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RESEARCH ARTICLE

Experiment of Adsorption Refrigeration System Using Activated Carbon and Propane as the Working Pair

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Abstract

In this paper, the experiment is performed on adsorption refrigeration system by using activated carbon and propane as the working pair. Two adsorption beds are used to make the refrigeration system working continuously. Each adsorption bed is filled with activated carbon around 2 kg, and refrigerant 0.4 kg or 0.7 liters. Propane is the natural hydrocarbon have no toxicity, zero ozone depletion potential, lower global warming potential and very good compatibility with other components but it is very flammable refrigerant. One more thing, it can be classified as the R-290 and can be substituted R-502 and R-22 so that it is very suitable to be used as adsorbate (refrigerant). In heating and cooling processes of the adsorption beds, the heating water 100°C and cooling water 15°C are required. Based on the experimental data, the continuous adsorption refrigeration system provides coefficient of performance, specific cooling power, cooling capacity and cycle time around 0.15, 2.35 W/kg adsorbent, 50 kJ and 3h30 min, respectively. Moreover, experimental data indicates that it is very clearly to raise the performance or reduce the cycle time of the adsorption refrigeration system, the cooling water temperature should be lower to decrease adsorption temperature and the heating water temperature should be higher to increase desorption temperature in the same cycle time.

INTRODUCTION

The severity of the ozone layer destruction problem due to refrigerants such as CFCs and HCFCs has been calling for rapid developments in environment friendly air conditioning technologies. Adsorption refrigeration systems have the advantage of being environmentally benign. Both their ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) are zero. The adsorption refrigeration system is becoming more important because it can be powered by other sources of energy like waste heat of exhaust gas from gas and steam turbines, solar energy, geothermal, biomass than electricity energy so that it is enable for energy saving. Nowadays, adsorption refrigeration systems becomes popular in many industries due to the increasing of cost for generating electricity and positive response respect to the environmental impact.

Much work has been conducted in the study of adsorption refrigeration systems driven by waste heat. Suzuki [1] gave a literature review relating to adsorption refrigeration systems. The review reveals that numerous investigations were reported on various configurations of adsorption refrigeration systems, experimental investigations and mathematical modeling of the steady state and transient behavior of adsorption cycles. It should be noted that the performance of adsorption refrigeration system depends hugely on the adsorption isotherms, kinetics and the isosteric heat of adsorbent adsorbate pair. A number of adsorbent adsorbate pairs have been studied theoretically and experimentally by different researchers for implementation in adsorption refrigeration and revealing their performance.

The basic principle of the adsorption refrigeration system is represented by Clapeyron diagram in Fig .1 where parameters *T*, *P* and *x* are temperature, pressure and adsorption capacity, respectively. The processes in loop of 1-2-3'-4' is the refrigeration cycle and the processes in loop of 1-2-3-4 is the adsorption cycle which represents the conditions of adsorbent. The process begins at point 1, where the adsorbent of first adsorption bed is at low temperature T_1 and at low pressure P_e (evaporating pressure). Process 1-2 represents the heating of the adsorbent containing adsorbate with increasing in pressure. The progressive heating of the adsorbent from 2 to 3 causes some adsorbate to be desorbed and its vapour is released to flow to condenser and it is then condensed inside. When the adsorbent reaches its maximum temperature T_3, desorption ceases and then the liquid propane from condenser is transferred into evaporator throughout a capillary tube. At the second adsorption bed, the adsorbent is cooled down by cooling water, decreases temperature of adsorbent from 3 to 4, which induces the system pressure to decrease from P_c to P_e. As the adsorbent is continually cooled down from T_4 to T_1, both evaporation and adsorption processes of propane are initiated. During this cooling period, heat is rejected to decrease temperature of adsorbent and to absorb adsorption heat. The temperature of adsorbent will reach to T_1 to complete the cycle.

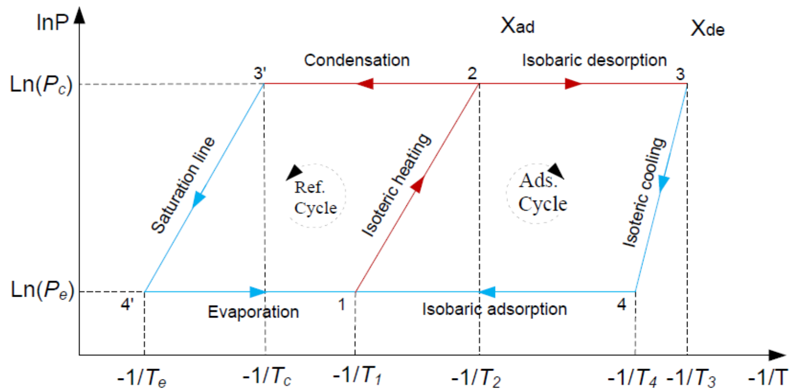

Fig. 1. Adsorption and refrigeration cycle on Clapeyron diagram

EXPERIMENTAL SETUP AND OPERATION

The main element and play important role of the experiment apparatus is adsorption bed. The adsorbent of activated carbons is being tested with propane within the adsorption bed whereas water is being selected as the heating and cooling fluids with the maximum operating temperatures of limited at 100°C. Fig. 2 represents the schematic diagram of the adsorption apparatus testing system. It consists of a hot water reservoir, a cold water reservoir, two water circulating pumps, two adsorption beds, an evaporator and a condenser.

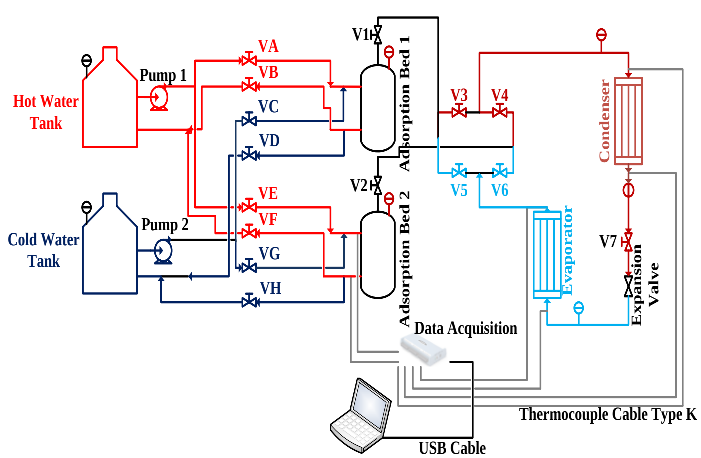

Fig. 2. Schematic diagram of the adsorption refrigeration apparatus

Adsorption refrigeration system uses two solid sorption beds to absorb and desorb a refrigerant to obtain therrmal compression. Two adsorption beds are used to make the refrigeration system working continually. The beds are same as used in previous work and detail construction of the beds can be find in paper [2]. However, there are significant change in system installation especially for refrigeration piping and testing construction. Each adsorption bed is filled with activated carbon around 2 kg. The adsorption bed desorbs refrigerant when heating process is given and the bed absorbs refrigerant vapor when cooling process is given. For this experiment, condensing unit is developed from Air Conditioner split that has capacity around 1.5 HP is used to produce chilled water. The chilled water can reach 15°C to cool the adsorbent. Meanwhile hot water is employed with total capacity of 5 kW consisting of two heaters to heat the adsorption bed. The temperature of heating and cooling water that used to heat and cool the adsorption bed are controlled by temperature controller. The heating water is set at 100°C and cooling water is set at 15°C. Before starting and running the processes of the cycle, both adsorption beds are cooled 1h by using 125 W of centrifugal pumps to circulate cooling water from the cold water tank to adsorption beds. The pressure inside both adsorption beds drop to 3.5 bar. One of the adsorption beds is heated and its pressure increases rapidly 12 bar in only 15 min. The propane refrigerant is conveyed to condenser by open a get valve between adsorption bed and condenser. In the condenser, the refrigerant vapor is cooled and condensed into liquid. The refrigerant condensates then expands to a lower pressure through a capillary tube and the low pressure condensation passes to an evaporator. Refrigerant vapor from the evaporator is reintroduced to another adsorption bed to complete the cycle. Data acquisition is used to record data by connecting with thermocouples and transfer data to computer through USB cable.

EXPERIMENTAL PROCEDURE

Leakage Test

The leakage is the main problem in adsorption system because adsorption refrigeration system when using water, methanol or ethanol as refrigerant, the operational pressure works under the atmospheric pressure. If there is leakage, the air will penetrate into the system so that the system will not operate efficiently and satisfactorily and problem with operation of cycle mode as well. The system without leak is assured by accomplishing leakage test. In order to prevent the leakage, the air is filled until 7 bar (maximum pressure of air compressor) to check the leakage into the system. The connection from air compressor to the system is closed by keeping one night to make sure that there is no leakage (no pressure drop on the pressure gauge).

Adsorbent Purification

Before putting adsorbent into the adsorption bed, the adsorbent has to be dried up by using a gas stove in 4 hours to release the moisture content from the adsorbent. After that the adsorbent is put into the adsorption bed and purified by heating water around 100℃ to take residuals out. Some residuals and moisture content remained from the dryer are vacuumed to atmosphere by vacuum pump. The vacuum and heating process were kept on until eliminating the moisture content and the level of the vacuum is constant. The vacuum period time depends on the moisture contended in the adsorbent. The lower pressure -30 in Hg which is the lowest pressure of the vacuum pump. The maximum of the adsorbent can reach 85℃ after long period of heating pressure.

Cooling Adsorption Process

In this process, the activated carbon was used as the adsorbent and propane was used as refrigerants. After the vacuum process was done, the adsorbent is cooled down until 20℃ by using the cooling water at 15℃. When the temperature of adsorbent reached to 20℃, a valve before enter to capillary tube is opened fully, and another valve at outlet of capillary tube is opened slightly to make the pressure drop and flow slowly into evaporator. The cooling effect will happen when the adsorbent can absorb the refrigerant. This process will go on until the adsorbent is saturated.

Heating Desorption Process

The temperature of the heating water 100℃ is used to heat the adsorbent from 15 to 85℃. Because of thermodynamic property of propane, the adsorbent hasn't arrived 85°C yet, but the pressure in the adsorption bed increases rapidly to desired pressure 12 bar so a valve start releasing the refrigerant to condenser. This process is going to continue until the refrigerant stop desorbing from the adsorbent. For using propane as refrigerant, the material employed in system must be strong enough to resist with its high operating pressure. It can be explosive and flammable when over high pressure or release to atmosphere with present of fire, respectively.

THEORETICAL ANALYSIS

In the adsorption refrigeration system, the evaluation of the performance of the system requires the knowledge of the cooling capacity from evaporator, heat generation in the adsorption bed, adsorption capacity, coefficient of performance and specific cooling power.

The cooling capacity is characterized by latent heat of vaporization of propane liquid collected during the condensation phase as shown in Eq. (1).

$$\boldsymbol{Q_C} = \Delta \boldsymbol{X}\left(\boldsymbol{h_{gas}}(\boldsymbol{T_E}) - \boldsymbol{h_{liquid}}(\boldsymbol{T_C})\right) \tag{1}$$

Where ΔX is the amount of liquid phase collected during condensation phase, $h_{gas}$is specific enthalpy of gas leaving the evaporator, h_{liquid} is specific enthalpy of liquid leaving the condenser.

The generator heat (Q_{gen}) is needed to generate the refrigeration from the adsorption bed to condenser as presented in Eq. (2).

$$\boldsymbol{Q_{gen}} = \boldsymbol{m_a C_{pa}}\Delta \boldsymbol{T_a} + \left(\boldsymbol{m_{r,i}} - \boldsymbol{m_{r,g}}\right)\boldsymbol{C_{pr}}\Delta \boldsymbol{T_r} + \boldsymbol{m_{r,g}}(\boldsymbol{h_2} - \boldsymbol{h_1}) + \boldsymbol{m_{r,g} h_{rg}} \tag{2}$$

Where Q_{gen} is heat generation, m_a is mass of adsorbent, $C_{pa}$is specific heat of adsorbent, ΔT_adifferent temperature of adsorbent from point 1 to 3, $m_{r,i}$is mass refrigerant in adsorbent, $m_{r,g}$is mass refrigerant in cycle, C_{pr} is specific heat of refrigerant, $\Delta T_r$is different temperature of refrigerant ($\Delta T_r = \Delta T_a$), $h_1$is specific enthalpy of vapour refrigerant, h_2 is specific enthalpy of liquid refrigerant.

The cooling coefficient of performance (COP) is the ratio of the cooling production to the heat input calculated by Eq. (3). This definition is taken to figure the system performance on focusing benefit got relating to heat needed for running the refrigeration cycle.

$$\mathbf{COP} = \frac{\boldsymbol{Q_e}}{\boldsymbol{Q_{gen}}} \tag{3}$$

Where Q_e is evaporator heat absorbed as long as cooling process and Q_{gen} is heat absorbed by generator estimated by Eq. (2) . This research considers the system of the cycle. Energy for driving the pump and heat losses either in hot water storage and cold water storage are not included in this analysis.

The specific cooling power (SCP) for the system is defined as the ratio of cooling capacity from evaporator over the cycle time in unit mass of adsorbent as defined in Eq. (4). This parameter reveals size of the adsorption system for a specific cooling capacity.

$$\mathbf{SCP} = \frac{\boldsymbol{Q_e}}{\boldsymbol{m_2 . t_{cycle}}} \tag{4}$$

Where t_{cycle} is cycle time for cooling process to give cooling product and m_2 is mass of absorbent in the adsorption bed.

RESULT AND DISCUSSION

Relation of Pressure with Cycle Time in Both Adsorption Beds

Fig. 3 shows the relationship between pressure and cycle time. There are four cycles and 3h30 min per each cycle were plotted continuously. At beginning, the first and second adsorption bed were cooled by using cooling water 15°C around cooling period of 1h to decrease pressure until minimum 6.5 bar and 3.5 bar, respectively. After cooling period of adsorbent over than 1h, the first adsorption bed was heated by using heating water 100°C. The pressure in the first adsorption bed increased dramatically in 15 min until 12 bar because of thermodynamic properties of propane. When the pressure of the first adsorption bed, reached 12 bar, a valve between first adsorption bed and condenser is open. After that the refrigerant is connected from the first adsorption bed to condenser to make condensate and flow to evaporator throughout capillary tube. The low pressure at the second adsorption bed will start adsorption refrigerant to make the cooling effect at evaporator. This process is kept going on around a period of 2h30 min to let the pressure drops and increases slowly in first and second adsorption bed, respectively.

Before starting the second cycle, both adsorption beds is cooled like the first cycle around period of 1h. After that the first adsorption bed is heated and second adsorption bed is cooled intermittently. In the same way, the third and fourth cycle are going to do like this. One adsorption bed is heated and the other is cooled before starting to each cycle, both adsorption beds is cooled firstly to reduce the pressure until lower pressure of evaporator. If pressure in the adsorption bed can not drop lower than the desired pressure of the evaporator, the adsorption system cannot receive the cooling effect. In this experiment, the pressure in first and second adsorption beds from each cycle are slightly different due to error indicator of pressure gauge.

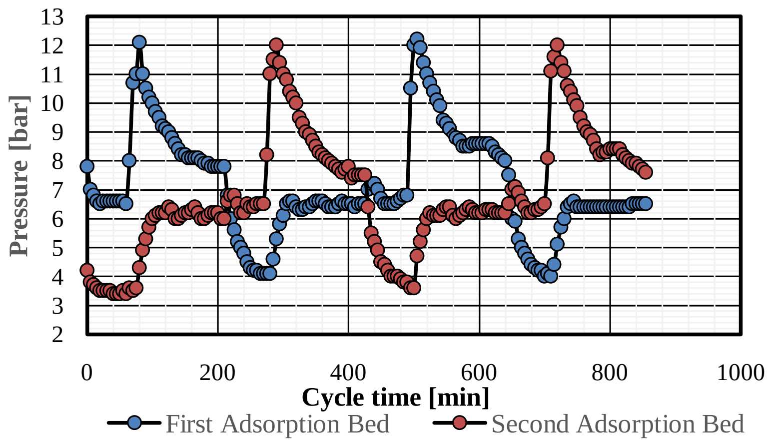

Fig. 3. The pressure in the adsorption beds related cycle time

COP Variation along the Cycle Time

Fig. 4 shows the value of COP for each cycle. The COP value is changing slightly from 0.1 to 0.2 because of effect of ambient temperature and variation of heating and cooling water temperatures, and it is also caused by effect of manual operation for the valve to control intermittent period of the cycle. The variation of heating and cooling water temperatures is caused by accuracy of temperature controller and flow exchange of heating and cooling water in the hose while alternatively cooling and heating processes of each adsorption bed.

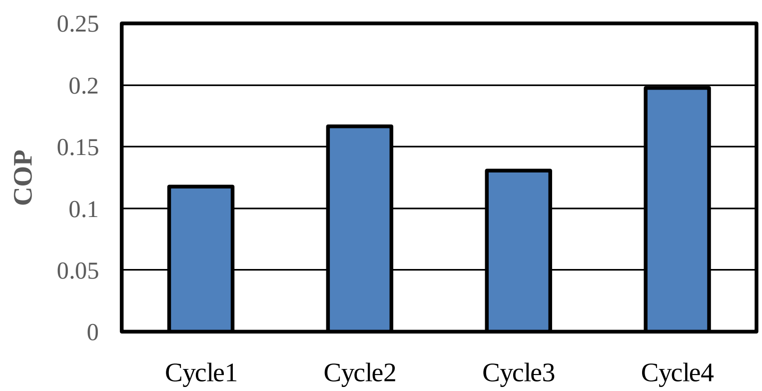

Fig. 4. COP along each cycle of propane as the adsorbate

SCP Variation along the Cycle Time

SCP value of each cycle is shown in Fig. 5. Each cycle has amount of specific cooling capacity has variation from 1.5 to 2.5 W/kg adsorbent. These amount are still low because each cycle takes long time around

3h30 min. Long heating and cooling periods besides soprtion and desorption process significantly affect on this values. It means that bed construction besides working pair has contribution on this performance.

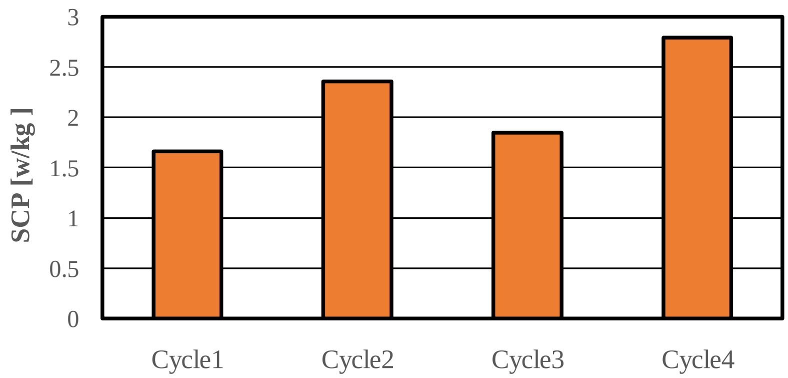

Fig. 5. SCP along each cycle of propane as adsorbate

Effect of Heating Water Temperature on COP and SCP

The temperature of the heat source effected on the COP and SCP is represented in Fig. 6. The values of COP are given on the right vertical axis and the values of SCP are given on the left vertical axis. According to this data, the COP and SCP are tested into three samples with different temperatures of heating water as the heat source 80, 90 and 100°C, respectively. Meanwhile temperature of the cooling water is kept at constant 15°C. At the beginning of the cycle, the COP and SCP are slightly difference because the adsorbent is cooled firstly around one hour to reduce the pressure in the adsorption bed. The COP and SCP initially increase with increasing temperature of the heating water along the cycle time. This is the reason of the higher temperature of the heat source, the higher heating rate received by the activated carbon, and the higher desorption temperature will be reached. Therefore, the COP and SCP will increase significantly by increasing the temperature of the heat source.

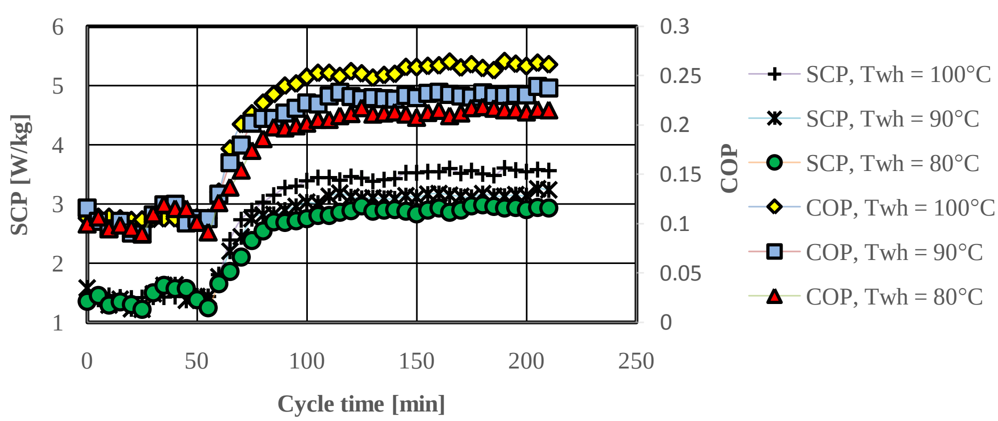

Fig. 6. Effect of heating water temperature on COP and SCP

Effect of Cooling Water Temperature on COP and SCP

Fig. 7 shows the effect of the temperature of the cooling water on the COP and SCP. The COP and SCP are recorded for three samples with different temperatures of cooling water 15, 20 and 25°C, respectively. As shown in the Fig. is that the values of COP are given on the right vertical axis and the values of SCP are given on the left vertical axis. Meanwhile the heating water temperature is kept at 100°C. Based on this data, at first, COP and SCP are not quite different between each sample due to the adsorbent is cooled to reduce pressure. The COP and SCP increase with decreasing the cooling water temperature because of the lower the temperature of the cooling water, the lower cooling rate of the activated carbon, and the adsorption temperature becomes lower. Therefore, the COP and SCP will be increased greatly by decreasing temperature of the cooling water.

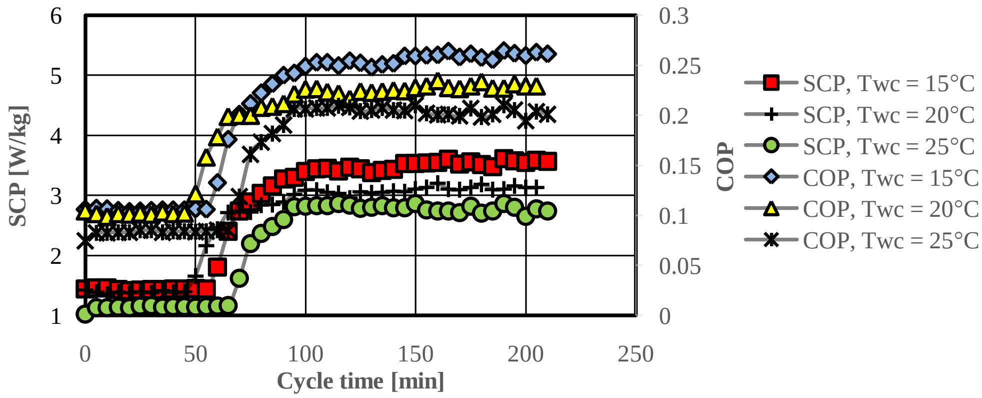

Fig. 7. Effect of cooling water temperature on COP and SCP

Comparison between Working Pairs

This experimental data and some data cited from other journals finally are estimated, compared to reveal how much difference or error are occurring. Sometime both data are quite or slightly different depend on data assumption, measuring temperature, manual operation, ambient temperature, inaccurate of compound pressure gauge and pressure drop as well.

To choose the appropriate pair in adsorption cooling applications, the running conditions and the aim of the application should be taken into account. For example when using the adsorption pair in solar cooling system, the important parameter governing of the choice is the driving temperature as it should be the minimum allowable temperature. The most important running conditions are the driving temperature, evaporation temperature and COP. Table 1 introduces a comparison between the adsorption working pairs on the basis of the best reached operating conditions. The comparison covers the already constructed systems and conducted the best results of them. For every pair, the running conditions were brought from existing systems and compared together to introduce the best one. Unfortunately, there are no journal that has shown the cooling capacity, COP, SCP or cycle time but just mentioned that the activated carbon can be used with propane as the working pair. One more thing, the COP, SCP, and the cycle time when using the activated carbon with methanol as the same working pair but provide different result from each journal because of the different heat transfer area of the adsorption bed, temperature measuring, different installation, and using different technology as well.

Table 1. Comparison between adsorption working pairs

Working pair	Cycle Time [min]	COP	T_e [°C]	T_d [°C]	SCP [W/kg]	Reference
Activated carbon/propane	210	0.15	10	80	2.35	Present work
Activated carbon/ammonia	N.A	0.61	-5	100	2000	[3]
Activated carbon/methanol	N.A	0.78	15	90	16	[3]
Activated carbon/ethanol	N.A	0.8	3	80	N.A	[3]
Silica gel/water	N.A	0.61	12	82	208	[3]
Zeolite/water	N.A	0.25	6.5	350	200	[3]
Zeolite/water	131.5	0.38	10	200	25.7	[4]
Activated carbon/methanol	86	0.101	-10.53	110	16.5	[5]
Activated carbon/methanol	36	0.088	N.A	N.A	25.2	[6]
	46	0.097	N.A	N.A	28.8	[6]
	56	0.12	N.A	N.A	32.2	[6]
	66	0.125	N.A	N.A	32.6	[6]
	76	0.115	N.A	N.A	33.6	[6]
	86	0.101	N.A	N.A	33.0	[6]

CONCLUSION AND SUGGESTION

The performance of the adsorption refrigeration system depends highly on the adsorption working pairs, process involved, and the well manufacturing of all the parts of system. Enhancing of heat transfer in the adsorption bed by improving thermal conductivity of adsorbent and by increasing the contact area between adsorbent and heating or cooling fluids is the basic step to reduce the cycle time. The adsorption bed is filled with activated carbon 2 kg and propane 0.4 kg or 0.7 liters. The period time for heating and cooling of the adsorption beds to reach desired temperature is around 60 min. Experimental result provides COP, SCP, cooling capacity and cycle time around 0.15, 2.35 W/kg adsorbent, 50 kJ and 3h30 min, respectively.

Any effort is needed to make the adsorption refrigeration system works well and efficiently. Generally a typical continuous adsorption refrigeration system should respect following step.

- The system apparatus must be strong enough to avoid explosion and flame because propane is very flammable and work at high operating pressure.
- The position of condenser must be higher than evaporator and be close to each other by letting the refrigerant flow into adsorption bed by gravity.
- The adsorption bed is the heart of the system and it has the greatest effect on the performance of the system. A good design of the generator leads to smooth operation and better results.
- The driving temperature should be over 100°C in order to generate higher volume of refrigerant from adsorbent. The cooling water to cool the adsorbent should be low enough to drop pressure in the adsorption bed to reach desired pressure of evaporator.
- Multi-stage and multi-bed of adsorption refrigeration system are recommended with the same activated carbon quantity in order to get higher cooling capacity.
- A high performance vacuum pumps can be used with special liquid nitrogen cold trap. Such instrument is easier to decrease the pressure to be the lower value without losing any refrigerant vapor.
- Different type of activated carbon such activated carbon fiber, or consolidated active carbon which have high adsorption capacity may be used to get better result.
- Increase heat transfer by extending heat transfer areas like finned tube, plate heat exchanger, plate-fin heat exchanger can shorten the cycle time effectively.

REFERENCES

[1] M. Suzuki, Application of adsorption cooling systems to automobiles, *Heat Recovery Systems* & *CHP* 13(4): 335–340, 1993,

[2] I M. Astina, D. M. Jati Purnomo, and Mao Odam, Continuous adsorption refrigeration system: experiment of methanol and R-134a with activated-carbon, *Proceeding 2nd AUN/SEED-Net Regional Conference on Energy Engineering*, 13-14 November 2014, Bangkok.

[3] M.A. Ahmed and A.E. Shehata, A Review: future of the adsorption working pair in cooling (http://ultracrib.com/wp-content/uploads/2014/04/1337695528.4453A-Rewiew-Future-of-the-Adsorpt.pdf)

[4] L.Z. Zhang, Design and testing of an automobile waste heat adsorption cooling system, *Applied Thermal Engineering* 20(1): 103–114, 2000.

[5] L.W. Wang, J.Y. Wu, R.Z. Wang, Y.X. Xu, and S.G. Wang, Experimental study of a solidified activated carbon-methanol adsorption ice maker, *Applied Thermal Engineering* 23(12):1453–1462, 2003

[6] L.W. Wang, R.Z. Wang, Z.S. Lu, C.J. Chen, K. Wang, and J.Y. Wu, The performance of two adsorption ice making test units using activated carbon and a carbon composite as adsorbents, *Carbon* 44(13): 2671–2680, 2006.