CHAPTER 3

PERFORMANCE ANALYSIS OF A MODULAR ADSORPTION COOLING SYSTEM HAVING SONIC VIBRATION AT EVAPORATOR

The evaporator is the component where cold methanol is produced. High evaporation rate brings either larger heat extraction or cooling capacity, as well as its COP. The sonic wave vibration was applied to the evaporator to enhance the vaporization process. The in depth study of the parameters affecting the evaporation process and the influences of the sonic wave are discussed in this Chapter.

3.1 Introduction

Adsorption-evaporation is normally a time-consuming process; therefore, large vapor production at the evaporator is necessary so that the sonic wave can assist.

The role of sonication on the adsorption and/or desorption processes has been well studied (Rege et al. 1998; Breitbach and Bathen 2001; Schueller and Yang 2001; Li et al. 2002; Breitbach et al. 2003; Diter 2003; Hamdaoui et al. 2003; Zang et al. 2003). Most focused on its benefits on the treatment of toxic chemicals or pollutants by adsorbent beds relating to environmental issues. However, the use of a physical wave to enhance the adsorption cooling system was not reported.

3.2 Experimental system design

This research developed a new design of modular activated carbon methanol adsorption system of which its adsorber, condenser and evaporator were in vertical alignment (Figure 3.1). The vertical solid adsorption refrigeration unit consists of 3 main parts, an adsorber, a condenser and an evaporator.

The modular design helps to simplify fabrication and improve compactness of the casing, increasing the flexibility to upscale, and reduce maintenance tasks. There was also a sonic generator attached to the evaporator to enhance the boiling of methanol during the adsorption process.

The calorimetric power was inputted into the refrigerant in the sonicated evaporator, as mentioned by Breitbach et al. (2003) where the temperature rise and mass flow rate of the water medium could be measured.

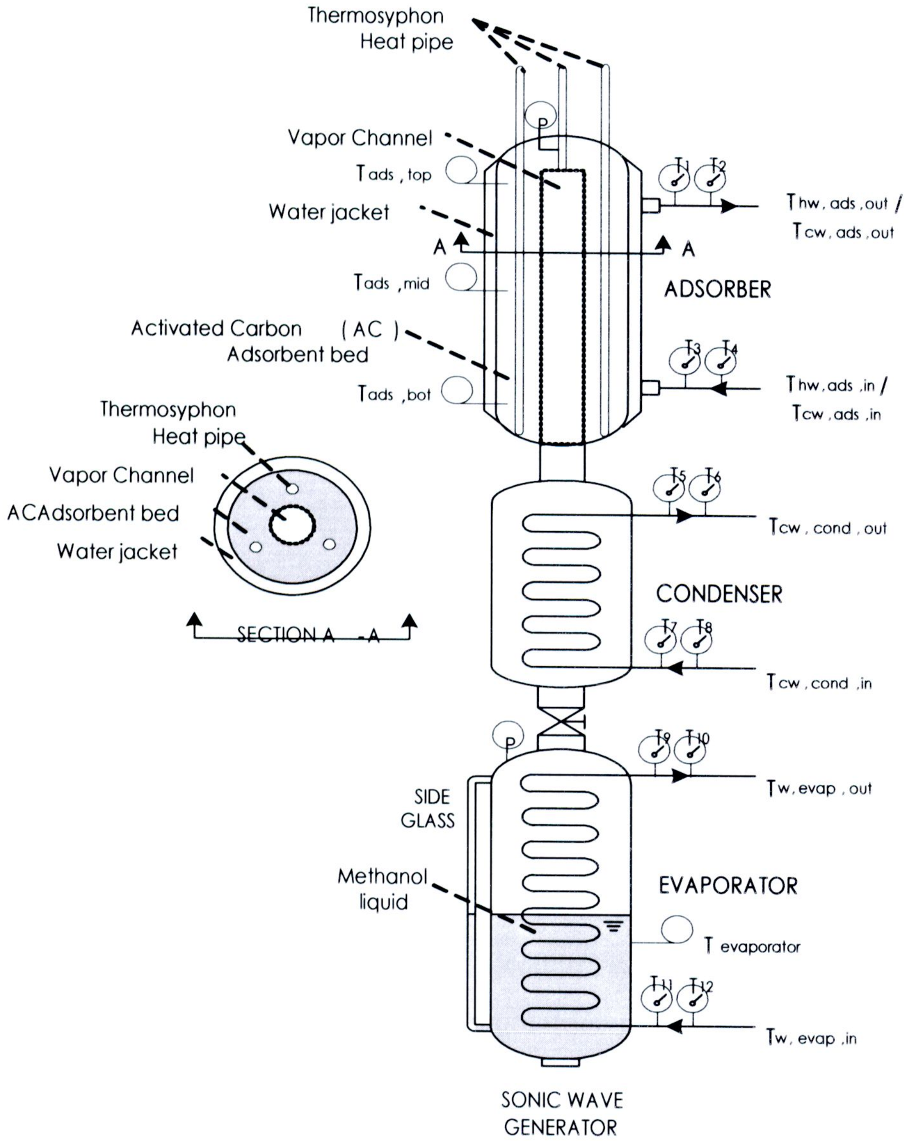

Figure 3.1 Schematic sketchs of the experiment apparatus

3.2.1 Adsorber

An adsorber was made of copper tube 7.62 cm in diameter and 100 cm in height. This adsorber was filled with 0.5 kg of 8×16 mesh size activated carbon produced from coconut shells. The adsorber was covered with a water jacket and the whole unit was well-insulated.

3.2.2 Evaporator

The evaporator of the adsorption system had the same dimensions as the condenser. The height of an evaporator and condenser sections were 100 and 50 cm, respectively.

During the evaporation of methanol, water was at the ambient temperature (28-35°C) circulating inside the copper coil, at the flow rate of 0.0018 kg/s. To enhance the vaporization process, a sonic wave generator model SUNON-DP200A was attached at the bottom of the evaporator. The maximum frequency of this sonic wave generator was 14 kHz.

3.2.3 Condenser

The condenser of the adsorption system was made from copper tubes 7.62 cm in diameter and 23 cm in length. Inside, there was 149 cm a copper coil with 10 mm diameter.

3.2.4 Instrumentation

3.2.4.1) Temperature

- Temperature measurements were taken by a set of K-type thermocouples having ± 0.1°C accuracy and recorded using a temperature data logger model TSUS-TASK24C.
- The temperature sensors were installed in the activated carbon, at the water inlet and outlet of the adsorber, the condenser and the evaporator.
- The evaporator temperature was measured by the thermocouple on the evaporator chamber's wall.

3.2.4.2) Pressure

- The pressures inside the adsorber and the evaporator were measured by two pressure gauges at ± 0.1 kPa accuracy.

3.2.4.3) Flow rate/ Volume

- The flow rate of water was calculated by measuring the mass of circulating water, during a period of time, and weighing the mass of water at ± 1 g accuracy.

- The methanol level inside the evaporator could be observed by a sight glass.

3.3 Experimental procedure

The operation of adsorption cooling undergoes through cycle, each comprising of 4 steps: heating, heating-desorption-condensation, cooling, and cooling-adsorption-evaporation.

3.3.1 Desorption process

- Hot water of 0.08 kg/s at 90°C circulated inside the water jacket to regenerate methanol vapor at the adsorber. Then, during the cooling phase, cold water circulated along the water jacket.

- The maximum temperature of the activated carbon was varied between 70°C and 90°C.

3.3.2 Condensation process

- The 5-15°C, 0.06 kg/s of cold water that circulating inside the copper coil.

3.3.3 Evaporation process

- The sonic wave was used to enhance the evaporation of methanol.
- The frequency of the sonic wave was varied between 8 and 14 kHz.

3.4 Experimental conditions

Table 3.1 shows a summary of the testing conditions of this research work.

Table 3.1 Summary of the testing conditions in this study

Parameter	Value
Mass of activated carbon (mesh size 8 x 16)	0.5 kg
Volume of methanol	900 cm^3
Desorption process	
Inlet hot water temperature	95°C
Mass flow rate of hot water	0.08 kg/s
Maximum temperature of activated carbon	70, 80, 90°C
Condensation process	
Inlet cooling water temperature	5, 10, 15°C
Mass flow rate of cooling water	0.06 kg/s
Evaporation process	
Inlet water temperature	28°C
Mass flow rate of cooling water	0.0018 kg/s
Frequency of the sonic wave	0, 8, 10 ,14 kHz
Adsorption process	
Inlet water temperature	28°C
Mass flow rate of cooling water	0.035 kg/s

3.5 Results and discussion

3.5.1 Thermal behavior of the adsorber

Thermal behavior of the adsorption cooling cycles, especially the adsorber, was discussed graphically in term of temperature profiles. Temperature evolutions from four adsorption cycles were depicted in Figure 3.2. For the first cycle, during desorption process, the adsorber was heated by about 90°C of hot water and the bed temperature was increased from its initial temperature, which was around 31.8°C.

Figure 3.2 shows the temperature profiles of the activated carbon bed (T_{ads}), the methanol in the evaporator (T_{evap}), the inlet and outlet of the circulating water at the evaporator ($T_{w,evap,in}$ and $T_{w,evap,out}$).

Temperature increased rapidly with time and the methanol was repelled from the activated carbon (Figure 3.2). Then the methanol vapor flowed to the condenser where the condensation took place and the condensate flowed downward to the evaporator. When the bed temperature reached 80°C, the desorption process stopped and the bed was cooled down, using the cooling water, until its temperature reached 30°C. The vapor pressure inside the adsorber dropped from approximately 180 kPa to 21 kPa. After that, the adsorption process starts and methanol vaporized back from the evaporator to the adsorber bed, while it extracted heat from the circulating water dropping the evaporator temperature down.

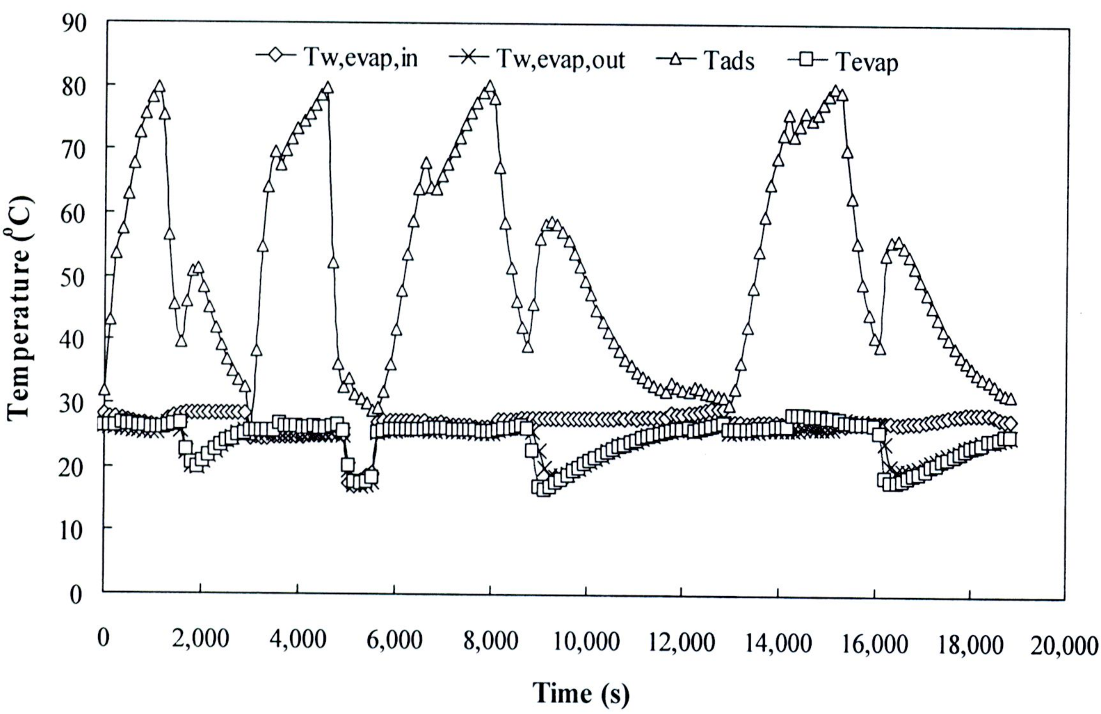

Figure 3.2 Temperature profiles of the bed and the evaporator including the evaporator circulating water.

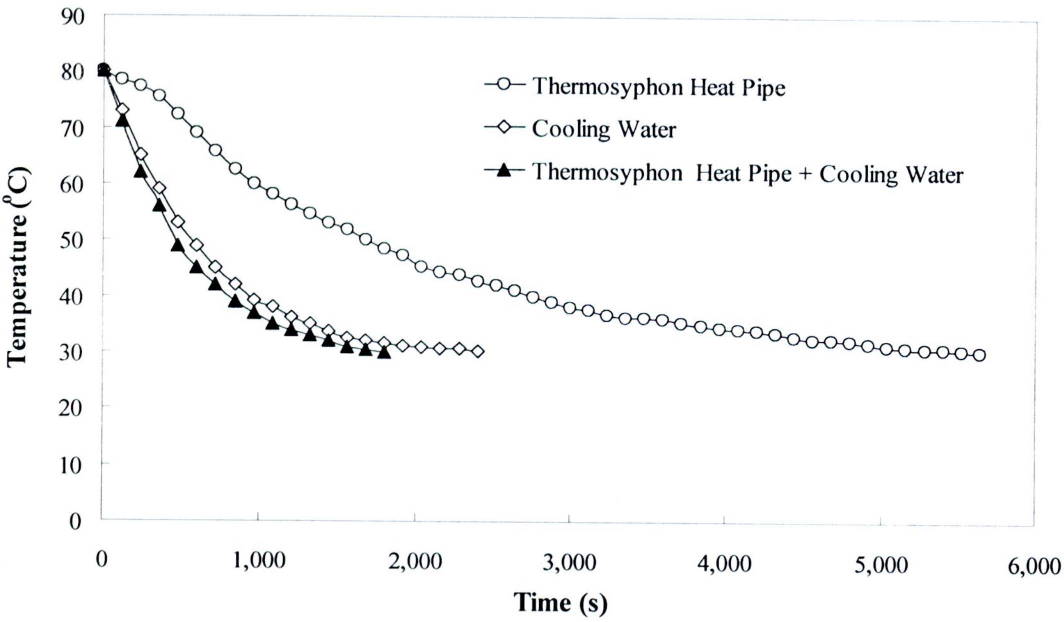

Figure 3.3 Cooling down time of activated carbon using various cooling methods

Temperature increased due to the adsorption heat. While the cooling was occluding on, the bed temperature dropped to its initial temperature and the evaporator temperature increased slightly. It could be seen that the outlet circulating water temperature at the evaporator was slightly higher than the methanol temperature in the evaporator. The first cycle was not assisted by the sonic wave, while the others were. It was obviously shown that the evaporator temperature in case of wave enhancement was lower than that without it.

During the cooling process, the activated carbon bed rejected heat to the environment through the thermosyphon heat pipe and the cooling water. Figure 3.3 shows the effect of cooling methods on the performance of cooling process of the activated carbon. In this experiment, the activated carbon was cooled down from 80°C to 30°C, but the mass flow rate and temperature of cooling water was kept constant at 0.03 kg/s and 27°C, respectively.

Three methods were applied; (1) cooling by thermosyphon heat pipe only, (2) cooling through cooling water circulation only and (3) cooling by both thermosyphon heat pipe and cooling water circulation.

3.5.2 Thermal behavior of the evaporator

In the adsorption and evaporation phase, methanol got heat from circulating water and vaporizes in the evaporator. The inlet temperature and the mass flow rate of circulating water were fixed at 30°C and 0.0018 kg/s, respectively. The performance of the evaporator was enhanced by the sonic wave. Sonication generated alternating low and high pressure waves in methanol liquid, leading to cavitations or formation and collapse of small bubbles. Cavitations collapse produced intense local heating, high pressure and enormous heating rate with very short lifetimes (Suslick, 2008). Therefore, methanol activated carbon and vaporized it easily. The energy of the sonic wave could be adjusted by changing the wave frequency. In this experiment, the frequency of the sonic wave was adjusted at 0 (or without wave), 8, 10 and 14 kHz.

The temperature evolutions of the evaporator under the sonic wave (Figure 3.4), which when using the sonic wave, the circuiting temperature of circulating water at an evaporator immediately changes compared to that of no wave (0 kHz).

3.5.3 Parameters affecting adsorption system performance

The relevant parameters that affected the adsorption system performance were (1) regeneration temperature, (2) cooling water temperature at condenser, and (3) cooling rate of the adsorber after the desorption process.

The regeneration or heat source temperature was indicated by inlet hot water temperature circulating throughout the water jacket. The mass flow rate of hot water was 0.08 kg/s while its temperature varied between 70, 80 and 90°C. The desorbed methanol vapor flowed downward and condensed in a condenser. The mass flow rate and the temperature of cooling water at the condenser were 0.06 kg/s and 10°C.

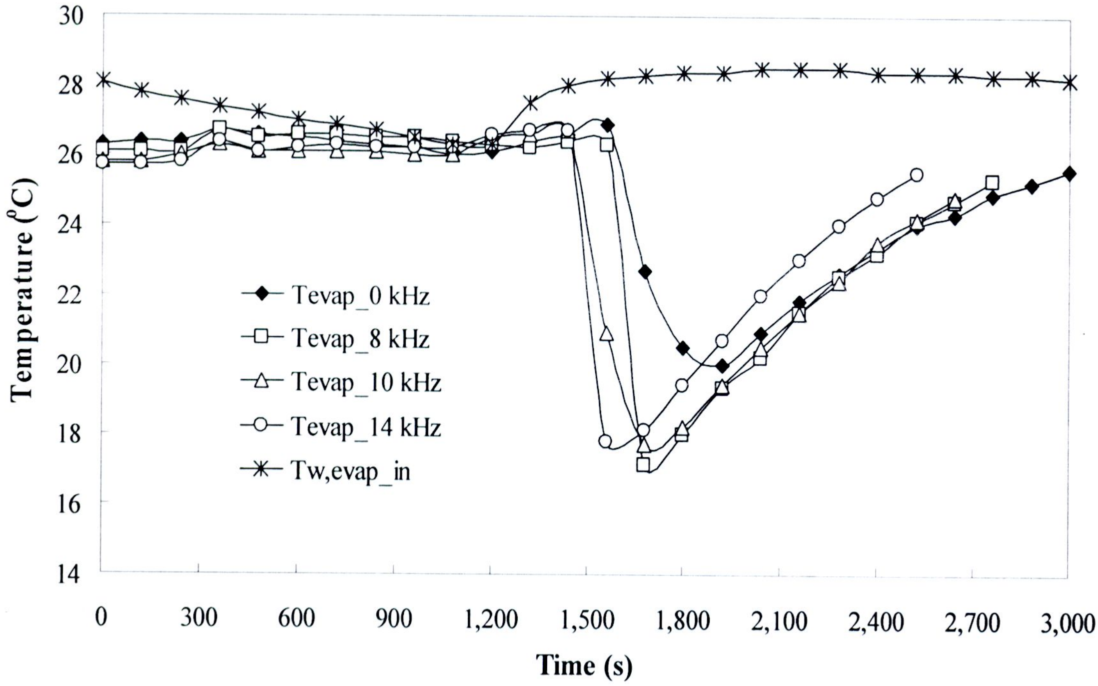

Figure 3.4 Temperature profiles of the adsorption system over time.

When applying the sonic wave at the end of the evaporator, the *COP* (from Equation (3.1)) should be calculated from

$$COP = \frac{Q_{evap}}{Q_{1-2} + Q_{2-3} + Q_{sonic}}. \tag{3.1}$$

Where Q_{sonic} is power supplied to the sonic wave generator. In this study, the power was 6.41, 27.94 and 65.85 W for the frequencies of 8, 10, and 14 kHz, respectively.

The effect of heat source temperature on the COP, SCP and VCP of the adsorber without sonic wave is shown in Figure 3.5. The COP and SCP increased with an increase of hot water temperature, while the VCP decreased. The COP, SCP and VCP were varied in the range 0.6872 – 0.6997, 44.30 – 53.25 W/kg of activated carbon, and 57.21 - 68.67 cm^3 of adsorber/ W, respectively. The details of *COP, SCP* and *VCP* calculations were shown in Appendix A.

During the desorption process, the desorbed methanol vapor from the activated carbon flowed downward and condensed in the condenser. The cooling water was flowing inside the internal copper tube to remove condensation heat of the flow rate. The flow rate of cooling water was kept constant at 0.06 kg/s and its temperature was varied at 5, 10 and 15°C. The adsorber started to be cooled down at the temperature of 80°C. The amount of condensate was measured and it was found to be inversely proportional to the cooling water temperature.

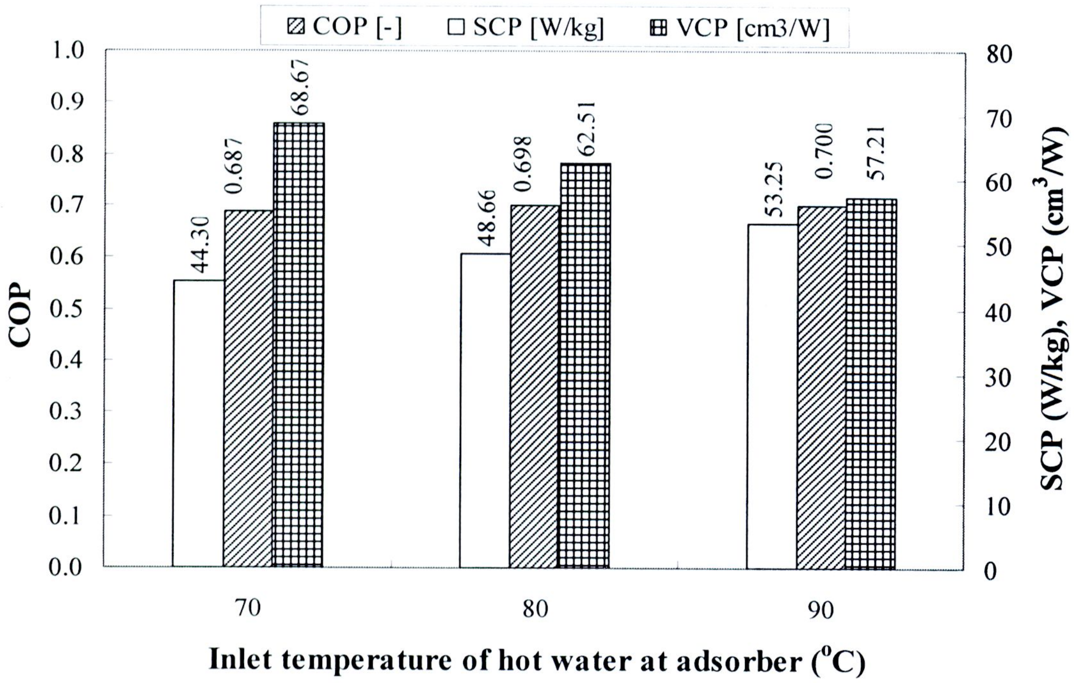

Figure 3.5 Relationship of COP, SCP and VCP with the heat source temperature without sonic wave.

The influence of cooling water in to condenser on the performance of adsorption system is illustrated in Figure 3.6. The *COP* and *SCP* were slightly decreased with the cooling water temperature. Inversely, *VCP* was slightly increased.

Larger temperature difference between the condenser and heat sink (or cooling water) temperature brought about more amount of condensate which resulted in larger evaporated methanol vapor in the following adsorption phase. At 5°C, 10°C and 15°C of cooling water temperature; the methanol volume was found to be approximately

67.5 cm^3, 63 cm^3 and 50 cm^3, respectively. Therefore, more heat of evaporation led to higher *COP* and *SCP*.

In the contrary, *VCP* was reduced thus greater system compactness was achieved during cooling. However, from 80°C to 90°C, *COP* slightly increased due to the limit of adsorbent methanol amount in the adsorbent bed.

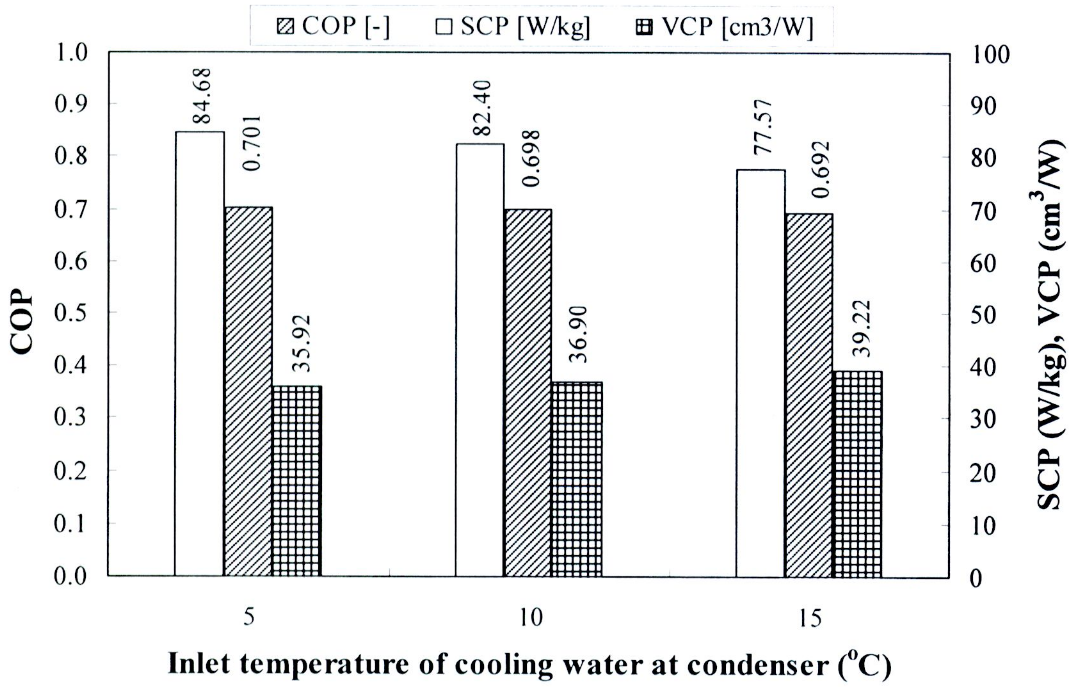

Figure 3.6 Effect of cooling water temperature on system performance without sonic wave.

Moreover, the minimum water temperature when using a sonic wave was lower than that of no wave case around 3°C. The result from Figure 3.7 was in agreement well with Figure 3.6 that the heat transfer rate of circulating water and the amount of vaporized methanol were increased with the frequency of the sonic wave.

Figure 3.8 shows the performance of the adsorption system. *COP*, *SCP* and *VCP*.

From the experiment, it was found that 8 kHz was the suitable wave frequency that gave highest *COP*.

In case of the *SCP* and *VCP*, it was found that these parameters were increased and decreased with the increasing of sonic wave frequency because of shortened cycle time and larger evaporation heat.

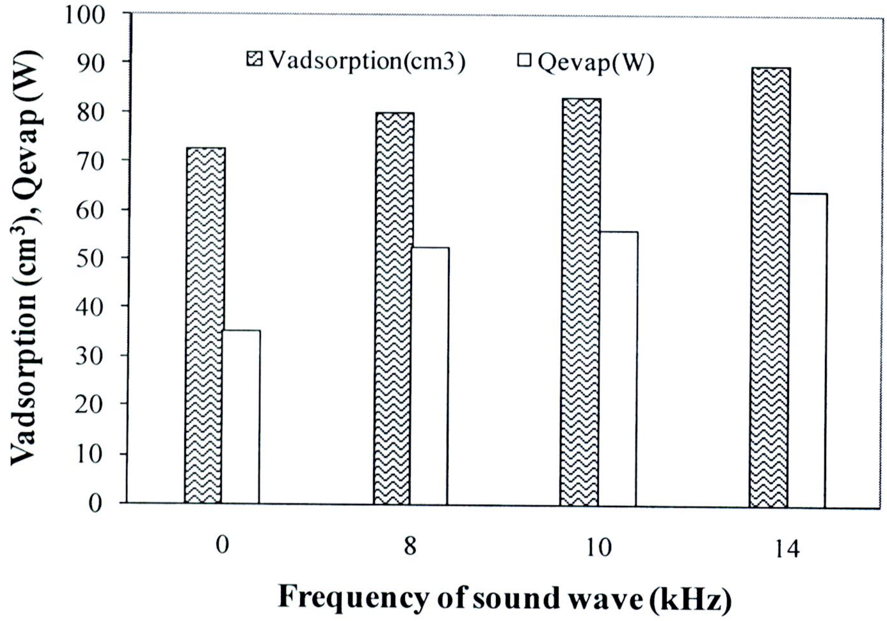

Figure 3.7 The effect of the sonic wave on the heat of vaporization and the volumetric methanol production.

3.6 Performance comparison with previous works

The comparison of adsorption system performance with previous works is summarized in Table 3.2. It was found that the *COP* of designed system is higher than those of Tiansuwan et al. (1998), Wu et al. (2002) and Wang et al. (2006a). These results may become from the effect of sonic wave that enhanced the methanol vaporization phenomenon in an evaporator.

However, the performance of the presented system is slightly lower than that of Qu et al. (2001) which used a plate finned shell and tube adsorber. The double pipe adsorber is easier to construct and the system is easily installed with a sonic wave generator to enhance its thermal performance. The technique could be conducted in many applications, for example, solar thermal process, waste heat recovery and so on.

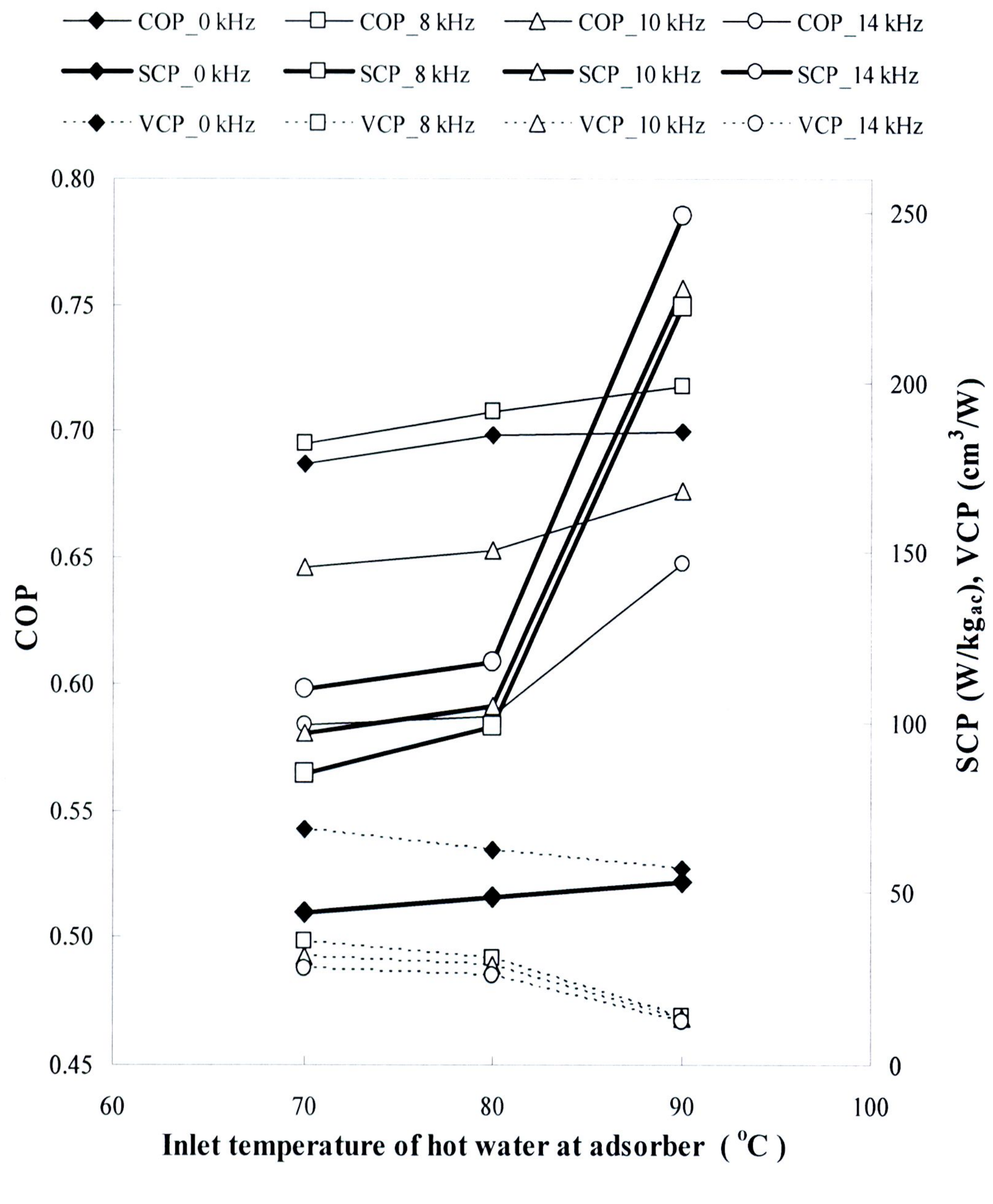

Figure 3.8 Effect of the sonic wave on system performance.

Table 3.2 Performance comparison with previous work.

	Present study	Tiansuwan et al. (1998)	Qu et al. (2001)	Wu et al. (2002)	Wang et al. (2006a)
Working pair	AC/Methanol	AC/Ethanol	AC/Methanol	AC/Methanol	AC/Methanol
Adsorber type	Double pipe	Double pipe	Plate finned shell and tube	Shell and tube	Shell and tube
Mass of AC (grams)	500	200	2,600 x 2	2,600 x 2	6,000 x 2
Inlet temperature of hot water at the adsorber (°C)	95	70-150 (hot oil)	95	100	100
Inlet temperature of cooling water at the condenser (°C)	5-15	25-45	30	6	25 (sea water)
Inlet temperature of water at the evaporator (°C)	28	20	5	21	30
Maximum COP	0.718	0.6	0.764	0.4	0.14
Maximum SCP (W/kg_{ac})	248.90	-	-	150	35
Minimum VCP (cm^3/W)	12.22	-	-	2.00	6.67
Application	Air conditioning	Refrigeration	Air conditioning	Refrigeration	Ice making

3.7 Conclusion

The application of a sonic wave to an adsorption cooling system, based on activated carbon-methanol working pair, was proposed in this paper. The influence of the heat source temperature on the adsorber, and the heat sink temperature at the condenser, during desorption/condensation phase were interpreted.

The adsorber was cooled down appropriately during cooling phase by the combination of two methods, cooling water and a thermosyphon heat pipe. The sonic wave adjustment frequency in the range of 8 kHz to 14 kHz was used to reduce the evaporation temperature and the time at the evaporator, so the system performance, indicated by COP, SCP and VCP, could be improved. The system performance was comparable to those from previous literature. The highest COP and SCP obtained from this system were 0.718 and 248.90 W/kg, respectively.