CHAPTER 1

INTRODUCTION

1.1 Statement and significance of the problem

Adsorption cooling is one of the sustainable refrigeration technologies which has been investigated and utilized in various applications, especially the industrial processes, for many years (Wang et al. 2006a). It consumes low levels of electrical energy compared to conventional refrigeration systems. The adsorption cooling has no crystallization problems in the adsorption system. It requires the simple control system, low operating costs, and has no emission, implying it is environmental-friendly (Wang and Zhang 2009).

For many years, a number of research works have been conducted to investigate the performance of the adsorption systems and their applications. Zhang (2000) studied an adsorption air-conditioning system that had sorption beds regenerated by exhaust gases of a bus. This system used zeolite and water as the adsorbent and working fluids, respectively, giving the coefficient of performance (COP) of about 0.38. Wang et al. (2001) used an activated carbon-methanol pair in an adsorption system, of which the adsorber was a tube and plate heat exchanger. The cooling power was about 3.8 kW with COP of 0.4. Tamainot-Telto and Critoph (2003) studied a modular adsorption air-conditioner, powered by hot air. Lu et al. (2004) developed an air conditioner using zeolite-water pairs that was powered by exhaust gases from a locomotive. The cooling power of this system ranged from 3 to 5 kW, with a COP of 0.21 and an inside cabin temperature between 4 and 6^{o}C lower than the ambient temperature. Yang et al. (2006) designed a compact adsorption air-conditioner with a cooling capacity of 1 kW and found that the COP was around 0.446. In addition, a number of theoretical studies, based on mathematical models and simulations, have been reported, e.g. Tiansuwan et al. (1998), Leong and Liu (2004), Maggio et al. (2006) and Wang et al. (2006b).

The role of sonication on an adsorption and/or desorption processes has been studied on a number of occasions (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 of them focused on the benefits of the treatment of toxic chemicals or pollutants by the adsorbent bed and were concerned with the environmental issues. However, the use of a physical wave to enhance the adsorption cooling system was not reported. The influence of ultrasound was usually experimented and investigated within the laboratory scale. When the sonic vibration was propagated through a liquid, the cavitation or micro bubbles in liquids are formed, grow and suddenly collapse, which is called ‘cavitation’ (Young 1989; Mason 1991). The wave vibration reduces bubble coalescence that increases the interfacial area for gas transfer, enhances gas transfer and reduces the thickness of liquid films. The acoustic streaming, caused by the sonic wave, also improves the mass transfer coefficients (Schueller and Yang 2001).

The adsorber and evaporator play an important role in the system performance as indicated by COP, SCP and VCP. Enhancement of their performance by the sonic wave vibrations is expected to improve the evaporation rate of the methanol at the evaporator, as well as desorption rate of methanol from the adsorber in other phase of the operating cycle. Therefore, this would result in higher performance indicators. Therefore, this dissertation has focused on a critical investigation of the adsorption cooling system using activated carbon-methanol, either by experimentation and parametric simulation studies. Accordingly, the verified model may be used to expand the prediction to the adsorption in air-conditioning units for industrial application.

1.2 Literature review

This section summarizes relevant work regarding adsorption cooling in three aspects; experimental work and prototype demonstration, modeling and simulation, and its applications.

1.2.1 Experimental work and prototype demonstration

The actual operation of a particular adsorption cooling system could be efficiently shown either by experiments or prototype demonstrations. A wide range of its cooling power production has been exhibited by various research teams depending on the system size, design and energy sources.

Tamainot-Telto and Critoph (2003) tested a modular adsorption air-conditioner with three module configurations. The unit was experimental and powered by hot air. The best performance was obtained from the module that had 125 μm fins around the evaporator/condenser and the adsorber (Figure 1.1) under typical conditions without any heat regenerative process (generation, condensing and evaporation temperature were 100^{o}C, 30^{o}C and 15^{o}C, respectively). It had a cooling of about 100 W that could be achieved with a SCP of 600 W/kg, and a COP of around 0.20. The COP could be increased to 0.5 with two bed regenerative cycles.

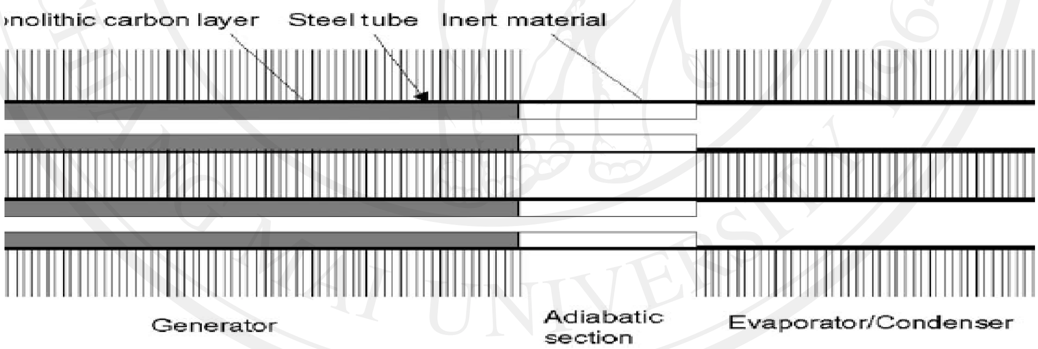

Figure 1.1 Schematic diagrame of the air conditioner module (Tamainot-Telto and Critoph, 2003).

Lu et al. (2004) tested a zeolite-water working pair in a locomotive air-conditioner (Figure 1.2) powered by exhaust gas, and achieved a cooling power of 3 - 5 kW, with a COP of around 0.21. The cabin temperature was between 4 and 6^{o}C lower than the ambient temperature, but the conventional air-conditioner usually operated at a temperature of 2-5^{o}C higher than the ambient temperature.

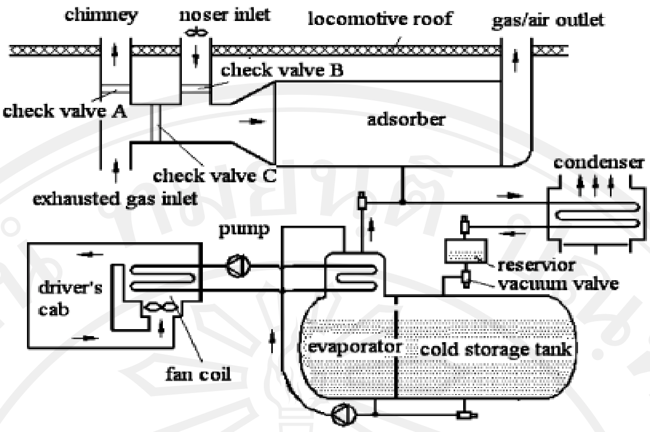

Figure 1.2 Schematic diagrame of the adsorption air conditioner installed in the locomotive (Lu et al., 2004).

An activated carbon-methanol adsorption air-conditioner (Figure 1.3), developed by Wang et al. (2001), contained two 26 kg adsorbers. The experimental temperatures of the heat source, evaporation and condensation were; 100^{o}C, 10^{o}C, and 24^{o}C respectively. The other design was tube-and-plate heat exchanger of which the tubes were covered with activated carbon, and a COP of around 0.4 and the cooling power of about 3.8 kW were achieved.

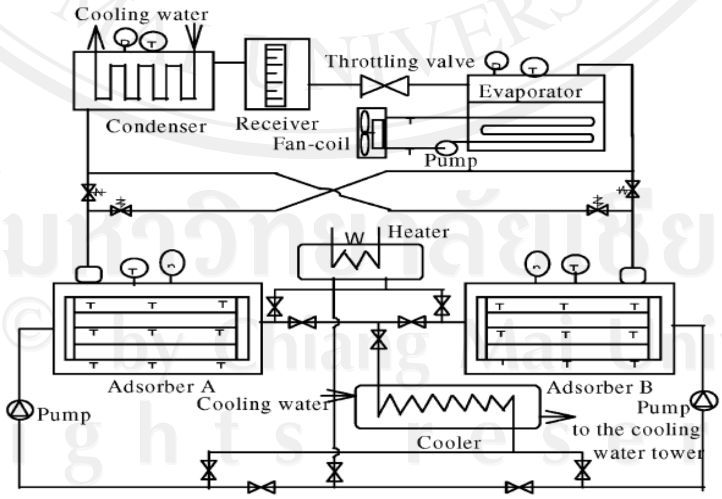

Figure 1.3 Schematic diagrame of the adsorption air conditioner (Wang et al., 2001).

An adsorption air-conditioner in a bus that had an adsorber with two concentric pipes was tested by Zhang (2000). The system was regenerated by the exhaust gas, and the adsorbent (zeolite) was placed between the inner and outer pipe and the water was the refrigerant. The cooling air flows through the inner pipe, to release or remove heat from the adsorbent. The system achieved a COP of around 0.38 and a SCP of 25.7 W/kg, while the Coefficient of Waste heat Cooling (WCOP) was about 0.31. In the case of the standard bus (12.2 m length, 2.6 m width, 3 m height, and 49 seats) with a 207 kW diesel engine, the cooling load was around 17.6 kW, and it contained a conventional air conditioner weighting about 300 kg. The system could satisfy the demands of the WCOP but did not achieve the SCP. The SCP was low because of the low thermal conductivity of the bed (0.2 W/m K) and the low wall heat transfer coefficient between the bed and the heat exchanger (25 W/m^2 K). This system could be applicable if an adsorbent bed was improved through heat transfer enhancement.

The above selected systems have shown that the adsorption cooling system, especially the adsorption air-conditioners, are suitable to generate an adequate low cabin temperature and it is quite bulky, therefore, a well designed adsorber and system control are necessary. An improvement on the heat and mass transfer adsorber should be performed. Some of the modeling and simulation element are discussed in the next section.

1.2.2 Modeling and simulation works

In addition to the experimental and demonstration of works, modeling and simulation are usually required to compare, between different designs, to optimize the design configuration, and to predict the systems performance under various operating conditions. Parametric study help to identify the suitable range of operating conditions and their achievable performance, and sensitivity analysis leads to optimal conditions.

Tiansuwan et al. (1995) found that there is the potential of using the local activated carbon-methanol pair for refrigeration. The theoretical COP could be up to 0.6 and the suitable size of the local activated carbon should be 2-3 mm (6 x 12 mesh sizes). Consequently, Tiansuwan et al. (1998) developed a mathematical model of an activated carbon-ethanol intermittent refrigerator. The 14.9 kg AC adsorber had 18 black-painted copper tubes of 50 mm (out side diameter, OD) with 1.5 mm thick wall and 1.2 m in length. Inside each tube there was 28.6 mm space OD and the coaxial tube had 8 mm holes drilled through it. The inner tube was wrapped in stainless steel net and used for the passage of the ethanol. The adsorber was heated and cooled by hot and cold oil, at prescribed temperatures, and the condenser temperature was controlled using cooled water at 20^0C. They estimated the temperature of the working pair, the amount of ethanol leaving and being reabsorbed, and the temperature in the refrigerated box. The simulated results agreed well with those of the experiment.

Wang et al. (2006a) simulated a new design adsorption refrigeration system for a fishing boat. A thermo chemical model consisting of two 60 kg AC adsorber was used to investigate the important parameters and their independent effects on the design and performance. The temperatures constrains were waste heat at 80-110^0C, heat sink at 30^0C, and environmental temperature at 30^0C. If heat and mass recovery was applied, the COP would increased by 60% with an optimal cycle time of 35 min. The SCP was about 35 W/kg at -10^0C evaporating temperature.

Maggio et al. (2006) developed, tested and carried out sensitivity analyses on a two-dimensional simulation model for a zeolite-water adsorption machine with two adsorbent beds with internal heat recovery. The simulation results demonstrated that the cooling COP increased with cycle time which was contrary to the SCP. The variation in the heat recovery phase affected the COP more than the specific power.

Then, a sensitivity analysis was performed to study the influence of the main heat and mass transfer parameters and to optimize the performance for a double-bed system with internal heat recovery. The main results of this parametric analysis were: (1) the vapor permeability of the consolidated adsorbent beds (K_d) must be higher than $5x10^{-12}$ m^2, (2) the heat transfer coefficient (h_{ms}) was lower than 100 W m^{-2} K^{-1} (for K_d below 10^{-12} m^2), and (3) a bed thickness of 2-3 mm was recommended to obtain high performance.

A two-dimensional non-equilibrium numerical model was also used by Leong and Liu (2004) for the zeolite-13X/water adsorption cooling system. The adsorber bed was a cylindrical double-tube that was heated or cooled by an external fluid. The model described the combined heat and mass transfer in the adsorbent bed. It comprised of three sub-models of heat and mass transfer properties in the adsorbent bed; (1) gas flow in the adsorbent bed model, (2) a linear force driven model, and (3) the equivalent heat transfer conductivity of adsorbent bed model. The thermal performance was influenced by the heat and mass transfer configuration parameters such as the heat and mass transfer coefficient, thickness of the bed, the diameter of particles and the porosity. The performance was strongly influenced by the adsorbent thickness and porosity of the adsorbent bed, while the variation of particle size had a minimal effect.

1.2.3 Application of adsorption system

There have been several applications that demonstrate that the adsorption cooling system would be applicable, e.g., air-conditioning rooms, water chiller, ice makers, refrigeration, etc. Their examples are depicted in this section.

1.2.3.1) Air-Conditioning

Yang et al. (2006) demonstrated a compact adsorption air-conditioner (Figure 1.4) with a cooling capacity below 1 kW. Two adsorption beds having microspore spherical silica gel and water that were constructed to generate continuous cooling. There was a set of methanol heat pipes that provided the cold effect. The two beds prodded cooling capacities and COPs of about 687 W, 0.307 and 790 W, 0.446, respectively. The whole air-conditioning unit, driven by a low grade heat source (< 90^0C), was quite small at 300 mm (depth), by 500 mm (width) and 950 mm (height).

1.2.3.2) Adsorption chiller

A silica gel-water adsorption chiller was developed by Wang et al. (2006a; Figure 1.5). The system was composed of three vacuum chambers, including two desorption/adsorption chambers and one heat-pipe working chamber.

In the adsorption chambers water was refrigerant, while methanol was used as the working substance in the heat-pipe chamber. There were two water evaporators (WE1, WE2) integrated into one methanol evaporator (ME). The cold effect provided by the evaporation of water in evaporators 1 or 2, and the vapor transferred to the methanol chamber, via heat-pipe evaporation/condensation process. Chilled water was directly cooled down in the methanol chamber.

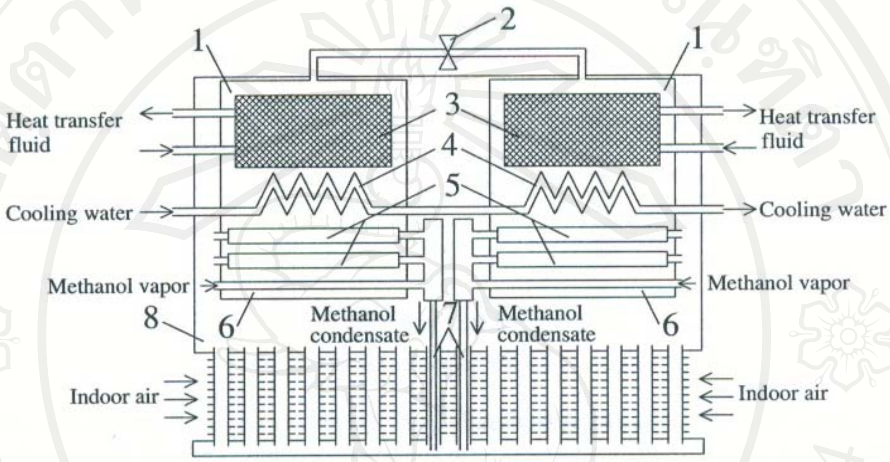

Figure 1.4 Schematic diagram of the compact adsorption room air conditioner.

1. Adsorption/desorption working chamber, 2. Electromagnetic vacuum valve, 3. Adsorber, 4. Water condenser, 5. Water tray, 6. Water evaporator (methanol condenser), 7. Methanol condensate returns tube, 8. Heat pipe working chamber (Yang et al., 2006).

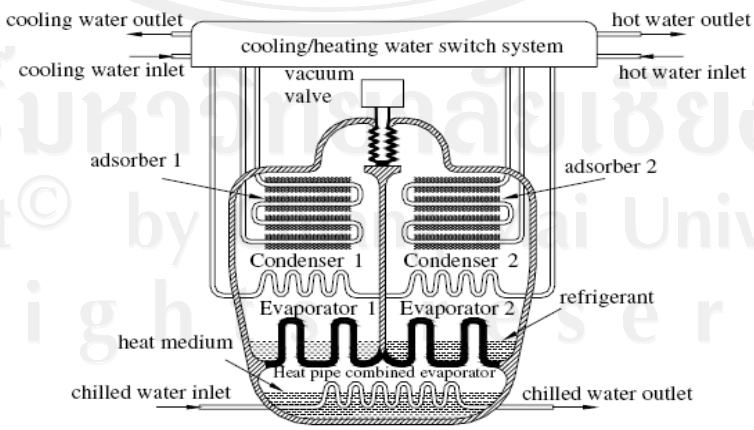

Figure 1.5 Schematic diagram of the heat-pipe type silica gel-water adsorption chiller (Wang et al., 2006b).

The two evaporators were connected by a heat-pipe heat exchanger (HPHE; Figure 1.6). The exterior surface of the copper tubes, namely water-evaporating surface (WE), was a porous medium to enhance the evaporation capability so that the volume of the evaporator could be minimized. The internal surface of the copper tubes was the methanol-condensing surface –the plain pipe. The methanol evaporated on the exterior surface of the heat exchanger tubes (methanol evaporating surface, ME) of the HPHE and condensed on the internal surface of the tubes in one WE (for example, WE1). WE1 worked simultaneously with WE2, that collected the condensation coming from the condenser through the divider. Therefore, WE2 temperature was higher than the temperature of the WE1, and the ME of the HPHE. As a result, the heat exchanger of the WE2 to the WE1 and the ME of the HPHE were isolated according to the working principle of a gravitation heat-pipe.

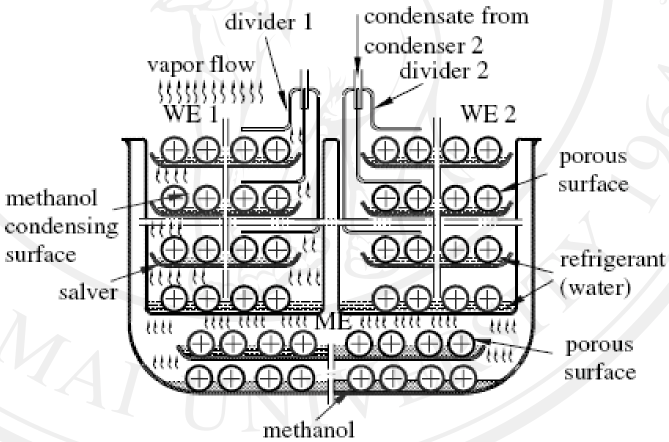

Figure 1.6 Schematic diagram of the heat-pipe combined evaporator (Lu et al., 2004).

A novel adsorption air-conditioner was developed by Wang et al. (2006b) to supply 8-12^{0}C chilled water for the fan coil in the locomotive operator cabin (Figure 1.7). It was driven by 350-450^{0}C exhaust gas generated by the internal combustion engine of the locomotive. The designed refrigerating power and coefficient of performance (COP) were 5 kW and 0.25, respectively. This system contained two adsorption/desorption chambers using zeolite-water, as a working pair. An adsorption, a condenser and an evaporator were housed together in the same adsorption/desorption chamber. None of valves was installed in the vacuum side.

In addition, a model was simulated and validated. It was expected that the refrigerating power of the machine was up to 10 kW, with a gas inlet temperature of 450^0C and an evaporating temperature of 6.5^0C. The adsorber could be heated from 97^0C to 423^0C, or cooled from 423^0C to 97^0C, in 1320 s.

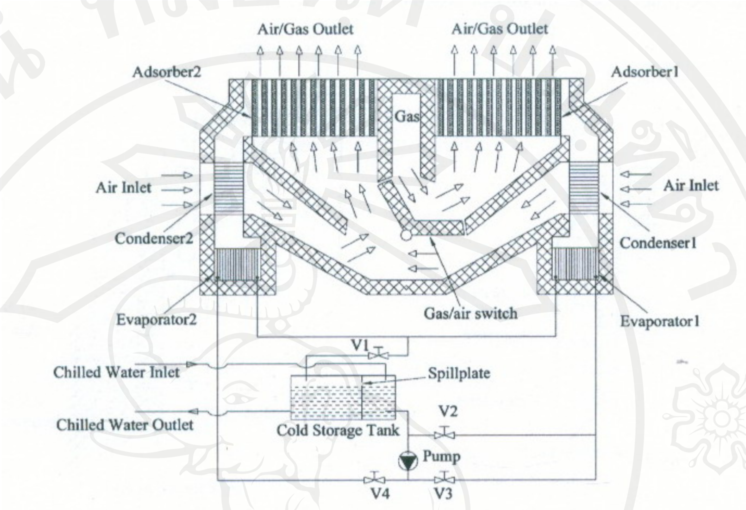

Figure 1.7 Schematic diagram of the air conditioner in the locomotive operator cabin (Wang et al., 2006b).

A big barrier to system performance was the heat and mass transfer in the adsorber bed. In this research work, a sonic wave generator was used to enhance heat transfer in the adsorption system component, the evaporator and adsorber, and to increase its overall performance. The design and mathematical model of the unit, under the sonicfication, are considered and discussed.

The experimental setup (Figure 1.8) consisted of one-bed adsorber, condenser, evaporator, heating/cooling water tank and methanol tank. There was a set of thermosyphon heat pipes attached with the adsorber. The experimental unit was designed as a modular system of which its adsorber, condenser and evaporator were in vertical alignment. Sonic wave generators were also attached to the evaporator to enhance the boiling of methanol during the adsorption process, and a sonic wave generator was used to enhance methanol decomposition in the adsorber during the desorption process. The experiments focused on the influence of number of cycles, cycle time, evaporation temperature and regeneration temperature on system performance.

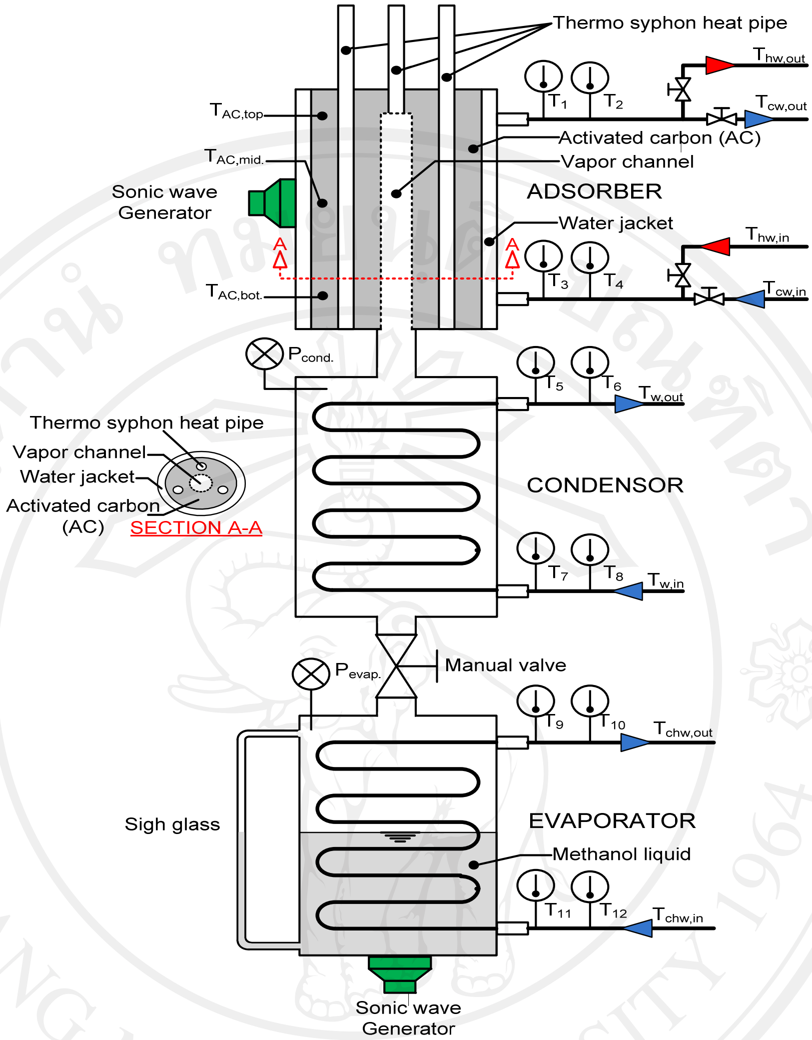

Figure 1.8 Schematic diagram of experimental set up.

1.3 Objective of the study

The main objective of this research was to increase the performance of an adsorption cooling unit using a sonic wave generator. Consequently, a model based on experiment results of the combined adsorption/sonic wave was developed. The specific objectives of this study were:

- to conduct experiment on a new design of an integrated adsorber-thermosyphon heat pipe for high heat rejection, and to determine the parameters affecting the system performance.

- to enhance the evaporation and desorption processes using sonic wave vibration at the evaporator and the adsorber.

- to develop a model based on the experimental data and the model used to simulate the system performance under various operating conditions. The optimal operating conditions were also investigated.

1.4 Scopes and methodology

1.4.1 Research scope

(1) The experimental set up was divided into three parts, operating in pseudo-continuous model. The adsorber had similar design as the tubes in a tube heat exchanger. Each operating cycle contained a heating period, a heating/desorption condensation period, a cooling period, and a cooling/adsorption/evaporation period. The experiments focused on the influence of number of cycles, cycle time, evaporation temperature, regeneration temperature and sonic wave frequency, on the system performance.

- The integrated adsorber-thermosyphon set was on a laboratory scale (cooling power < 0.5 kW). The thermosyphon refrigerant was methanol with a filling ration of approximately 50% - 80%.

- The experiment relied on a single-effect adsorption unit using activated carbon-methanol working pairs. A sonic generator was integrated at the evaporator and adsorber to see the effect on heat and mass transfer, and compared the results with those without the generator.

(2) The theoretical part was based on a computer simulation of developed mathematical models of the integrated evaporator/adsorption-sonic wave generator. A one-dimensional lumped parameter model for the adsorber-thermosyphon system was carried out.

(3) The system model

- Adsorbent carbon- activated pairs were produced from coconut shells (mesh size 8 x 16).

- The adsorbate was methanol (laboratory).

- Water is the heat transfer fluid for heating and cooling of the adsorber, evaporator and condenser.
- The sonic wave generator had a wave frequency ranging from 8-14 kHz.

(4) Independent variables

- The cycle time of system.
- The sonic wave frequency.
- The inlet water transfer fluid goes into the adsorber during desorption period, into the evaporator during adsorption period, and into the condenser during condensation period.

(5) Dependent variable

- The cooling power (kW)
- The coefficient of performance (COP)
- The specific cooling power (SCP)
- The volumetric cooling capacity (VCP)

1.4.2 Research methodology

The methodology of this research was:

- to compile all the relevant information (theory/concept/principles, literature review, conventional design/installation procedures, measurements and instrumentation, operation manual for the air-conditioner prior experimental results, etc.).
- to study (1) the lumped model to investigate the integrated adsorber-thermosyphon, evaporator sonic wave generator, adsorber sonic wave generator, performance, and (2) the lumped parameter method to predict single-bed adsorption machine performance.
- to design, fabricate, assemble, install, and carryout preliminary tests, on (1) the integrated adsorber-thermosyphon, and (2) the integrated adsorption cooling system with combined evaporator- sonic wave generator, and/or the adsorber sonic wave generator.

- to design the experiments.

- to develop an experiment to study the influence of the heating or cooling water temperature, thermosyphon heat pipe, and sonic wave frequency. The experimental results were analyzed to achieve a coefficient of performance (COP), the specific cooling power (SCP) and the volumetric cooling capacity (VCP).

- to design an experimental unit as a modular system of which its adsorber, condenser and evaporator are in vertical alignment.

i. The modular design helps to simplify fabrication, improve flexibility to scale up and reduce maintenance tasks.

ii. A sonic wave generator was attached to the evaporator to enhance the boiling of methanol during adsorption process.

iii. The calorimetric power was the input to the refrigerant in the sonic wave evaporator (Breitbach et al., 2003) where the temperature rise and the mass flow rate of the water medium could be measured.

- to develop a model, based on the experiment data, which is used to simulate the system performance under various operating conditions. Optimal operating conditions were also investigated.

1.5 Expected benefits

The data from this research can be used to design and develop adsorption air-conditioning system for commercial applications. This can be achieved through:

- in depth experimental and simulation results of the integrated adsorber-thermosyphon heat pipe and adsorption-sonic wave generator.

- predictive modeling for an adsorption air-conditioner.

- the development of a model based on the experimental data, which is used to simulate the system performance under various operating conditions. The optimal operating conditions were also investigated.