CHAPTER 2

THEORY AND METHODOLOGY

This chapter reviews the theory and research works involved in the adsorption system with the applications of sonic wave on adsorption/desorption. The methodology used in this research is also discussed in each related as well.

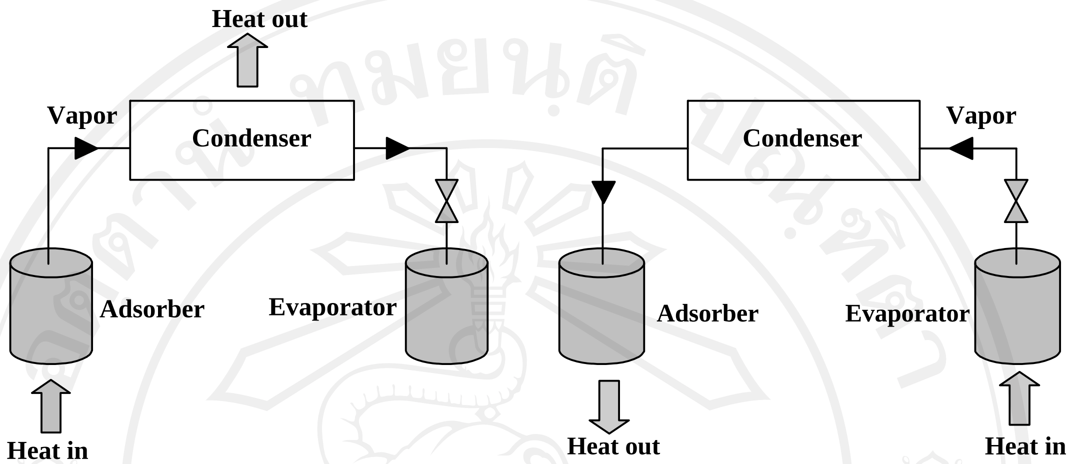
2.1 Theory

2.1.1 Introduction

During the past two decades, we have seen the rapid increasing in energy supply for air-conditioning system. The International Institute of Refrigeration (IIR) estimated that approximately 15% of all electrical energy generated worldwide was consumed in the refrigeration and air-conditioning processes (Wiess et al. 2003). Moreover, the electrical demand for air-conditioning system is continuously increasing (Pons et al. 1999). To solve this problem, many attempts have been made to discover methods not only to increasing the performance of air-conditioning systems but also to develop new efficient air-conditioning technology.

An adsorption system is one of the sustainable air-conditioning technologies and it has been investigated and applied to industrial processes for many years. An adsorption system does not have problems of coolant pollution, crystallization, and fractionation as absorption systems do. There are less vibrations, it is simpler to control, has lower operating cost and especially is produced from environmental friendly material. The system principally consists of three main parts, an adsorber, a condenser and an evaporator (Figure 2.1).

During the adsorption process, the working fluid inside the evaporator located in air-conditioning room absorbs heat from its surrounding and vaporizes. Then the vapor flows to the adsorber and it is take on by the internal adsorbent. During the desorption process, for example external heat energy, waste heat from the process is supplied to the adsorber. The heat repels the working fluid from the adsorbent and it flows back to the condenser it under goes condensation. After that the liquid working fluid is return to the evaporator by gravity or pump power.



a) Desorption Process. b) Adsorption Process.

Figure 2.1 Basic operating principle of adsorption process.

For many years, many investigations have been done into the performance of adsorption system and its application. For example, (Zhang, 2000) studied the adsorption air-conditioning system that had sorption beds regenerated by the exhaust gases of a bus. This system used zeolite and water as the adsorbent and working fluids, respectively. The COP of this system was 0.38. (Wang et al. 2001) used activated carbon-methanol pairs in the adsorption system. They designed an adsorber as a tube and plate heat exchanger and found that the cooling power was 3.8 kW with a COP of 0.4. Tamainot-Telto and Critoph (2003) studied modular adsorption air-conditioner, which was powered by hot air and Lu et al. (2004) developed an air conditioner with the zeolite-water pairs 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 a temperature inside the cabin between 4 and 6^{o}C lower than ambient temperature. Yang et al. (2006) 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 researchers developed mathematical models to predict the performance of the adsorption system (Tiansuwan et al. 1998; Leong and Liu 2004; Maggio et al. 2006 and Wang et al. 2006c).

We can conclude that the performance of the adsorption system depends on the design concept, working pair and operating conditions.

2.1.2 Adsorption refrigeration cycle

The adsorption cycles are comprised of four process; heating, desorption-condensation, cooling, adsorption-evaporation, all discussed in this part. The relationship between pressure (P), temperature (T) and concentration (x) of the working fluid in the adsorption cycle is shown as a P-T-x diagram (Figure 2.2). The operation takes place in 4 processes.

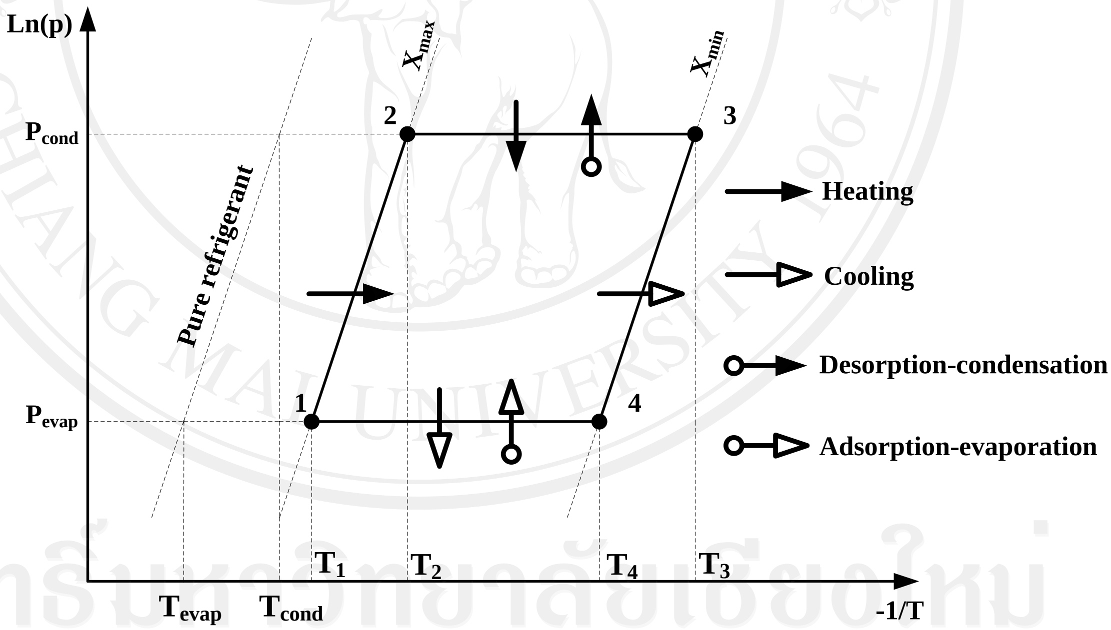


Figure 2.2 P-T-x diagram of an adsorption cycle.

Processes 1-2 is an isosteric heating processes, in which the adsorbent temperature is increased from T_1 to T_2 and the vapor pressure of working fluid adsorbed in the adsorbent is also increased from P_{evap} to P_{cond}.

Processes 2-3 is an isobaric desorption processes where the adsorbent undergoes still heating and the temperature of the adsorbent is increased from T_2 to

T_3. During this process, the working fluid is expelled from the adsorbent under a constant vapor pressure which results in reducing the working fluid concentration in the adsorbent (from x_{max} to x_{min}). The desorbed working fluid vapor is reduced in the condenser and the condensate is kept in the evaporator.

Processes 3-4 is an isosteric cooling process where the adsorber is cooled to reduce its temperature from T_3 to T_4 and consequently the system pressure reduces from P_{cond} to P_{evap}.

Processes 4-1 is an isobaric adsorption process. At this stage, the adsorber is continuously cooled down from T_4 to T_1 at a constant pressure while the working fluid condensate re-evaporates and is re-adsorbed in the adsorber. In the evaporator, as there is evaporation of methanol, heat is extracted from its surrounding and thus the surrounding temperature reduced. The application of sound-wave vibration at the evaporator could stimulate the evaporation process, which results in faster vapor generation.

In this research, the activated carbon and methanol are used as the working pair and the following assumptions are considered:

(1) the vapor of methanol is assumed to be an ideal gas.

(2) the activated carbon has uniform size and homogeneous properties.

(3) all the components of the system are well-insulated.

According to the energy conservation principle, the energy input to the isosteric heating process 1-2 is primarily supplied to increase the temperature of the adsorber material from T_1 to T_2 as

$$\left(m_{mt}c_{mt} + m_b c_b + m_b c_{met} x_{b1}\right)\frac{dT_{b,1-2}}{dt} = Q_{1-2}\,. \tag{2.1}$$

Where m_{mt} is mass of the metal tube in the adsorber, m_b is mass of activated carbon, x_{b1} is maximum concentration of methanol in activated carbon, c_{mt} c_b and c_{met} are specific heats of metal tubes activated carbon and methanol, respectively.

The equation of x_{b1} is

$$x_{b1} = x_0 .\exp\left[-k\left(\frac{T_{b1} + 273.15}{T_e + 273.15} - 1 \right)^n \right]. \tag{2.2}$$

From Dubinin-Astakov equation of pressure, we have temperature and adsorption volume is

$$P_1 = P_0 .\exp\left\{ \frac{1}{T_{b1}} \left[-\frac{1}{D_{od}} \ln\left(\frac{x_{b1}}{x_0} \right) \right]^{\frac{1}{n}} \right\}. \tag{2.3}$$

In the case of the isobaric desorption process 2-3, the methanol is repelled from the activated carbon. The heat of adsorption equation is as follows

$$\left(m_{mt} c_{mt} + m_b c_b + m_b c_{met} x_{b,2-3} \right) \frac{dT_{b,2-3}}{dt} = Q_{2-3} + m_b \Delta H_d \frac{dx_{b,2-3}}{dt}. \tag{2.4}$$

Where $x_{b,2-3}$ is the desorption quantity which change with temperature, $x_{b,2-3}$ and ΔH_d can be expressed as

$$x_{b,2-3} = x_0 .\exp\left[-k\left(\frac{T_{b,2-3} + 273.15}{T_c + 273.15} - 1 \right)^n \right] \tag{2.5}$$

$$\Delta H_d = RA \frac{T_{b,2-3} + 273.15}{T_c + 271.15}. \tag{2.6}$$

In the isosteric cooling process 3-4, the adsorber releases heat while valve is open. Thus the adsorbent temperature drops and vapor pressure decreases to evaporation pressure along the isosteric line (3-4). The cooling process can be determined from

$$\left(m_{mt}c_{mt} + m_b c_b + m_b c_{met} x_{b3}\right)\frac{dT_{b,3-4}}{dt} = Q_{3-4}\,. \tag{2.7}$$

Where Q_{3-4} is the cooling power of water and x_{b3} can be expressed as

$$x_{b3} = x_0\,.\exp\left[-k\left(\frac{T_{b3}+273.15}{T_c+273.15}-1\right)^n\right]. \tag{2.8}$$

For this step and pressure difference, we have

$$P_3 = P_0\,.\exp\left\{\frac{1}{T_{b3}}\left[-\frac{1}{D_{od}}\ln\left(\frac{x_{b3}}{x_0}\right)\right]^{\frac{1}{n}}\right\} \tag{2.9}$$

During the heating and desorption process, the sonic wave is applied to enforce the regeneration of methanol from the AC adsorbent.

For the isobaric adsorption process 4-1, the methanol evaporates and the temperature of adsorber reduces from T_4 to T_1. The adsorption-evaporation process can be determined from:

$$\left(m_{mt}c_{mt} + m_b c_b + m_b c_{met} x_{b,4-1}\right)\frac{dT_{b,4-1}}{dt} = Q_{4-1} - m_b\,\Delta H_a\,\frac{dx_{b,4-1}}{dt}\,. \tag{2.10}$$

Where, $x_{b,4-1}$ and ΔH_a are as follows

$$x_{b,4-1} = x_0\,.\exp\left[-k\left(\frac{T_{b,4-1}+273.15}{T_e+273.15}-1\right)^n\right] \tag{2.11}$$

$$\Delta H_a = RA\frac{T_{b,4-1} + 273.15}{T_e + 271.15}. \quad (2.12)$$

Assuming the heat recovery process is shot and two adsorbers do not reach the state of desorption and adsorption, the equation for heat recovery process is

$$Q_{1-2} = Q_{3-4} \quad (2.13)$$

The energy conservation equations with hot water and cold water in the adsorber are

$$Q_{1-2} = \dot{m}_{hw} c_{hw}\left(T_{hw,in} - T_{hw,out}\right) \quad (2.14)$$

$$Q_{1-2} = U_{ads} A_{ads} \frac{\left(T_{hw,in} - T_{hw,out}\right)}{\ln\left[\left(T_{hw,in} - T_b\right)/\left(T_{hw,out} - T_b\right)\right]}. \quad (2.15)$$

From Equation (2.14) and (2.15) we can option that

$$T_{hw,out} = T_b + \left(T_{hw,in} - T_b\right) e^{\left[-U_{ads}A_{ads}/\left(\dot{m}_{hw} c_{hw}\right)\right]}. \quad (2.16)$$

Assuming the heat taken by the cold water (medium-temperature source) is all used to cool the methanol desorbed. There is no liquid remaining in the condenser, as the methanol is all condensed as saturated liquid at the exit. The equation for the condenser is show in equation (2.17) in the process of desorption.

$$m_{cond}\, c_{cond} \frac{dT_{cond}}{dt} = U_{cond}\, A_{cond}\left(T_{cond} - T_{wi,cond}\right) - m_b L_{met} \frac{dx_{b,2-3}}{dt} \quad (2.17)$$

The equation for the prediction of the condenser temperature used in the simulation of the adsorption cooling system.

$$T_{cond}(i) = \frac{[(m_b.c_{met}.T_b) + (m_b.L_{met}) + \left(\frac{dt}{dx_{b,2-3}}\right).U_{cond}.A_{cond}.T_{wi,cond})]}{[(\left(\frac{dt}{dx_{b,2-3}}\right).U_{cond}.A_{cond}) + (m_b.c_{met})]} \qquad (2.18)$$

Assuming the temperature of the evaporator is consistent, then the equation for the evaporator in the process of adsorption is show in equation (2.19) according to the method of lumped parameters

$$m_{evap}c_{evap}\frac{dT_{evap}}{dt} = m_b c_{met}\frac{dx_{b,4-1}}{dt}\left(T_{cond} - T_{evap}\right) - m_b\frac{dx_{b,4-1}}{dt}L_{met,evap} + U_{evap}A_{evap}\left(T_{wi,evap} - T_{evap}\right) \qquad (2.19)$$

The equation used for the prediction of the evaporator temperature used in the simulation of the adsorption cooling system

$$T_{evap}(i) = \frac{\left[(m_b.c_{met}.dx_{b1}.T_{cond}) - (m_b.dx_{b4}.L_{met,evap}) + (U_{evap}.A_{evap}.T_{wi,evap}.dt) + (m_{evap}.c_{met}.T_{evap,i-1})\right]}{\left[(m_{evap}.c_{met}) + (m_b.c_{met}.dx_{b1}) + (U_{evap}.A_{evap}.dt)\right]} \qquad (2.20)$$

If no heat is lost and the latent heat of vaporization (L_{met}) is assumed to be constant, the amount of cooling at the evaporator can be calculated as

$$Q_{evap} = m_b L_{met}\left(x_{\max} - x_{\min}\right). \qquad (2.21)$$

During this process, a sonic wave generator is used to enhance the boiling of the working fluid in the evaporator. The temperature difference between the adsorber and evaporator is reduced and thus a higher heat rate at the evaporator can be expected.

The coefficient of performance (COP), the specific cooling power (SCP) and the volumetric cold production (VCP) are normally used to determine the adsorption system performance. These parameters could be evaluated from

$$SCP = \frac{Q_{evap}}{m_b \times t_{ads}}, \tag{2.22}$$

$$VCP = \frac{V_{ads} \times t_{ads}}{Q_{evap}}, \tag{2.23}$$

and

$$COP = \frac{Q_{evap}}{Q_{1-2} + Q_{2-3} + Q_{sonic}}. \tag{2.24}$$

Where t_{ads} is the adsorption time, V_{ads} is the volume of adsorber, and Q_{sonic} is the power supplied to the sonic wave generator.

The main drawbacks of the adsorption cycle were its low coefficient of performance (COP), small specific cooling power (SCP), and long cycle time. Development mainly focused on enhancing the cycle performance (Pons and Poyelle, 1999) to:

a) find new better working pair and improve the adsorption performance.

b) propose a new type of adsorption cycle.

c) intensify the heat and mass transfer in the adsorbent bed.

d) decrease the cycle time.

In proposing new type of cycle, numerous cases have been discussed besides the basic cycle, as below (Routhremss, 1984). The basic cycle is suitable for recovering heat from an intermittent heat source, such as an industrial waste heat or solar energy. There are number of different basic cycles.

1) Two-bed continuous cycle. This may be used to recover low-grade thermal energy and provide a continuous cooling effect.

2) Continuous heat recovery cycle. This technique provides the same functions as the two-bed continuous but it has greater thermal efficiency.

3) Thermal wave cycle. This one has the highest theoretical coefficient of performance, but it is difficult to be reproduce in the prototype system.

4) Multi effect cycle. This concept can get a high thermal efficiency, but it is complicated and not widely used.

2.1.3 Inception of sonic wave

The mechanical wave induced by the sonic wave generator, a create variation in the pressure or density. When it propagates through the medium, it is attenuated by absorption, by cavitation bubbles, by particles, at interfaces (Breitbach et al., 2003). The high sound intensities produce nonlinear phenomena or acoustic cavitations to exceed the liquid tensile stress. During the rarefaction cycle of the sonic wave, a large negative pressure is applied to the liquid, little gas bubbles are formed during the expansion cycle of the sound wave, and grow over one or several cycles to many times its initial size (Juang et al., 2006). The bubbles are either stable for many cycles, or transient, when they grow to critical size and violently collapse, during the compression part of the wave. Therefore, the energy is released causing extreme thermodynamics conditions thus very high temperature and pressure in the vicinity of the imploding bubbles, and a large shear force in the surrounding liquid (Mason, 1991). As the bubble collapses, localized areas of high temperatures lead to increasing of system temperature slightly and the localized pressures in the fluid created high-speed micro-jets with high-pressure shock waves as well (Hamdaoui et al., 2003). The waves and the associated microdisturbances of cavitation bubbles near the surface of solid reduce the mass transfer boundary layer and therefore increase the mass transfer efficiently (Penn et al., 1959).

The suitability in using sonic wave to enhance the boiling heat transfer of methanol, inside an evaporator, is shown in terms of COP, SCP, VCP and cycle time.

2.1.4 Working pairs

The working pairs for absorption/adsorption are composed of adsorbent-adsorbate and the adsorbate is sometimes called the refrigerant. For example, chloride salts-ammonia, zeolite-water and activated carbon-methanol where ammonia, water, methanol, respectively are adsorbates.

The major requirements and criteria in selecting the appropriate refrigerant and working pairs for air-conditioning system are summarized in Table 2.1 and Table 2.2.

The heat consumed or released due to the thermo-chemical process is utilized for production of heating or cooling. From Table 2.1 three refrigerants, namely, water, ammonia and methanol, give sufficient high latent heat, even though the working pressures are not very favorable.

If water is used as the working fluid or adsorbate, it gives advantages during the phase change (i.e. from liquid to vapor), of which heat of vaporization is high, owing to the hydrogen bonding in the complex polymer state existing in liquid water. During vaporization, the hydrogen bond in the liquid water inhibits the break-up to individual molecules, so high heat is required for vaporization.

Table 2.1 Example refrigerant and special properties (Cacciola and Restuccia, 1994).

Formula	Name	Normal boiling point (K)	Density (kg/m^3)	Heat of vaporization (kJ/kg)	Heat of vaporization (MJ/m^3)
NH_3	Ammonia	238	681	1368	932
HCHO	Formaldehyde	254	815	768	626
SO_2	Sulphur dioxide	235	883	605	534
H_2O	Water	373	958	2258	2163
SO_3	Sulphur trioxide	318	1780	508	905
CH_3OH	Methanol	338	791	1102	872
C_2H_5OH	Ethanol	352	789	842	665
C_2H_3N	Acetonitrile	354	782	766	599
CH_3NH_2	Methyl Amine	266	703	836	588

The adsorbent should be available in large quantities, cheaply and chemically inert with no side reactions. The internal structure of the adsorbent is composed of a network of interconnecting microscope pores. This bed can attract and hold the working fluid vapor due to physi-sorption and capillary condensation.

Table 2.2 Example refrigerant pairs and their heat adsorption (Srivastava and Eames, 1997).

Adsorbent	Adsorbate	Heat of adsorption [kJ/kg$_{adsorbate}$]	Remarks
Silica gel	Methanol	1000-1500	Unsuitable above 200°C
″	Water	2800	Used mainly for desiccant cooling
Activated alumina	Water	3000	-
Zeolite (various grades)	Water	3300-4200	Natural zeolites have values lower than synthetic zeolites
″	Ammonia	4000-6000	-
″	Carbon dioxide	800-1000	-
″	Methanol	2300-2600	Unsuitable: they react at 100°C
Activated carbon	Ethylene	1000-1200	-
″	Ammonia	2000-2700	-
″	Water	2300-2600	-
″	Methanol	1800-2000	-
″	Ethanol	1200-1400	-

Zeolites and activated carbon (AC) are considered to be the most interesting solid-adsorbents (Meunier and Douss, 1990, Cacciola and Restuccia, 1994). However, they have smaller pore diameters, and have higher heat of adsorption and regeneration temperature. The use of a crystalline aluminosilicate (i.e. zeolite) has been investigated due to its nonlinear adsorption isotherms. Zeolites, also called molecular sieves, can be obtained naturally, or by synthesis (e.g. type 4A, 5A, 10X, 13X). Type 13X or NaX could adsorb a wide range of adsorbates because of their large pore diameter.

Table 2.3 Suitable application ranges for adsorbent-adsorbate pairs
(Cacciola and Restuccia, 1994).

Absorbent-Absorbate pairs	Applications				
	Freezing ($T<-20^oC$)	Refrigeration ($T \approx 0^oC$)	Air-Conditioning ($T \approx 5\text{-}15^oC$)	Space heating ($T \approx 60^oC$)	Industrial Heat pump ($T > 100^oC$)
Zeolite-H_2O			✓	✓	✓
Zeolite-NH_3	✓				
AC-NH_3			✓	✓	
AC-H_3OH		✓	✓		

The suitable application range of adsorbent-adsorbate pairs is given in Table 2.3 Activated carbon-Methanol appears to be suitable for higher operating temperature ranges (air-conditioning mode).

2.1.5 Heat source and heat sink

Solid adsorption cooling requires both a thermal source and sink. High temperature source could be low grade heat, such as waste heat, solar energy and biomass conversion.

2.1.5.1) Waste heat

Waste heat is available from various sources, e.g. exhaust gas from engine condensates, coolant, industrial waste streams, etc. The adsorption cooling system normally requires input as intermediate heat energy; therefore, waste heat is considered to be an appropriated energy source.

The efficiency of a diesel engine is about 35%, and in the operation of water-cooled engines, about 35% and 30% of the input energy is wasted in the coolant and exhaust gas, respectively (Zang, 2000). Thus, recovering the waste heat can improve energy management when such engines are employed. The use of this heat to regenerate the bed of adsorption systems is one of the alternatives to increase the overall efficiency of the diesel engine.

Air-conditioning on vehicles could be another reasonable application for adsorption systems powered by exhaust gases, especially bus and locomotives. These kinds of vehicles could carry adsorption system and usually have a large volume and mass. The adsorption unit also seems to be suited for refrigeration in fishing boat since it is generally powered by diesel engines, and the engine exhaust gas could run the adsorption refrigeration systems instead of the vapor compression units that are normally used.

2.1.5.2) Renewable energy sources

Renewable energy sources could also lead to achieving the goal of CFC-free refrigerant/air-conditioning systems, and environmentally friendly energy utilization system. Adsorption cooling promises a safe alternative to CFC-based refrigeration devices. From this point of view, a number of researches investigated the possibility of an adsorption air condition/refrigeration system driven by a renewable heat source.

Solar energy is clean energy with sufficient potential energy for an adsorption system. The solar cooling system is generally comprised of three sub-systems: the solar energy conversion system, the refrigeration system and the cooling load. The appropriateness of each application depends on cooling demand, power and the temperature level of the refrigerated object, as well as the environment. A number of possible "paths" from solar energy to "cooling services" are shown in Figure 2.3.

Starting from the inflow of solar energy there are obviously two significant paths to follow; solar thermal collectors to heat, or Photo voltaic (PV) cells to electricity. For solar thermal collectors, different collectors, and different collector types produce different temperature levels. This indicates that the temperature level can be matched to various cycle demands.

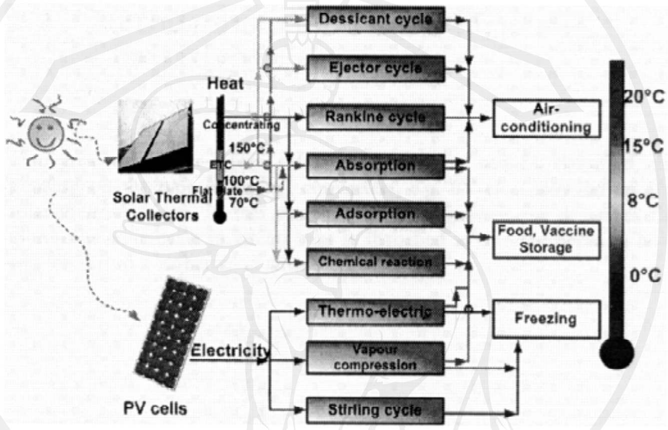


Figure 2.3 Solar cooling paths (Pridasawas, 2006).

For air-conditioning, at a service temperature of 15-20^{o}C, the capacity is generally high and the energy removed from the chilled space has a low potential to be converted into useful energy. The solar thermal-driven system is more suitable for the air-conditioning system than the PV-driven system, due to lower installation costs.

2.2 Methodology

The methodology of this research is:

2.2.1 Compilation of all relevant information.

2.2.2 Design, fabrication, assembly, installation, and preliminary testing, on:

- integrated adsorber-thermosyphon heat pipe.

- integrated adsorption cooling system with combined evaporator-sonic wave generator.

- the experimental setup unit is shown in Figure 2.4.

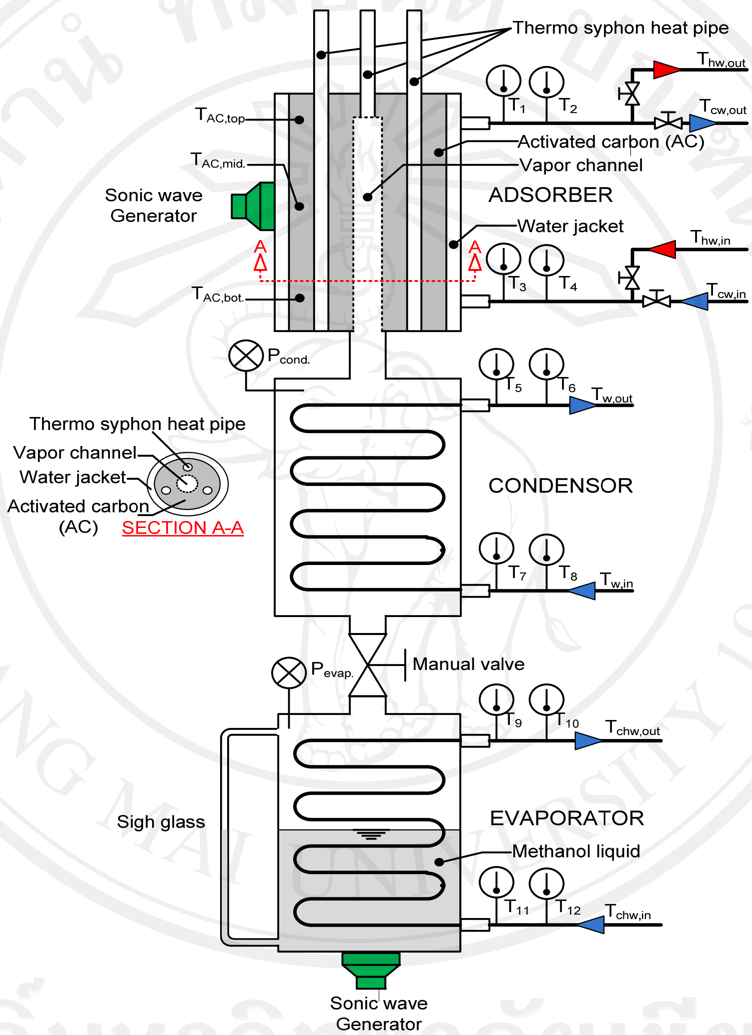


Figure 2.4 schematic sketchs of the experiment apparatus.

Figure 2.4 shows a schematic sketch of the vertical solid adsorption refrigeration unit. It consists of 3 main parts, an adsorber, a condenser and an evaporator. The experimental unit was designed as a modular system of which its adsorber, condenser and evaporator were in vertical alignment. The modular design helped to simplify fabrication, improve compactness of casing, increase flexibility to scale up the design, and reduce maintenance tasks. There were sonic wave generators attached at the evaporator and the adsorber to enhance the boiling of methanol during the adsorption process and regeneration of methanol during desorption process, respectively. In the Figure 2.4, at the adsorber, there was a set of thermosyphon heat pipes to enhance the heat rejection during cooling. During desorption of methanol, the unit was insulated.

2.2.2.1) Adsorber

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

2.2.2.2) Evaporator and condenser

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

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

2.2.2.3) Thermosyphon heat pipes

The thermosyphon heat pipe system was made of copper tubing of 1.0 cm in diameter and 150 cm in length. Thermosyphon heat pipes without fins. Three heat pipes having (methanol) working fluid were filled with 50% volume ratio and installed into the adsorbent bed.

2.2.2.4) Measurements

- Temperature measurements were take by a set of K-type thermocouples having ± 0.1°C accuracy and recorded by a temperature data logger (model TSUS-TASK24C).

The sensors were installed in the activated carbon, at the water inlets and the outlets of the adsorber, the condenser and the evaporator.

The evaporator temperature was measured by the thermocouple at the evaporator chamber's wall.

- Pressure measurement:

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

- Flow rate:

The flow rate of water was calculated by measuring the mass of circulating water during a period of time and the digital weighting apparatus measured the mass of water at ± 1 g accuracy. The methanol level inside the evaporator could be observed by a sight glass.

2.2.2.5) Experimental operation

- During desorption-condensation, hot water (0.08 kg/s at 95°C) was circulated inside the water jacket to regenerate methanol vapor at the adsorber. In the experiment, the sonic generator was used to vibrate the adsorber to increase the methanol desorption from the bed. At the same time a stream of 0.06 kg/s cold water at 5-15°C was circulated inside the copper coil to condense the methanol vapor which was kept in the evaporator. The heating was performed until the bed temperature reached a specified value of 70 – 90°C.

- During the cooling phase, cold water was circulated along the water jacket to cool down the bed temperature to be about 40°C. The evaporation-adsorption starts.

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

- The maximum frequency of each sonic wave generator, at the adsorber and the evaporator, was 14 kHz.