Performance Analysis of Adsorption Refrigeration System with Water-Thermosyphon Cool Adsorber and Evaporator Enhanced with Near-Ultrasonic Wave

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Abstract

Here we present an experimental study of the single-effect adsorption cooling system using activated carbon-methanol working pair. The test unit was comprised of an adsorber, a condenser and evaporator in vertical alignment. Heating and cooling of adsorber was mainly done by hot and cold water circulating through the water jacket. The evaporator and condenser was heated or cooled by flows of water through the internal coil. The adsorber was analyzed for its cooling rate when cooling was done by two approaches, either cooling water and/or three thermosyphon heat pipes, which both methods gave shortest cooling time. The investigated heat source and sink temperatures are; hot water temperature supplied to adsorber (70, 80, 90 ^{o}C), and cooling water temperature supplied to condenser (5, 10, 15 ^{o}C). An ultrasonic wave generator was attached to the bottom end of the evaporator, to generate wave frequency varied by 8, 10, and 14 kHz during evaporation phase. The ultrasonic wave can obviously reduce the evaporation time of methanol, as well as to improve the system performance in terms of COP, SCP and VCP. The system performance was considerably comparable to those from literatures. The highest COP and SCP obtained from this system was 0.718 and 248.90 W/kg, respectively.

Key words: Performance, Solid adsorption, Ultrasonic wave, Thermosyphon heat pipe, Activated carbon, Methanol

1. Introduction

The past two decades have seen the rapid increasing of energy supply to an air-conditioning system. The International Institute of Refrigeration (IIR) estimated that approximately 15% of all electric produced worldwide is used for refrigeration and air-conditioning processes [1]. Moreover, the electrical demand for an air-conditioning system has continuously increased every year [2]. To solve this problem, many attempts have been done to find out methods not only for increasing the performance of an air-conditioning system but also for the new efficient air-conditioning technology.

An adsorption system is one of the sustainable air-conditioning technologies which has been investigated and applied to the industrial process for many years [3]. This technology has been adapted to reduce the energy consumption of a conventional air-conditioning system. An adsorption system doesn’t have problems on coolant pollution, crystallization, and fractionation like absorption systems. It has less vibration, simple control, lower operating cost and especially environmental friendly. This system principally consists of three main parts, an adsorber, a condenser and an evaporator.

For many years, many research works have been done to investigate the performance of adsorption system and its application. For examples, Zhang [4] studied the adsorption air-conditioning system having sorption beds regenerated by the exhaust gases of the bus. This system used zeolite and water as adsorbent and working fluid, respectively. The COP of this system was 0.38. Wang et al. [5] used activated carbon-methanol pair in the adsorption system. They designed an adsorber to the tube and plate heat exchanger and found that the cooling power was 3.8 kW with 0.4 COP. Tamainot-Telto and Critoph [6] studied modular adsorption air-conditioner, which was powered by hot air. Lu et al. [7] developed an air conditioner with zeolite-water pair that could be powered by the exhaust gases from a locomotive. The cooling power of this system ranged from 3 to 5 kW, with a COP of 0.21 and the temperature inside the cabin was between 4 and 6 ^{o}C lower than the ambient temperature. Yang et al. [8] designed a compact adsorption air-conditioner with a cooling capacity of 1 kW and found that the coefficient of performance (COP) was around 0.446.

Moreover, many researches developed the mathematical model for predicting the performance of adsorption system such as Tiansuwan et al. [9], Leong and Liu [10], Maggio et al. [11] and Wang et al. [12].

From many literatures, it can be concluded that the performance of the adsorption system depends on the design concept, working pair and operating condition. In this work, the new design of the adsorption system is proposed and moreover, the performance of this system is enhanced by an ultrasonic wave. The ultrasonic wave generator is attached on the evaporator surface for increasing the vaporization of working fluid. The deep details of this system are explained in the later section. The output of this work aims to partial-fill the knowledge of adsorption technology.

2. Materials and Methods

Fig. 1 shows the schematic sketch of the experimental apparatus. It consists of 3 main parts, an absorber, a condenser and an evaporator. An absorber was made of copper tube having 7.62 cm diameter and 100 cm length. This absorber was filled with 0.5 kg of 8×16 mesh size activated carbon produced from coconut shell. Note that the external surface of adsorber was covered with the water jacket and moreover, the 3 thermosyphon heat pipes were inserted into the adsorber. It should be note that each of thermosyphon has 1.0 cm and 150 cm length. The length of an evaporator and condenser sections of the thermosyphon were 100 and 50 cm respectively. This thermosyphon was filled with methanol at 50% of the volume of evaporator section. Since during the desorption process, the heat energy has to input to the adsorber for repelling the methanol from the activated carbon. Therefore, at this stage, the 95 °C and 0.08 kg/s hot water was circulated inside the water jacket and the condenser part of the thermosyphon was covered with the insulation for protecting the heat loss from an absorber. After the desorption process, the activated carbon should be cooled down. Therefore, at this stage the cold water was circulated along the water jacket and the insulation covered the condenser section of thermosyphon was removed and allowed the thermosyphon to be operated.

A condenser of adsorption system was made from copper tube having 7.62 cm diameter and 23 cm length. Inside this container, the copper coil was located. The length of this coil was 149 cm with 10 mm diameter. During the condensation process, the 5-15 °C cold water was circulated inside the copper coil for promoting the condensation process. Note that, the condensate was turn down to store at the evaporator of the adsorption system.

An evaporator of adsorption system has the same dimension as a condenser. During the evaporation of methanol, the 28-35 °C water was circulated inside the copper coil at the flow rate of 0.0018 kg/s. Moreover, the sound wave generator was attached at the bottom of an evaporator for enhancing the evaporated of methanol.

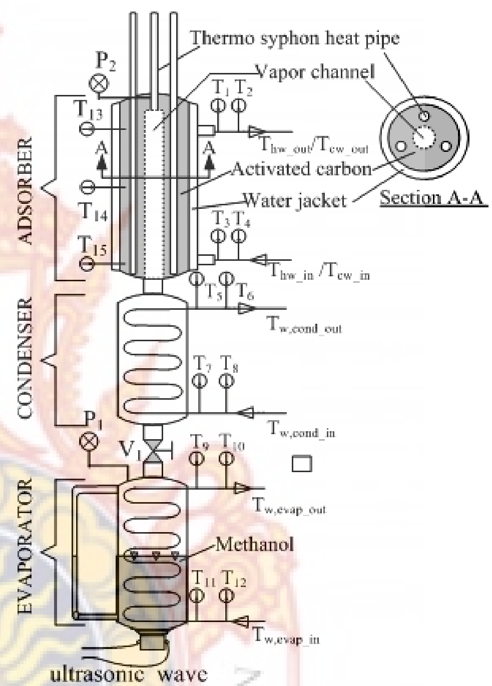

Fig. 1 Schematic sketch of the experiment set-up

In this experiment, the K-type thermocouples having ± 0.1 °C accuracy were used for measuring the temperature of activated carbon (3 points) and the inlet and the outlet of water at an adsorber, a condenser and an evaporator (2 points per position). Moreover, the pressures inside an adsorber and an evaporator were measured by the high precision pressure gage having ± 100 Pa. Note that, the level of methanol inside an evaporator was indicated by using a sight glass.

3. Results and discussion

3.1 Parameter affecting adsorber performance

In the adsorption system, an adsorber is heated in the desorption process by using hot water. After that the activated carbon has to cool down before and during the starting of adsorption process. Consequently, the performances of these two parts were investigated as follows;

The effect of heat source temperature on the performance of adsorber is shown in Fig. 3. Actually, in this work, the hot water circulated along the water jacket of adsorber was acted as the heat source and transfer heat to the activated carbon filled in the adsorber. Therefore, the methanol adsorbed by the activated carbon was repelled.

In this part, the mass flow rate of hot water was 0.08 kg/s while its temperature was varied at 70, 80 and 90 °C. Note that the vapor of methanol was flow downward to a condenser which having the cooling water circulated inside. The mass flow rate and the temperature of cooling water were 0.06 kg/s and 10 °C. The parameters used for evaluating the performance of the system were the coefficient of performance (COP), the specific cooling power (SCP) and the volume capacity power (VCP).

From Fig. 3, it is found that the COP and SCP increase with the temperature of hot water, while the VCP decreases with the increasing of water temperature. It should be notice that, the COP of this system is around 0.6872 – 0.6997. The SCP and VCP vary in the ranges of 44.30 – 53.25 W/kg of activated carbon and 52.12 - 68.67 cm^3 of adsorber/W. These results could be explained as follows;

When the temperature of heat source is increased, the amount of methanol repelled from the activated carbon is increased. This result brings to get the increasing of liquid methanol in the storage tank (evaporator). Therefore, in the evaporation process, the energy extracted from the circulated water at an evaporator should be increased. However, the increasing of heat transfer of an evaporator is higher than that of an adsorber, therefore, the COP of system is increased especially when the hot water temperature is increased from 70 to 80 °C. However, the COP of system is slightly increased when the hot water temperature is increased from 80 to 90 °C. This result may be come from the limit of amount of methanol in the activated carbon.

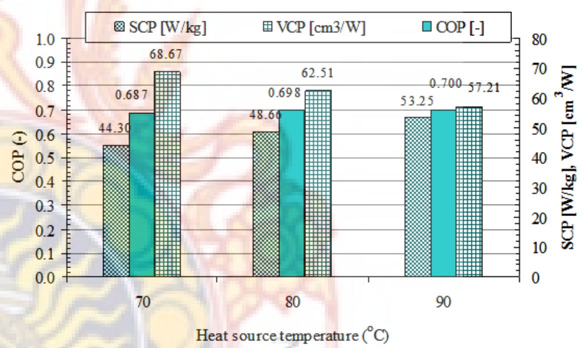

Fig. 2 The relationship between COP, SCP and VCP with the temperature of activated carbon.

During cooling process, the activated carbon bed is rejected heat to the environment by the thermosyphon heat pipe and the cooling water. Fig. 5 shows the effect of cooling method on the performance of cooling process of the activated carbon. In this experiment, the activated carbon is cooled down from 80 °C to 30 °C. It is found that when using only thermosyphon heat pipe or only cooling water the cool down times are approximately 5,640 s and 2,400 s respectively. When both of thermosyphon and cooling water is used, the cool down time is reduced to 1,800 s. The mass flow rate and temperature of cooling water is kept constant at 0.03 kg/s and 27 °C, respectively.

Since the thermosyphon heat pipe does not require the external energy for operating. Therefore, the combined cooling processes are the good choice to decrease the temperature of the activated carbon.

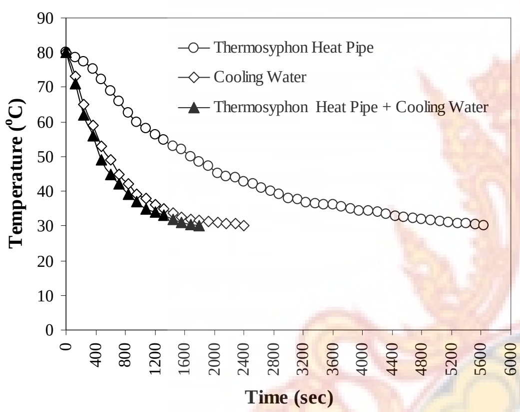

Fig. 3 Cool down time of activated carbon at various cooling methods.

3.3 Parameter affecting condenser performance

During the desorption process, the desorbed methanol vapor from the activated carbon is flowed downward to be condensed in the condenser. The cooling water is flowed inside the internal copper tube to remove heat of condensation. The flow rate of cooling water is kept constant at 0.06 kg/s and its temperature is varied from 5, 10 and 15 °C. The adsorber is started to be cooled down from temperature of 80 °C. The amount of condensate is measured that is found inversely proportional to temperature of cooling water. At 5 °C, 10 °C and 15 °C of cooling water temperature; the methanol volume is approximately 67.5 cm^3, 63 cm^3 and 50 cm^3, respectively.

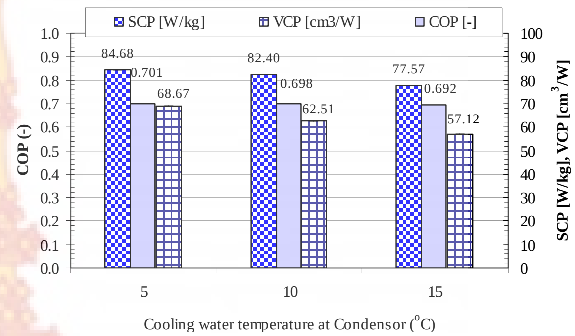

Fig. 4 Effect of cooling water temperature on system performance.

The influence of cooling water of condenser on the performance of adsorption system is illustrated in Fig.6. COP and SCP are slightly decreased with the cooling water temperature. Inversely, VCP is increased. Larger temperature difference between condenser and heat sink (or cooling water) temperature brings about more amount of condensate, so that larger evaporated methanol vapor in the following adsorption phase. Therefore, larger heat of evaporator obtained leading to higher COP and SCP.

3.3 Parameter affecting condenser performance

In the adsorption and evaporation phase, methanol receives heat from circulating water and vaporizes in the evaporator. The inlet temperature and the mass flow rate of circulating water are fixed at 30 °C and 0.0018 kg/s, respectively. The performance of evaporator is enhanced by ultrasonic wave. Ultrasonication generates alternating low and high pressure waves in methanol liquid, leading to cavitation or formation and collapse of small bubbles.

Cavitational collapse produces intense local heating, high pressure and enormous heating rate with very short lifetimes, providing a unique interaction of energy and matter [14]. Therefore, methanol is activated to be vaporized easily. The energy of ultrasonic wave can be adjusted by changing the wave frequency. In this experiment, the frequency of ultrasonic wave is 0 (or without wave), 8, 10 and 14 kHz.

The performances of evaporator under the ultrasonic wave are shown in Figs. 9. Moreover, the minimum water temperature when using ultrasonic wave is lower than that of no wave case approximately 3 °C. The result from Fig. 8 also agrees well with Fig. 7 that the heat transfer rate of circulating water and the amount of vaporized methanol are increased with the frequency of wave.

Fig. 5 shows the performance of adsorption system, COP, SCP and VCP. It should be noted that when apply the ultrasonic wave to the end of evaporator, the COP (from Eq.(9)) should be calculated from

$$COP = \frac{Q_{evap}}{Q_{1-2} + Q_{2-3} + Q_{ul}} \quad (9)$$

Where Q_{ul} is the energy supplied to the ultrasonic probe. For the frequency of 8, 10, and 14 kHz, this energy is 6.41, 27.94 and 65.85 W respectively.

From the experiment, it is found that when using 8 kHz of wave frequency the performance is the highest. This result can be explained as follow;

Since, the ultrasonic generator consumes electrical energy. The electrical energy consumption depends on the wave frequency. Although, the increasing of wave frequency brings to get higher heat transfer rate of an evaporator. It also increases the energy consumption. Therefore, the optimize frequency of wave in this case is 8 kHz. In case of SCP and VCP, it is found that these parameters are increased and decreased with the increasing of wave frequency because of shorten cycle time and larger evaporation heat.

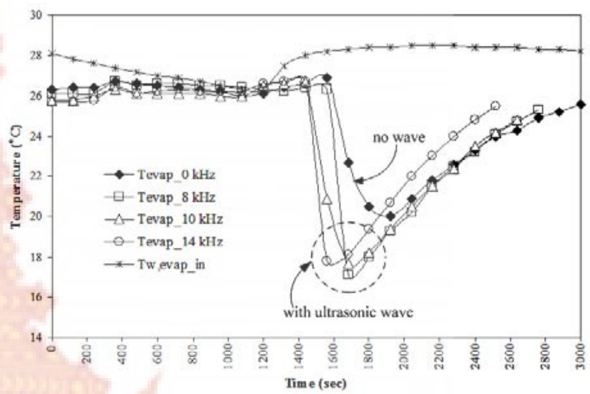

Fig.5 Temperature profiles of adsorption system with time

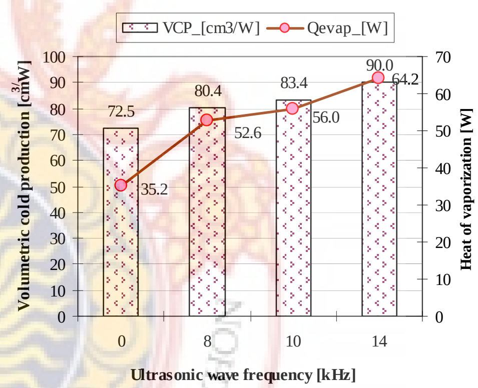

Fig. 6 The effect of ultrasonic wave on the heat transfer rate and the VCP.

4. Conclusions

In this paper we proposed and tested the application of an ultrasonic wave to an adsorption cooling system, based on activated carbon-methanol working pair. The experimental results showed that the adsorber was cooled down appropriately during cooling phase by two methods, cooling water and thermosyphon heat pipe.

The influence of heat source temperature on the adsorber, and heat sink temperature at the condenser, during desorption/ condensation phase was also interpreted. The ultrasonic wave adjusting frequency in the range of 8 kHz to 14 kHz was used to reduce evaporation temperature at the evaporator, so that the system performance indicated by COP, SCP and VCP can be improved. The system performance was considerably comparable to those from literatures. The highest COP and SCP obtained from this system was 0.718 and 248.90 W/kg, respectively.

5. Acknowledgements

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