Hence the COP of the system can be calculated from Eq. (6).

$$COP = \frac{Q_{eva}}{Q_{input}} = \frac{Q_{eva}}{\int \dot{Q}_{input} \, dt} \qquad (7)$$

3. Experimental Setup and Procedure

The thermophysical properties and equilibrium state of a working pair should be well known in order to be able to provide performance of adsorption refrigeration system. The purpose of this experiment is to investigate the adsorption characteristics, such as adsorption capacity, equilibrium behavior, effects of heat source temperature, and effectivity of diffusivity of AC-ethanol pair which is a fixed pair used in this experiment. The experimental apparatus consists of the following components:

- ✓ Two adsorption beds
- ✓ Condenser
- ✓ Evaporator
- ✓ Capillary tube/Expansion valve
- ✓ Gate valves (V1, V2, V3, V4, V5, V6)
- ✓ Ball valves (BV1, BV2, BV3, BV4, BV5, BV6, BV7, BV8)
- ✓ Two temperature controllers (Hot and cold water)
- ✓ Hot water tank
- ✓ Cold water tank
- ✓ Three water pumps (two pumps for both adsorption bed and one pump for condensor).
- ✓ Thermocouples type K (T1, T2, T3, T4, T5, T6, T7, T8)
- ✓ Pressure gauges (P1, P2, P3, P4)

Both adsorption beds are the same as with previous work [9, 10]. However configuration of the system is exactly same as the work in paper [10] but this experiment is operated at vacuum pressure. The schematic of the experimental apparatus can be ilustrated in Fig. 4.

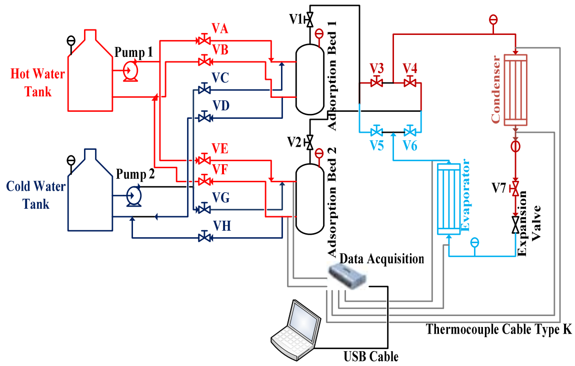

Fig. 4. Schematics of experimental apparatus [9]

Preparation and measurement procedure is similar with previous work [10]. AC was dried with the stove around 30 minutes and its temperature reach more than 180˚C to remove the water content. After the AC drying was completed, the dried AC is put into the adsorption beds. The leakage testing for the adsorption bed is first taken place by inserting the compressed air into the adsorption bed until the pressure gauge pointed 7 bar and put it into the water checked for the bubble from the adsorption bed. After piping and other equipments were installed completely, they are checked for leakage at the joint and welding points by using the soap-water and compressed air.

Before running the experiment, the AC in two adsorption beds is degassed at the temperature about 100ºC under the high vacuum pressure about 16 hours to make sure that the AC bed doesn't contain the unnecessary gases. After the vacuum process was accomplished, the ethanol is charged into the ethanol container and wait for cooling the AC until 25ºC, the ethanol from the ethanol container is charged into the adsorption bed. The adsorption process takes place by the adsorbing gaseous ethanol with the AC in the bed. The temperature of the evaporating of the ethanol is -2ºC.

Desorption process of ethanol is undertaken by heating, after the ethanol changed phase to gas, it is flown into the condenser and condenses inside. Finally, gaseous ethanol is flown into the capillary tube and evaporator and cooling effect is gotten in the evaporator. The gaseous ethanol from the evaporator is absorbed in the adsorption bed 2 so that adsorption process undergoes inside. View of testing apparatus is shown in Fig. 5. The highest position of the component is condensor in order to get gravity effect to flow the refrigerant from condesnsor to evaporator. The adsorption bed is put at the lowest position. The position play important role in order the system work properly.

It also indicates the vacuum process of the apparatus is undergoing in the figure. The cooling and heating water systems are loacted in the floor. Both systems are not indicated in the figure. Since the system work in vacuum pressure, the vacuum process should be conducted well in order to reduce content of air in the system. Dropping in refrigerant is also introduced to reduce fraction of the other gases, beside it just depends on the vacuum level only as result of the vacuum process.

Fig. 5. Testing apparatus of adsorption system

Operation parameter and state measurements are conducted to reveal performance of the system. Data acquisition instrument records state points of the apparatus for obtaining the data of temperature. Omega data acquisition Multi-function I/O USB model OMB-DAQ-2416 has 32 channels can be used to record data from thermocouple and other signal in milivolt. K-type thermocouple is used as temperature sensor with 0.1°C of accuracy. The data acquisition can be operated in multi-function measurement, and control modules for the USB bus The pressures are manually recorded from bourdon manometer and flow rate of cold water and hot water are derived from head different of pump.

The flow rate can be regulated by adjusting pump head pressure in this experiment. The pump is a device to flow fluids using mechanical action. It is used to flow the water through the piping system to the water jacket of the adsorption bed for controlling inside process. It is basically simple and more reliable, even though it requires characteristic of the pump. The pump will be used to circulate both hot and cold water with temperature varies from 20°C – 100°C.

4. Experimental Results

The experiments were carried out within only a pair of AC-ethanol with driving different heat source temperature and different cooling medium temperature. The heat source uses hot water with 90°C - 100°C and cooling medium uses water 20°C, 25°C, and 30°C. The experiments were run to test six cycles in order to make sure that mesuarement data obtained are good and have good consistencies. Some data may be an error by operation and equipment. In this experiment, the system is run continuously until six cycles of intermittent operation of adsorption bed in order to make variety of data validity. Furthermore, the data is recorded by hand and data acquisition with a data sampling rate 0.0167 (1 sample per minute). For data record by hand is pressure when heating every 5 minutes.

4.1 Bed Heating Temperature

Fig. 6 shows the heating temperature of the beds when using hot water 100°C and cooling water 20°C. All the curves of each cycle are not significantly changed, but it has little change because of error of measurement and manual operation from one cycle to the next cycle. The time of heating is 95 minutes for reaching the bed temperature is 85°C.

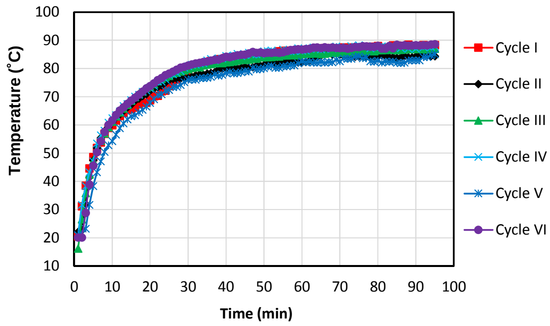

Fig. 6. Heating temperature history of the bed (100°C - 20°C)

When heating temperature of the beds for hot water 100°C and cooling water 25°C, the time needed to heat the adsorption beds until 85°C after starting of heating is 90 minutes. On the other hand, in case of heating temperature of the adsorption beds when using hot water 100°C and cooling water 30°C, there is the same trend, but the time taken to heat the adsorption beds raise up to 85°C is 80 minutes. It means that shorter temperature is nedded due to the initial temperature of cooling water is higher.

4.2 Bed Cooling Temperature

Fig. 7 shows the temperature of cooling beds when using hot water temperature 100°C and cooling water temperature 20°C. There are not much different through all cycles of each curve, but it has little changed because of an error of data acquisition, thermocouple, operator and temperature of cooling water unstable. On the other hand cycle I and IV, the first cycle of cooling process are lower than other four cycles because of adsorption bed was kept one night and start a new cycle in the morning. It means that initial condition significantly affects on temperature history.

Temperature history of cooling beds for other setting for 100°C of hot water and 25°C of cooling water, and when using 100°C of hot water and 25°C of cooling water have similar behaviors. As most common behaviors are that the heat rate will have higher value at initial process due to the larger different temperature, and their values will decrease during the cooling process.

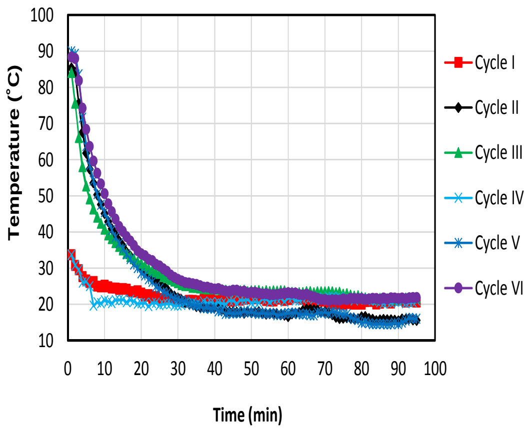

Fig. 7. Cooling temperature history of the bed (100°C - 20°C)

4.3 Heating Pressure and Time of the Adsorption Bed

Fig. 8 shows the heating pressure of adsorption beds. Those pressures show the operating pressure for adsorption system and all curves are not significantly changed, but it has a little error because of temperature of hot water is unstable from one cycle to another cycle and other error are from the operator's eyes and error of pressure gauge.

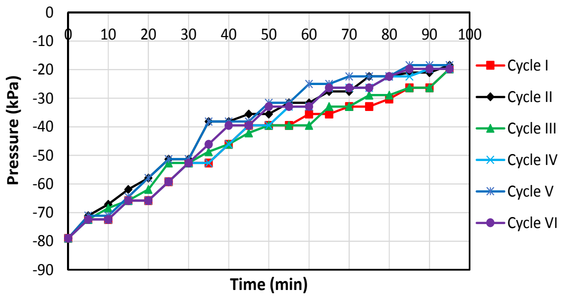

Fig. 8. Heating pressure history of the bed (100°C - 20°C)

Heating process needs more time. Shorter time of the heating will increase performance of the adsorption system. Table 2 indicates time consumption and final temperature of AC in the bed. Cooling water and cold water have contribute on the heating time. Temperature of inside bed will affect on maximum pressure achieved in desorption process.

Table 2. Heating time for several setting

Heat source - sink	Heating (°C)		Pressure (abs, kPa)	Time (min)
	From	To		
100 - 20 (°C)	20	90	81.58	95
100 - 25 (°C)	25	90	85.52	90
100 - 30 (°C)	30	90	85.52	80
90 - 20 (°C)	20	78	81.57	125
90 - 25 (°C)	25	78	80.26	115
90 - 30 (°C)	30	78	80.26	105

4.4 COP of the System

The COP of the system is illustrated in Figs. 9 and 10 for different setting of hot water and cold water. All figures shown that, COP each cycle in operation process is changing because of three factors. First, the system operated by manual to adjust the valve to decrease the pressure from the condenser pressure to the evaporating pressure. Second factor is the position of the evaporator near the adsorption bed. When, that adsorption bed was heated then the air temperature around the evaporator and adsorption bed is heated, it effects to the cooling capacity of the system. Last factor, the cooing capacity changed because of the error of the thermocouple measurement.

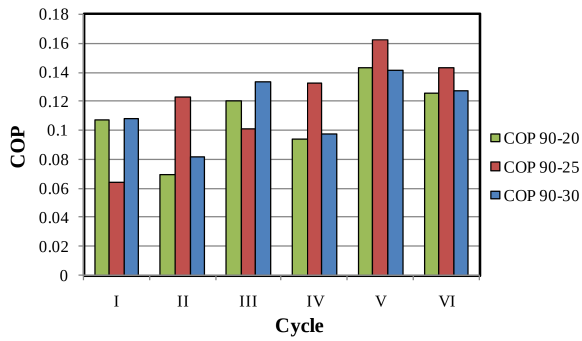

Fig. 9. COP fluctuation for hot water 90°C

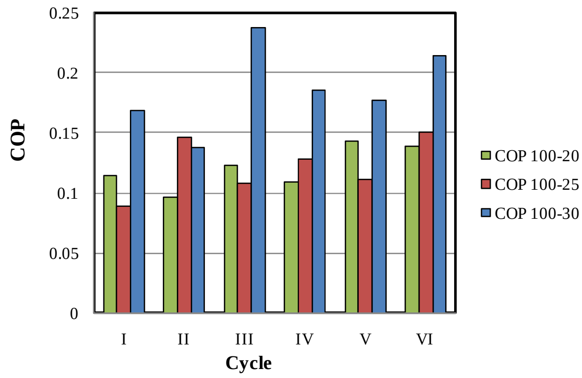

Fig. 10. COP fluctuation for hot water 100°C

5. Discussions

5.1 Comparison of Bed Heating and Cooling Temperature

Numerical work was conduct to analyze the bed temperature history in heating and cooling process. The result from the numerical analysis shows that the time for heating process of the adsorption bed is faster than experiment as illustrated in Fig. 11, because of, the simulation result is the theoretically, the parameters which used in the simulation are not changed and the adsorption bed heating process is considered as the adiabatic process. But the result from the experiment, there are some factors effected to the system such as: effect of the ambient temperature, error of thermocouple measurement and the temperature of hot water tank is unstable.

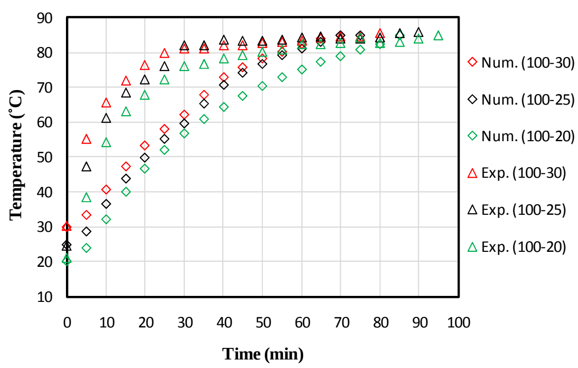

Fig. 11. Temperature of Bed by Using $T_{h,w}$ =100°C

The time for cooling of the adsorption bed from the analysis cannot reach the target temperature, it needs more time to cool the bed to the required temperature as shown in Fig. 12. Because of the starting temperature of analysis and experiment is different.

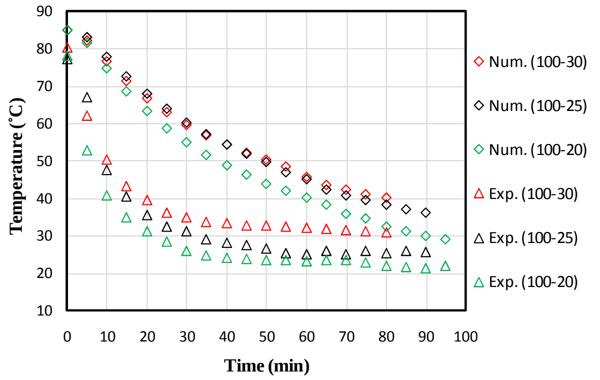

Fig. 12. Temperature of Bed by Using $T_{h,w}$ =100°C

5.2 Effect of Mass Flow Rate of Hot Water on COP

The effect of hot water flow rate on COP is shown in Fig. 13. The COP increase with lower hot water flow rates. In this case the cooling capacity that produced by the system assumed to be constant, when the hot water flow rate decreases which means that the heat input to the adsorption bed also decreases, inversed COP increased.

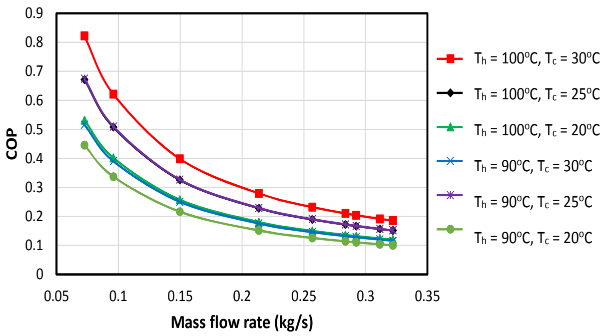

Fig. 13. Effect of Hot Water Flow Rate on COP

Table 3 represents summary of research results reported esspecially for AC used as absorbents. Using of methanol as absorbate for AC were extensively investigated. Most COP of AC-methanol pairs got COP lower than 0.2. However using water as absorbate got the best COP among the others. The present work using AC-ethanol just can reach COP 0.19. It means that performance of ethanol in adsorption system is not significant superior than methanol.

6. Conclusions

The experiment with two adsorption beds was conducted with this research. The maximum of the adsorption capacity of ethanol by the AC is C_0 = 0.302 kg/kg AC when using cooling water temperature 25°C and hot water 100°C. In case of using hot water temperature 100°C and cooling water 30°C, the experimental apparatus performed that the cooling capacity is 23.61 kJ, COP is 0.19 and cycle time is two and half hours.

Table 3. Refrigeration research with AC adsorbents

Researchers	Pairs	T_{des}	COP
Astina et al. [9]	AC methanol AC R-134a	100 °C	0.12 0.15
Astina and Kisa [10]	AC propane	100 °C	0.15
Attalla et al. [11]	AC-R-134a	60°C	n/a
Tso et al.[12]	(AC, Silica gel, $CaCl_2$)-water	115°C	0.7
Wang et al. [13]	AC-methanol	n/a	0.08
Oliveira et al.[14]	AC-ammonia	n/a	0.06
Ji et al. [15]	AC-methanol	n/a	0.12
Ramji et al.[16]	AC-methanol	n/a	0.19
This work	AC-Ethanol	100 °C	0.19

Nomenclature

P	Pressure of refrigerant [bar]
A	Differential molar work of adsorption
COP	Coefficient of Performance
T	Adsorption temperature
D	Characteristic adsorption
E	Energy characteristics
C	Adsorption capacity [kg/kg]
c	Specific heat [kJ/kg·K]
k	Empirical constant of adsorption
m	Mass [kg]
$\dot{m}$	Mass flow rate [kg/s]
N	Empirical constant of adsorption
Q	Heat energy

Subscripts

ab	Absorb
cw	Cold water
s	Saturation
hw	Hot water
w	Water
eva	Evaporator
in	Inlet
out	Outlet
o	Maximum
p	Pressure

Acknowledgments

The authors would like to thank AUN/SEED-net/JICA for funding this research field.

References

[1] Mohanraj M, Jayaraj S, Muraleedharan C, Environment friendly alternatives to halogenated refrigerants – a review, Int. J. Greenhouse Gas Control 3:108-119, 2009. DOI: 10.1016/j.ijggc.2008.07.003

[2] Halimic E, Ross D, Agnew B, Anderson A, Potts I, A comparison of the operating performance of alternative refrigerants, Appl. Therm. Eng. 23:1441–1451, 2003. DOI: 10.1016/s1359-4311(03)00081-4

[3] El-Sharkawy I I, Uddin K, Miyazaki T, Saha B B, Koyama S, Miyawaki J, Yoon S H, Adsorption of ethanol onto parent and surface treated activated carbon powders, International Journal of Heat and Mass Transfer, 73:445-455, 2014. DOI: 10.1016/j.ijheatmasstransfer. 2014.02. 046

[4] Wang R Z, Oliveira R G, Adsorption refrigeration-an efficient way to make good use of wast heat and solar energy, International Sorption Heat Pump Conference, 2005. DOI: 10.1016/j.pecs.2006.01.002

[5] Habib K, Saha B B, Chakraborty A, Koyama S, Srinivasan K, Performance evaluation of combined adsorption refrigeration cycles, International Journal of Refrigeration, 34:129-137, 2011. DOI: 10.1016/j.ijrefrig. 2010.09.005

[6] Anyanwu E E, Review of Solid Adsorption solar refrigeration II: An overview of principles and theory, Energy Conversion and Management, 45:1279-1259, 2004. DOI: 10.1016/j.enconman.2003.08.003

[7] Saha B B, El-Sharkawy I I, Chakraborty A, Koyama S , Yoon S H, and Ng K C, Adsorption rate of ethanol on activated carbon fiber, J. Chem. Eng. Data, 51: 1587-1592, 2006. DOI: 10.1021/je060071z

[8] Yong L, Wang R Z, Adsorption Refrigeration: A Survey of novel technologies, Recent Patents on Engineering, 1: 1-21, 2007.

[9] Astina I M, Bun K, Experiment of adsorption refrigeration system using activated carbon and propane as the working pair, International Journal of Advanced Research, 3 (9): 620-627, 2015

[10] Astina I M, Purnomo D M J, Mao O, Continuous Adsorption Refrigeration System: Experiment of Methanol and R-134a with Activated-Carbon, RCEneE 2014, Proceeding 2nd AUN/SEED-Net Regional Conference on Energy Engineering, Bangkok, 13-14 November 2014, Bangkok, 2014

[11] Attalla M, Sadek S, Experimental investigation of granular activated Carbon/R-134a pair for adsorption cooling system applications, Journal of Power and Energy Engineering, 2: 11-20, 2014, DOI: 10.4236/jpee.2014. 22002

[12] Tso C Y, Chao H, Activated carbon, silica-gel and calcium chloride composite adsorbents for energy efficient solar adsorption cooling and dehumidification systems, International Journal of Refrigeration, 35: 1626-1638, 2012, DOI: 10.1016/j.ijrefrig.2012.05.007

[13] Wang L W, Wu J Y, Wang R Z, Xu Y X, Wang Y X, Li, X R, Study of the performance of activated carbon–methanol adsorption systems concerning heat and mass transfer, Applied Thermal Engineering, 23: 1605–1617, 2003, DOI:10.1016/S1359-4311(03)00104-2

[14] Oliveira R G, Silveira V, Wang R Z, Experimental study of mass recovery adsorption cycles for ice making at low generation temperature, Appl Therm Eng, 26:303–311, 2006.

[15] Ji X, Li M, Fan J, Zhang P, Luo P, Wang L, Structure optimization and performance experiments of a solar-powered finned-tube adsorption refrigeration system, Applied Energy, 133: 1293–1300, 2014.

[16] Ramji H R, Leo S L, Tan I A W, Abdullah M O, Comparative study of three different adsorbent-adsorbate working pairs for a waste driven adsorption air conditioning system based on simulation, IJRRAS, 18, 2014.

[17] Johnson E, Global warming from HFC, Environ. Impact Assess. Rev., 18: 485–492, 1998. DOI: 10.1016/s0195-9255(98)00020-1

[18] Wang D, Wu J, Influence of intermittent heat source on adsorption ice maker using waste heat, Energy Convers Manage, 46: 985–98, 2005.