CHAPTER 4

PERFORMANCE ANALYSIS OF A MODULAR ADSORPTION COOLING SYSTEM WITH A SONIC VIBRATION AT THE ADSORBER

The adsorption cooling system not only enhanced its performance by the sonic wave at the evaporator but also at the adsorber. Sonication is to increased the regeneration rate of methanol from the activated carbon adsorbent. Therefore, its performance indication, COP, SCP could be increased. The analysis of experimental result on a modular adsorption cooling unit are discussed in this chapter.

4.1 Introduction

An adsorber and evaporator are the key components of an adsorption cooling system. Recently, Wongsuwan et al. (2011) have shown that sonic waves can improve the performance of a modular adsorption cooling system using activated carbon-methanol as the working pair.

A sonic wave generator was found to enhance the heat transfer required for the boiling of methanol during the adsorption and evaporation processes and to reduce the evaporation time. Oh et al. (2002) applied an ultrasonic wave to a phase change material (PCM). A container was filled with paraffin wax, which was the PCM, an ultrasonic probe was attached to the bottom of the container, and an electric heater covered the outside surface of the container. When the wave was applied to the paraffin wax, the PCM vibrated, resulting in a melting time that was around 2.5 times lower than that of the case without an ultrasonic wave. Kim et al. (2004) studied the vibrations caused by an ultrasonic wave in the case of pool boiling and natural convection heat transfer. A wire-type electric heater was submerged in a liquid pool, and a wave was then transferred into the liquid. The vibration caused by the ultrasonic wave promoted rapid boiling.

A sonic wave was expected to enhance the adsorber performance, and the increased desorption rate would result in a higher COP and SCP. A sonic wave generator was used to enhance methanol decomposition in the adsorber during the desorption process.

This research focused on the application of a sonic wave during the regeneration process in the adsorber. Extensive experimental work was performed to analyse the influence of a sonic wave on the COP, SCP and VCP of a modular adsorption cooling unit, at various frequencies and various adsorber inlet heat sources and heat sink temperatures.

A sonic wave was applied to the external surface of the adsorber to enhance the expulsion of methanol from the activated carbon. The goal of this research was to improve knowledge on the application of sonic waves.

4.2 Sonic wave inception

The mechanical wave induced by a sonic wave generator creates variations in pressure or density. When the wave propagates through a medium, it is attenuated by absorption, by cavitation bubbles, by particles, and at the interfaces (Breitbach et al., 2003). The high sound intensities produce either nonlinear phenomena or acoustic cavitation that exceeds the liquid tensile stress. During the rarefaction cycle of a sonic wave, a large negative pressure is applied to the liquid, and small gas bubbles form during the expansion cycle of the sound wave, which grows to many times their initial size over one or more cycles (Juang et al., 2006). The bubbles are either stable for many cycles or transient, so that they grow to critical size and then violently collapse during the compression part of the wave.

The energy that is released causes extreme thermodynamic conditions in the vicinity of the imploding bubbles, such as very high temperatures and pressures, and large shear forces occur in the surrounding liquid (Mason, 1991). As the bubbles collapse, localised areas of high temperature lead to slight increases in system temperature, and localised areas of high pressure in the fluid create high-speed micro-jets with high-pressure shock waves (Hamdaoui et al., 2003). These waves, and the associated microdisturbances of cavitation bubbles near the surface of a solid, reduce the mass transfer boundary layer and thus effectively increase mass transfer (Penn et al., 1959).

4.3 Experimental set-up

The research was based on a number of experimental sets. Figure 4.1 shows a schematic diagram of the modular adsorption cooling unit. The cooling unit consisted of 3 main parts: an adsorber, a condenser and an evaporator.

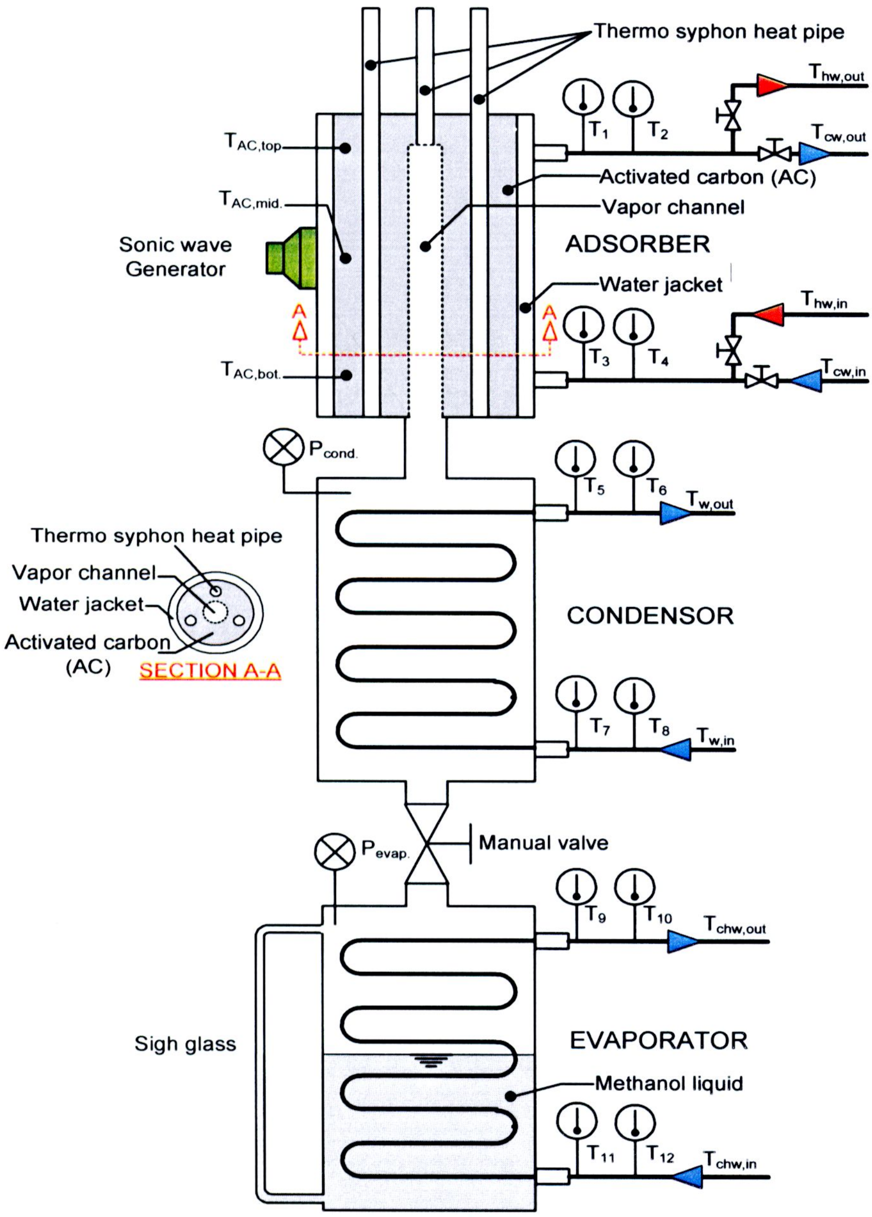

Figure 4.1 A schematic diagram of the modular solid adsorption cooling unit.

4.3.1 Adsorber

The adsorber was made of a copper tube 7.62 cm in diameter and 100 cm high. The adsorber was filled with 0.5 kg of activated carbon made from coconut shell, with a mesh size of 8×16. The external surface of the adsorber was covered with a water jacket, and the whole unit was well insulated.

To enhance decomposition of the working fluid in the adsorber, a model SUNON-DP200A "sonic wave generator" was attached to the centre of the side of the adsorber.

4.3.2 Condenser

The condenser in the adsorption system consisted of a copper tube 7.62 cm in diameter and 23 cm in length, with a copper coil, 149 cm in length and 10 mm in diameter, inside.

4.3.3 Evaporator

The evaporator in the adsorption system had the same dimensions as the condenser. During the evaporation of methanol, cold water at 10 - 20°C was circulated inside the copper coil at a flow rate of 0.0018 kg/s.

4.3.4 Instrumentation

4.3.4.1) Temperature

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

4.3.4.2) Pressure

- The pressure inside the adsorber and the evaporator was measured using two pressure gauges, with an accuracy of ± 0.1 kPa.

4.3.4.3) Flow rate

- The flow rate of water was calculated using the mass of circulating water during a specified period of time.

4.3.4.4) Methanol level

- The methanol level inside the evaporator was observed with a sight glass. The digital weighing apparatus had an accuracy of ± 1 g.

4.3.5 Operation

- During the condensation process, ambient temperature water (24-28°C) was circulated inside the copper coil at 0.06 kg/s.
- During the desorption process, hot water at 95°C was circulated inside the water jacket at a rate of 0.08 kg/s to regenerate methanol vapour in the adsorber.
- During the cooling phase, cold water was circulated in the water jacket. The frequency range of this wave generator was 8-14 kHz.

Table 4.1 contains a summary of the experimental conditions. During the desorption process, the maximum temperature of the activated carbon varied between 80^0C and 90^0C. During the heating-condensation process, a sonic wave was applied to the external surface of the adsorber to enhance methanol decomposition and release it from the activated carbon.

Table 4.1 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	80, 90°C
Frequency of the sonic wave	0, 8, 10, 14 kHz
Condensation process	
Inlet water temperature	24-26°C
Mass flow rate of water	0.06 kg/s
Evaporation process	
Inlet cooling water temperature	10, 15, 20°C
Mass flow rate of cooling water	0.0018 kg/s
Adsorption process	
Inlet water temperature	24- 26°C
Mass flow rate of cooling water	0.035-0.045 kg/s

4.4 Results and discussion

The operation of adsorptive cycles was analysed and discussed through four aspects of the cycles:

- The thermal behaviour of the adsorption system, i.e., inlet heating water of the adsorber and the sonic wave frequency.

- The parameters affecting the adsorber, i.e., the regeneration temperature, the water temperature in the condenser, and the cooling rate of the adsorber after the desorption process.
- The valve opening effect, i.e., temperature when the valve opened, wave frequency.
- The parameters affecting the evaporator, i.e., cold water temperature, wave frequency.

4.4.1 Thermal behaviour of adsorption system

Figure 4.2 shows the temperature profiles from four adsorption cycles with or without a sonic wave: the activated carbon bed (T_{ads}), the methanol in the evaporator (T_{evap}), and the inlet and outlet temperatures of the circulating water in the evaporator ($T_{w,evap,in}$ and $T_{w,evap,out}$).

A sonic wave was applied to the adsorber during the desorption–condensation process. During each cycle, the temperature of the activated carbon varied from 70 to 90°C. The vapour pressure inside the adsorber dropped from approximately 256.35 kPa to 19.44 kPa.

The cycle time decreased with increasing wave frequency. For a wave frequency of 14 kHz, the cycle time was around 25% less than that of the case without a wave. The explanation for this result is as follows:

The sonic wave penetrated from the jacket surface through the water covering the activated carbon container. The penetrating wave could promote vibrations between the outer surface of the activated carbon container and the fluid media. The vibration of the activated carbon container would thus enhance the heat transfer rate between the activated carbon and the adsorbed methanol. Consequently, a higher methanol desorption rate would be achieved.

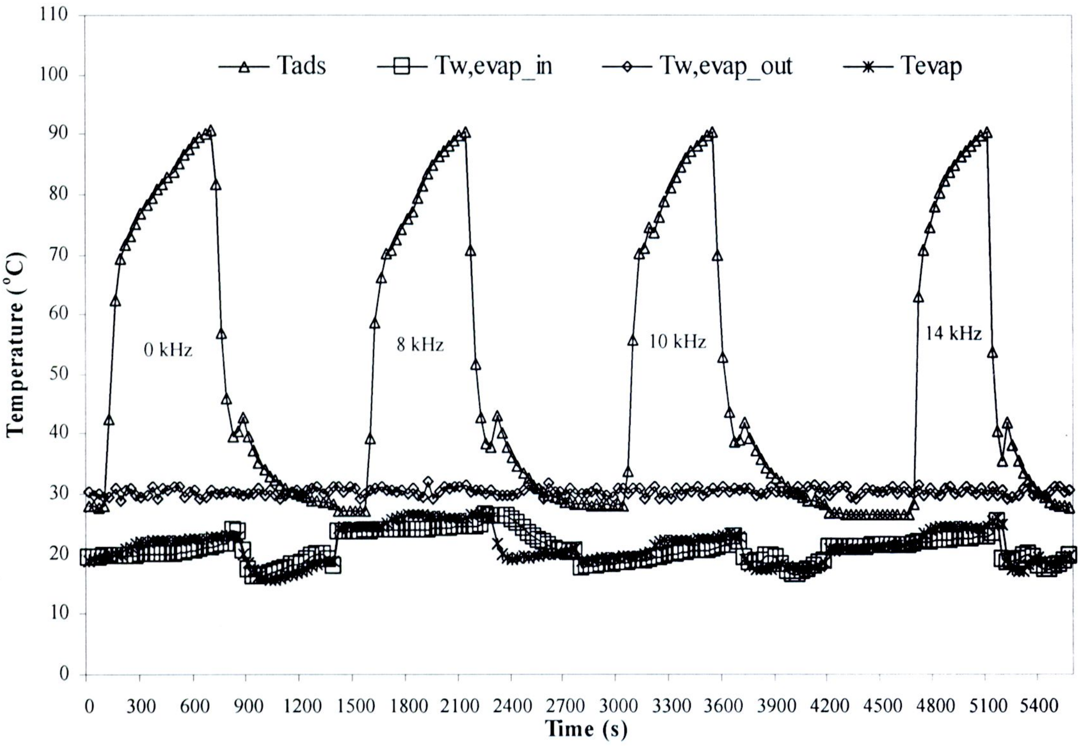

Figure 4.2 Temperature profiles of the adsorption system.

4.4.2 Parameters affecting adsorber performance

The relevant parameters that affected the adsorption system performance were the regeneration temperature, the water temperature in the condenser, and the cooling rate of the adsorber after the desorption process.

The regeneration or heat source temperature is the inlet temperature of the hot water circulated through the water jacket. The mass flow rate of the hot water was 0.08 kg/s, and its temperature varied from 80 to 90°C. The desorbed methanol vapour flowed downward to condense in a condenser. The mass flow rate and the temperature of the water in the condenser were 0.06 kg/s and 24°C.

The effect of a hot water inlet temperature of 90°C on the volume of evaporated methanol ($V_{met.}$), and the COP, SCP and VCP of the adsorber for sonic wave frequencies of 0 kHz (no wave), 8 kHz, 10 kHz and 14 kHz are shown in Figures 4.3 - 4.6.

The volume of evaporated methanol ($V_{met.}$), the COP and the SCP increased with increasing hot water temperature and sonic wave frequency, whereas the VCP decreased. Unlike the other indicators, a lower VCP indicates better efficiency.

For a heat source temperature of about 90°C, the $V_{met.}$, COP, SCP and VCP vary from 13.46 – 51.92 mL (85.74-285.74%), 0.3783 – 0.5929 (8.83-49.05%), 40.36 – 172.77 W/kg of activated carbon (218.21-328.07%), and 17.61-75.38 cm^3 of adsorber volume per W (218.19-328.05%), respectively.

The experimental results indicate that 14 kHz is the wave frequency resulting in the highest expelled volume of methanol from the activated carbon, the highest COP and SCP and the lowest value of VCP.

During the desorption process, the desorbed methanol vapour from the activated carbon flowed downward and condensed in the condenser. The cooling water flowed inside the internal copper tube to remove the heat of condensation. The flow rate and temperature of water were kept constant at 0.06 kg/s and 24°C. The adsorber cooling began at temperatures of 80 and 90°C. The amount of condensate was inversely proportional to the hot water temperature in the adsorber.

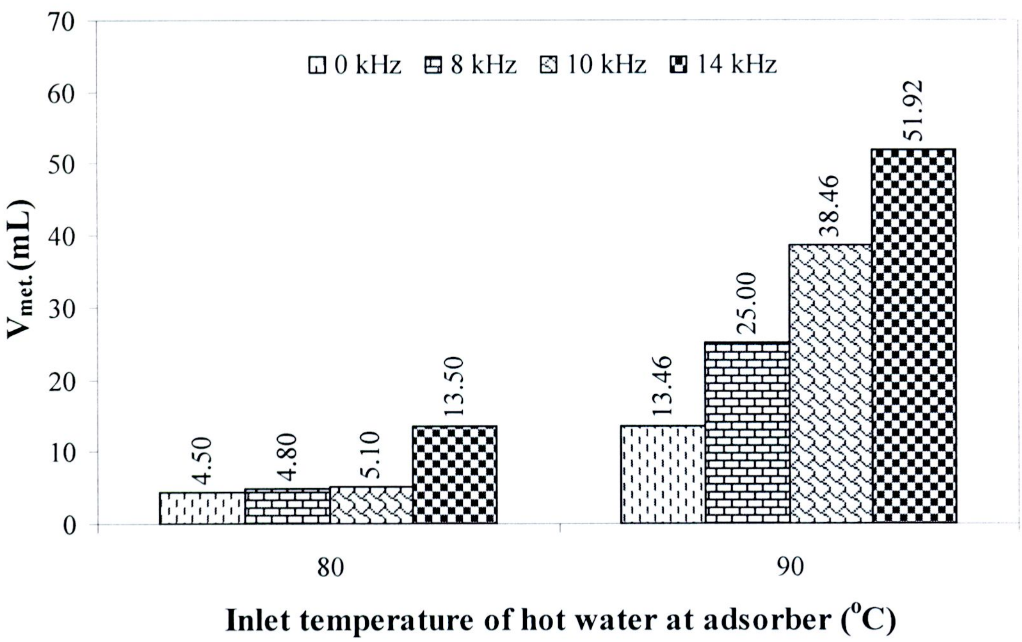

Figure 4.3 Effect of the hot water temperature at the inlet of the adsorber on the volume of methanol condensate.

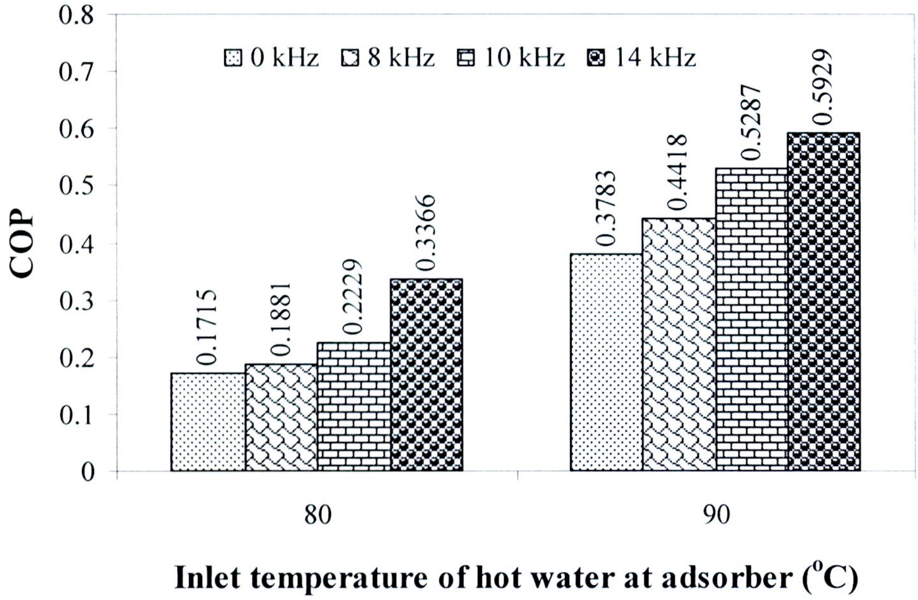

Figure 4.4 Effect of the hot water temperature at the inlet of the adsorber on system performance.

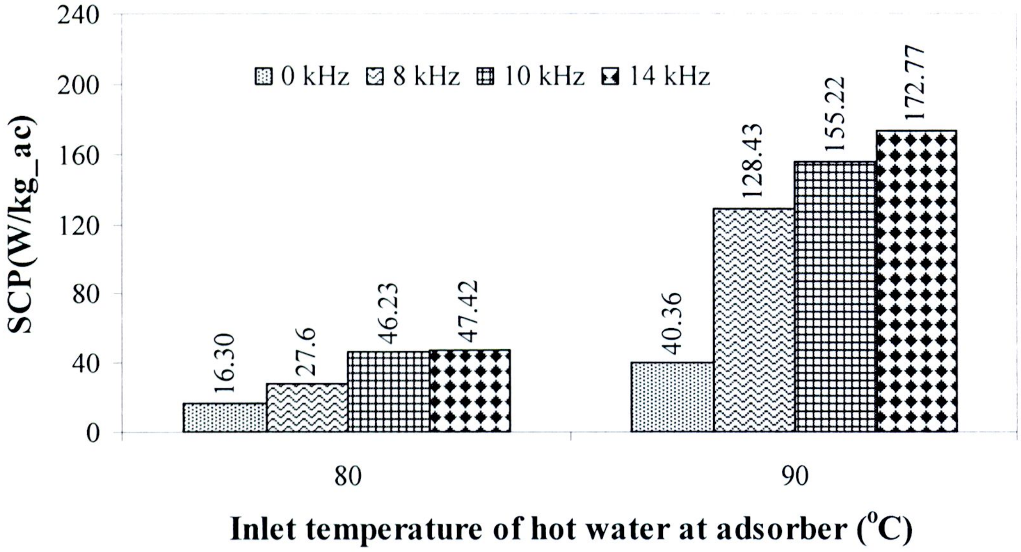

Figure 4.5 Effect of the hot water temperature in the adsorber on specific cooling power.

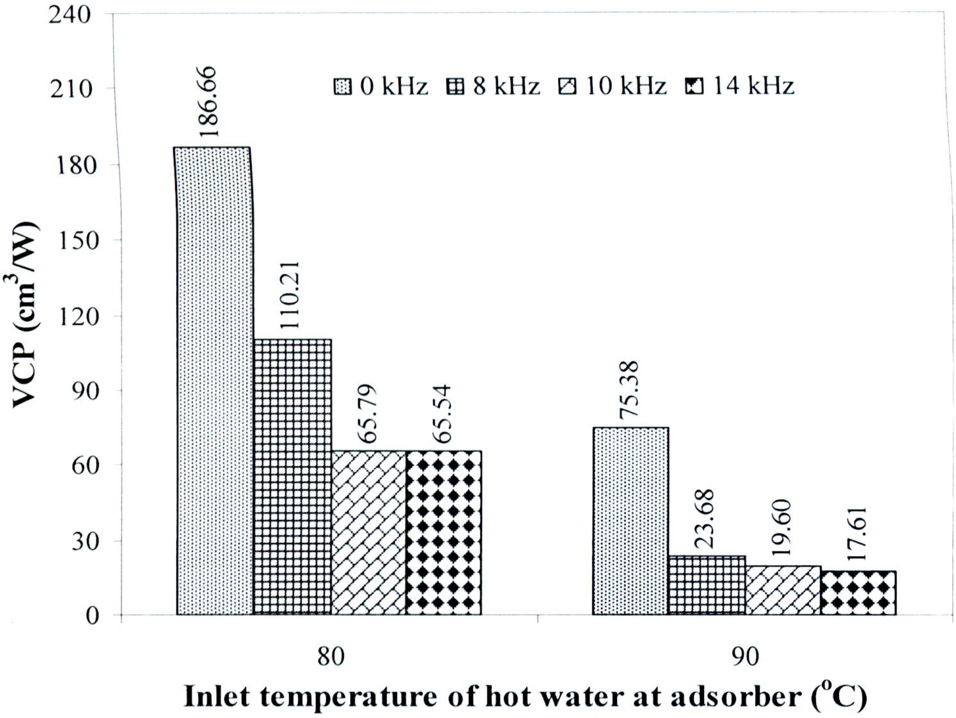

Figure 4.6 Effect of the hot water temperature at the inlet of the adsorber on volumetric cold production.

Table 4.2 Effect of valve opening temperature.

	T_{ac_valve} (°C)	Frequency of Sonic Wave (kHz)			
		0	8	10	14
V_{met} (mL)	60	8.54	13.46	23.08	50.92
	70	13.46	25.00	38.46	53.85
COP (-)	60	0.3304	0.3802	0.4975	0.5929
	70	0.3783	0.4418	0.5287	0.6196
SCP (W/kg_ac)	60	48.68	51.28	97.84	172.77
	70	40.36	128.43	155.22	229.15
VCP (m^3/W)	60	62.48	59.32	31.09	13.27
	70	75.38	23.68	19.6	17.61

4.4.3 Effect of valve opening temperature

During the desorption process, the desorbed methanol vapour from the activated carbon flowed downward to be condensed in the condenser. The cooling water flowed inside the internal copper tube to remove the heat of the condensation. The flow rate and temperature were kept constant at 0.06 kg/s and 24°C. The temperature of the circulating water at the inlet of the adsorber for the "valve open" condition was either 60 or 70°C, whereas adsorber cooling was initiated at a temperature of 90°C.

The effect of the open valve hot water inlet temperature on the volume of the evaporated methanol ($V_{met.}$) and on the COP, SCP and VCP of the adsorber for sonic wave frequencies of 0 kHz (no wave), 8 kHz, 10 kHz and 14 kHz are shown in Table 4.2. For cases where a wave is applied, the volume of evaporated methanol ($V_{met.}$), the COP and the SCP increase with both the increasing temperature of the hot water at the "valve open" condition and the sonic wave frequency, whereas the VCP decreased.

At an open valve temperature of about 70°C, the $V_{met.}$, COP, SCP and VCP varied from 13.46 – 53.85 mL (85.74-300.07%), 0.3783 – 0.6196 (14.37-38.95%), 40.36 – 229.15 W/kg of activated carbon (218.21-328.07%), and 17.61-75.38 cm^3 of adsorber volume per W (218.19-328.05%), respectively.

4.4.4 Parameters affecting evaporator performance

In this section, the performance of the evaporator is presented. The evaporator was first filled with liquid methanol, which then adsorbed heat from the circulating water, resulting in the vaporisation of methanol and a decrease in the circulating water temperature.

The flow rate of the cooling water was kept constant at 0.0018 kg/s, and its temperature varied from 10 to 15 to 20°C.

Table 4.3 Parameters affecting evaporator performance.

	T_{cw_evap} (°C)	Frequency of Sonic Wave (kHz)			
		0	8	10	14
V_{met} (mL)	10	4.50	5.77	6.75	7.20
	15	7.69	10.17	15.38	19.23
	20	13.46	25.00	38.46	51.92
COP (-)	10	0.1501	0.1553	0.1751	0.2019
	15	0.2600	0.3290	0.3992	0.4151
	20	0.3783	0.4418	0.5287	0.6196
SCP (W/kg_ac)	10	16.88	18.47	27.09	29.04
	15	36.61	51.53	55.10	68.50
	20	40.36	128.43	155.22	172.77
VCP (m^3/W)	10	180.23	164.69	112.29	104.73
	15	83.08	59.03	55.20	44.41
	20	75.38	23.69	19.60	17.61

The resulting performance of the evaporator as the cooling water temperature changed is shown in Table 4.3. The volume of methanol evaporated from the evaporator (V_{met}) increased with the temperature of the cooling water; for temperatures of 10, 15 and 20°C, the evaporated methanol volume was 4.50 mL, 7.69 mL and 13.46 mL, respectively.

The COP and SCP increased with an increase in cooling water temperature, but the VCP decreased. These results could be explained as follows.

When the temperature of the cooling water rises, the amount of methanol that is vaporised increased. It follows that the volume of evaporated methanol during the next evaporation process will also increase, which results in a higher transfer rate for the evaporation process and better system performance.

4.4.5 Performance comparison with previous work.

A comparison of the adsorption system performance with previous work is summarised in Table 4.4. The *COP* of the designed system is higher than those of Tiansuwan et al. (1998), Wu et al. (2002) and Wang et al. (2006b). The improved performance is a result of the effect of the sonic wave, which improves desorption of methanol from the activated carbon bed. However, the performance of this system is slightly lower than that of Qu et al. (2001), who used a plate finned shell and tube adsorber.

Table 4.4 Performance comparisons 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 water at the condenser (°C)	24-26	25-45	30	6	25 (sea water)
Inlet temperature of cooling water at the evaporator (°C)	10-20	20	5	21	30
Maximum COP	0.619	0.6	0.764	0.4	0.14
Maximum SCP (W/kg_{ac})	229.15	-	-	150	35
Minimum VCP (cm^3/W)	17.61	-	-	2.00	6.67
Application	Refrigeration	Refrigeration	Air conditioning	Refrigeration	Ice making

Nevertheless, the double pipe adsorber is easier to construct, and the system can easily be installed with a sonic wave generator to enhance its thermal performance. This technique could be used in many applications, such as solar thermal processes, waste heat recovery and others.

4.5 Conclusion

In this study, we proposed and tested the application of a sonic wave generator to the adsorber in an adsorption cooling system using activated carbon-methanol as the working pair. Desorption was accomplished using two methods: circulating hot water through the water jacket and applying a sonic wave in the range of 8-14 kHz.

The sonic wave was used to increase the temperature in the adsorber to improve system performance, as indicated by the COP, SCP and VCP. The highest COP, SCP and VCP obtained from this system were 0.619, 229.15 W per kg of activated carbon, and 17.61 cm^3 of adsorber volume per W, respectively.