Chapter 2

Basic Adsorption Refrigeration System and Literature Survey

2.1 Basic Adsorption Refrigeration system

Adsorption is the process by which molecules of a fluid are fixed on the walls of a solid material via connections of the Van der Waals type [7] The adsorbed molecules undergo no chemical reaction but simply lose energy when being fixed to the adsorption bed resulting in an exothermic energy output.

This report is not intended to give a comprehensive description of adsorption technologies. The reader is referred to the relevant literature such as Wang and Oliveiraand Critoph et al [8]. Nevertheless, the general principle of the basic adsorption refrigeration cycle is given in Figure 2.1. The refrigeration circuit usually consists of three main components; a solid adsorbent bed, a condenser and an evaporator. Some system employ isolating valves between the various components and some utilize expansion valves between the condenser and the evaporator.

The adsorption refrigeration cycle relies mainly on the natural affinity of the adsorbent bed (when at low temperature) to attract the refrigerant vapor from the evaporator thus creating a lower pressure in the evaporator. Once the adsorbent bed closes to the saturation point, the valve between the evaporator and the absorber is closed and heat is applied to adsorbent bed, thus releasing the refrigerant vapour which then gets collected and condensed in the condenser before returning to the evaporator. Once this cycle is completed the heat on the adsorbent bed is removed and in some cases forced cooling is introduced onto the adsorber until the adsorption conditions are established and then the valve between the evaporator and the adsorbed is reopened. Figure 2.1 presents a schematic of the basic adsorption cycle. The refrigerant uptake (x) is defined as the ratio of the mass of the adsorbed refrigerant to the mass of dry adsorbent. Starting with the state point 1, in which the adsorbent is cold and saturated with the refrigerant, heat is applied to the adsorber–desorber heat exchanger. This causes in heating up the adsorbent, which consequently results in desorbing a certain amount of the refrigerant. Accordingly, the system pressure increases, ideally without changing the refrigerant uptake (so-called isosteric preheating), until the minimum desorption temperature is reached (state point 2). At this temperature the system pressure becomes equal to the saturation pressure corresponding to the temperature (T_{con}) of the heat sink available for receiving the heat of condensation. The desorption process starts from this point on and the refrigerant is condensed, ideally at a constant pressure (processes 2 and 3 in Figure 2.3). The desorption process proceeds until the adsorbent temperature reaches the maximum available desorption temperature and the refrigerant uptake reaches the cycle minimum uptake (x_{min}) (state point 3).

The second working phase begins as the adsorber–desorber heat exchanger is cooled by rejecting its heat to the ambient. The adsorbent is pre-cooled and becomes able to adsorb refrigerant vapor. This causes in decreasing the system pressure, ideally without changing the refrigerant uptake within the adsorbent. As the adsorber–desorber heat exchanger is further pre-cooled a portion of the previously desorbed and condensed refrigerant is adsorbed and the latent heat of vaporization is drawn from the remaining liquid refrigerant in the evaporator. This causes in decreasing the refrigerant temperature from state point 5 to state point 6 at the end of the pre-cooling process (3 - 4). The adsorption process, within which the cooling effect is produced, starts from state point 4 and proceeds by further cooling the adsorber–desorber heat exchanger until the whole amount of refrigerant is evaporated upon removing the cooling load from the surrounding space (refrigerator’s cabin) and adsorbed in the adsorbent. Unlike vapor compression and absorption refrigeration, the basic adsorption/desorption process is not a continuous one.

An adsorption bed is charged with refrigerant at low temperature and pressure; when adsorption slows down or stops, the adsorption bed is heated and high temperature and pressure gas is released from the bed. To obtain a continuous cooling effect from an adsorption refrigeration system normally two or more adsorbent beds are used in the system. In a typical Two-bed cycle, the evaporator and the condenser would be connected to both beds through a series of valve. The heated bed would be opened to the condenser to allow desorption while the other would be opened to the evaporator to allow for adsorption. The heating and cooling of the beds and valve directions would be swapped between the two cycle to provide “continuous” heating or cooling (actually oscillating between high and low cooling rates). The addition of more adsorption beds allows a steadier cooling rate and also permits the use of heat rejected from the adsorption process to be used as part of the energy input for the regeneration of the fully charged beds. These “advanced” cycles improve efficiency at the cost of adding a pump and heat recovery loops.

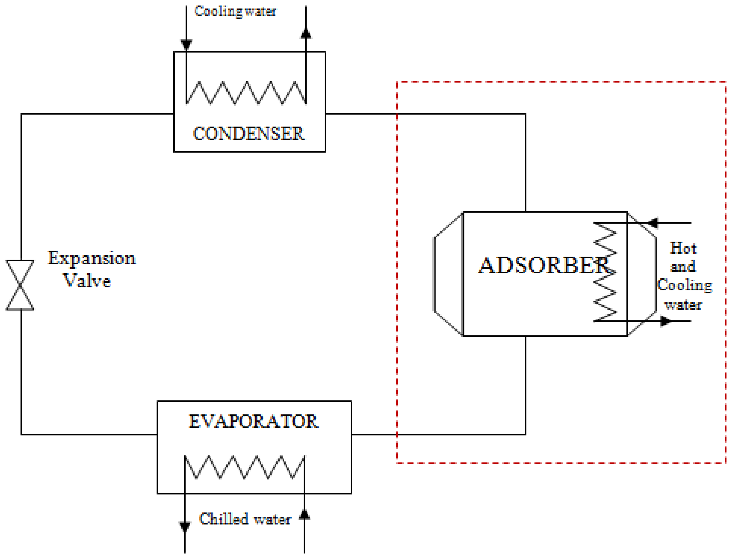

Figure 2.1 Schematic of an adsorption refrigeration cycle

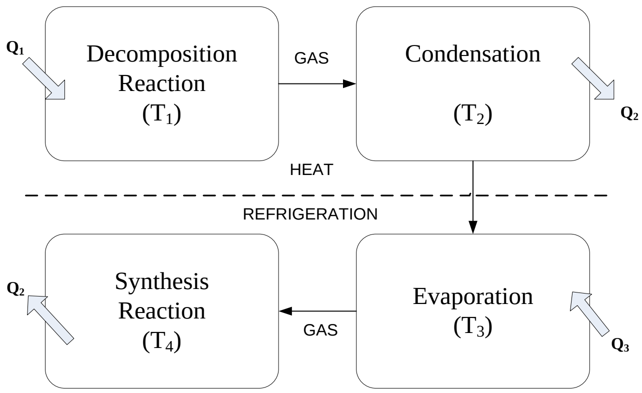

Figure 2.2 Basic principles of adsorption refrigeration cycle [9]

The principles and operating cycle of chemical adsorption refrigeration are illustrated in Figure 2.1. A cycle consists of four steps: decomposition reaction, condensation, evaporation and synthesis reaction represented, respectively by points 1-4 in Figure 2.3.

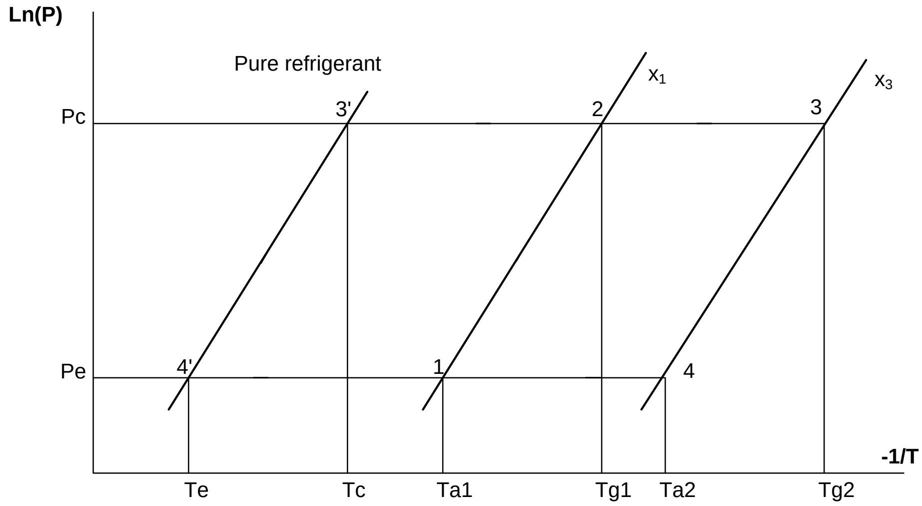

Figure 2.3 ln(P) vs -1/T Diagram for the basic chemical reaction system [9]

2.2 Development of Adsorption System

2.2.1 Multi-Bed System

Sato [10] analyzed a multi-bed strategy, where heat removal from adsorber is performed by the refrigerant emanating from one or more evaporator(s). It is more practical to have the evaporator devoted to cooling the chilled water, with the evaporator refrigerant being superheated at the adsorbers.

Sato et al. [11] invented an adsorption type refrigerator which has four adsorbers in the system with two adsorbers different from the other two in adsorption capacity. Total adsorption capacity of refrigerant of second and fourth adsorber is rendered to be not less than 0.2 times and not more than 0.8 times of the total adsorption capacity refrigerant of first and third adsorber. Thus, coefficient of performance of an adsorption type refrigerator is raised while maintaining a sufficient cooling capacity for utilization.

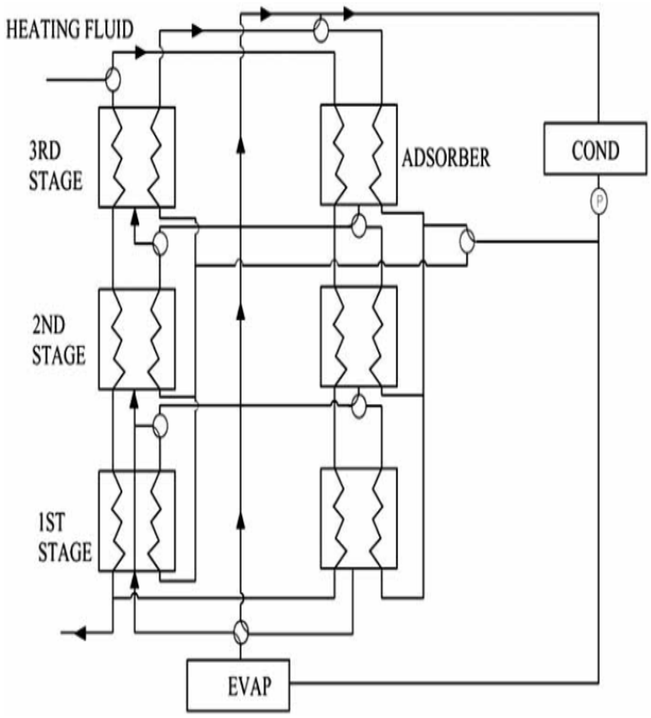

Figure 2.4 Multi-stage, multi-adsorber adsorption refrigerator [10]

2.2.2 Heat and Mass Recovery

Three main technologies to improve the process have been extensively developed [11]:

2.2.2.1 Regenerative Processes with Temperature front

Shelton [11] disclosed a heat driven heat pump system wherein a temperature gradient is established lengthwise in the adsorbent bed in order to establish a thermal wave in the bed as shown in Figure 2.5. As a heat transfer fluid is circulated through the system by a reversible pumping means, the beds are cycled between an upper and a lower operating temperature, creating the thermal wave within the bed of solid adsorbent.

2.2.2.2 Regenerative Processes with Heat and Mass Recovery

Critoph [12] patented an adsorption cooling system comprises two adsorbent beds each with an associated thermal management system. The thermal management systems are identical and consist of a circulating supply of a control fluid which passes through the adsorbent bed, a pump, a heat exchanger and an inert bed. Heat removed from the adsorbent beds by the control fluid is supplied to the inert beds and is stored to be subsequently regenerated to heat the adsorbent beds in a later half of the operating cycle of the thermal compressor. The thermal compressor is energy efficient by virtue of the heat recycling (recovery) which is performed. In a recent patent granted to Critoph [13], another thermal driven adsorption system was described to provide energy-efficient heating or cooling by exploiting heat regeneration in an adsorption system.

In the patent issued by Xia et al. [14], mass recovery was applied in the two beds system. The improvements were in the order of 7-22% for the SCP and 20–30% for the COP, depending on the application and operation conditions

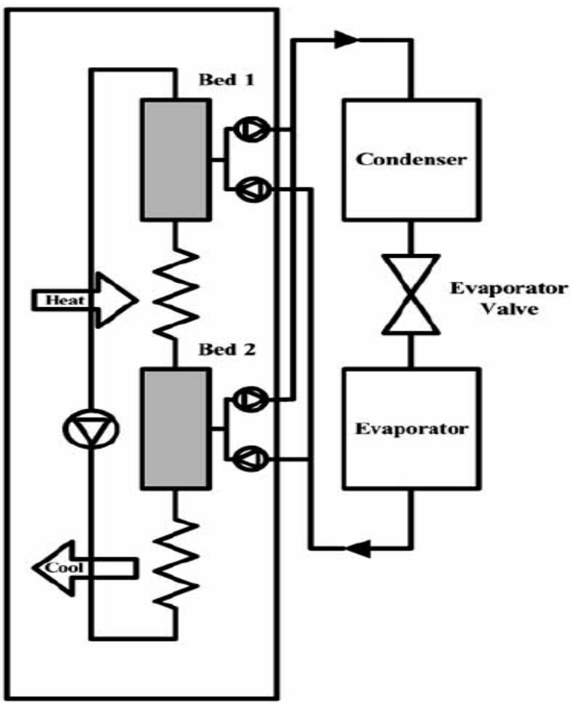

Figure 2.5 Thermal wave refrigeration system [13]

2.2.3 Involving Rotating Adsorbers

Rotary structure has been used for heat regeneration in adsorption system and providing continuous cooling effect. Critoph [12,13] described a rotary thermal regenerative adsorption system, which has a number of adsorbent module circumferentially about a rotational axis partly within a steroidal conduit as shown in Figure 2.5. A heat transfer fluid flows from an inlet of the conduit to the outlet in counter-flow with respect to the rotational movement of the adsorbent modules. Separate fluid channels encase the evaporation/condensation zones of the vessels to enable transfer of heat between the vessels and the fluid flowing in channels. In this system, heat is regenerated in a particularly simple and convenient manner. As a result the compressive device is capable of achieving higher efficiencies than existing adsorption devices.

2.2.4 Application of Heat Pipe Technology

The high initial costs of the machines and the low heat transfer rates of the adsorbers are among the limitations to commercialize adsorption systems. Based on the principle of heat pipe, a novel silica gel-water adsorption chiller [15] has been designed in Shanghai Jiao Tong University (SJTU) in China to solve these problems. There are three vacuum chambers in this adsorption chiller: two adsorption/ desorption (or evaporation/condensation) vacuum chambers and one heat pipe working vacuum chamber as the evaporator. One adsorber, one condenser and one evaporator are housed in the same chamber to constitute an adsorption/desorption unit. The evaporators of two adsorption/desorption units are combined together by a heat pipe heat exchanger in Figure 2.6 to obtain continuous cooling effect. Since heat pipe can achieve a high heat flux, and no moving parts are used to drive the heat transfer fluid, the whole system can be made in expensive and more reliable. In this chiller, a vacuum valve is installed between the two adsorption/desorption vacuum chambers to increase its performance especially when the chiller is driven by a low temperature heat source. The reliability of the chiller has been enhanced significantly due to using fewer valves.

2.2.5 Novel Control Strategies

There are various valves and other components which need to be controlled during the operation of the adsorption system.

Nagashima and Inoue at Denso described a novel method in which switching of a four-way valve on the outlet side is effected with a lag of several seconds from the switching of a four-way valve on the inlet side. Using this method, the reduction of a refrigerating capacity upon switching could be restrained to the minimum [16].

Tanaka devised a cooling system for cooling first and second heat-generating members. In this system, the first heat-generating member is cooled by a refrigerator, and cold produced by the refrigerator is stored in a cold storage unit, so that both the first and second heat-generating members can be continuously cooled by only using a single adsorption unit [17].

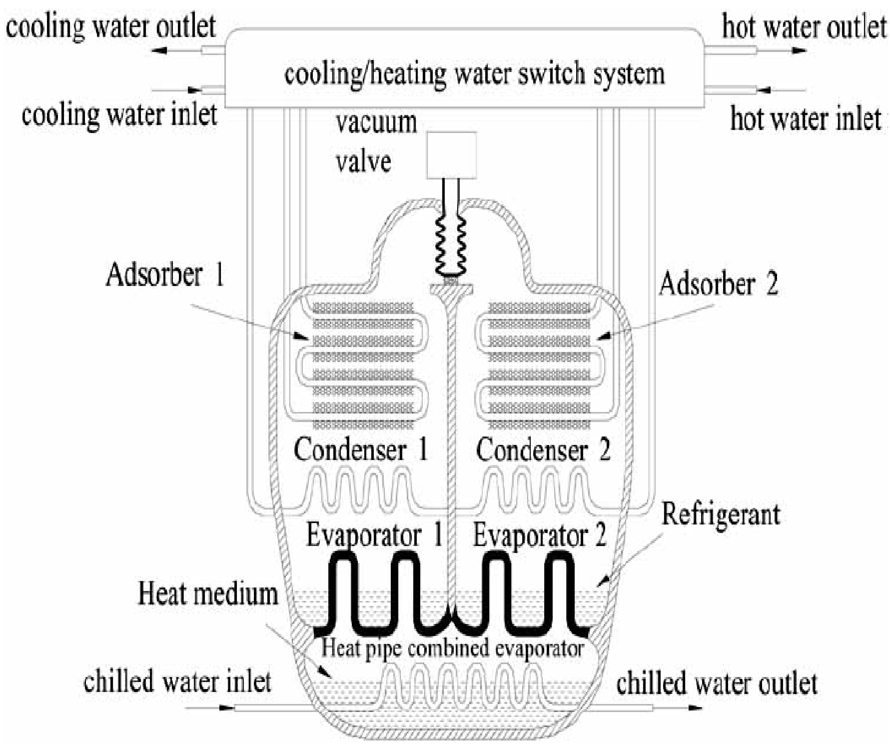

Figure 2.6 Schematic diagram of the heat pipe type silica gel-water adsorption chiller [15]

2.2.6 Adsorption System with Heat Storage

Researcher at Denso invented an adsorption refrigeration machine which uses a tank for cooling liquid storage. Figure 2.7 shows the machine with two adsorbers sealed with an adsorbent Silica gel to adsorb a steam refrigerant and a liquid refrigerant and providing refrigerating capacity. A snubber is used when switching from the desorption process to the adsorption process is affected. The temperature variation of cooling liquid is relaxed by mixing together cooling liquid circulating the absorbers and cooling liquid stored in the snubber.

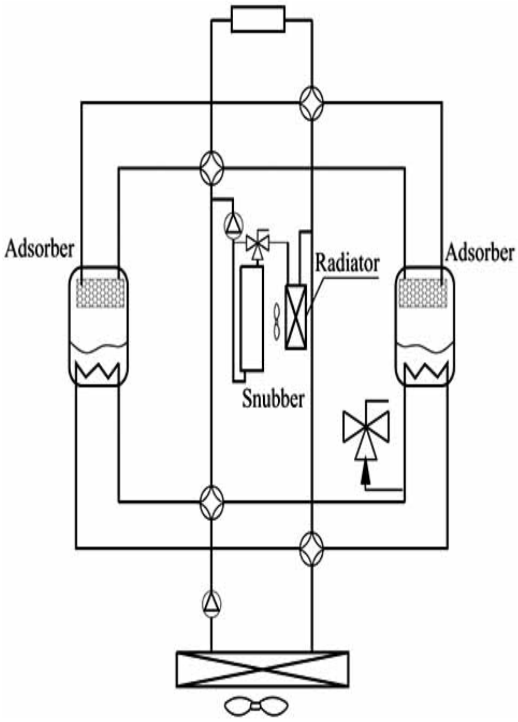

Figure 2.7 Adsorption refrigerating machine with energy storage [17]

2.2.7 Hybrid System

A refrigerating unit which combined adsorption cycle with compressive cycle was disclosed by Inoue and Honda at Denso. As illustrated in Figure 2.8, the refrigerating unit is provided with a compressor, a condenser, an evaporator to cool the refrigerant and an adsorbent bed which has an adsorbent that generates heat during the adsorption of moisture and absorbs heat during the releasing of moisture. Mitsui et al. invented an adsorption heat pump comprising two adsorbent beds, an evaporator, a condenser, and a refrigerant steam pressure machine for raising the pressure of the refrigerant steam and transporting it.

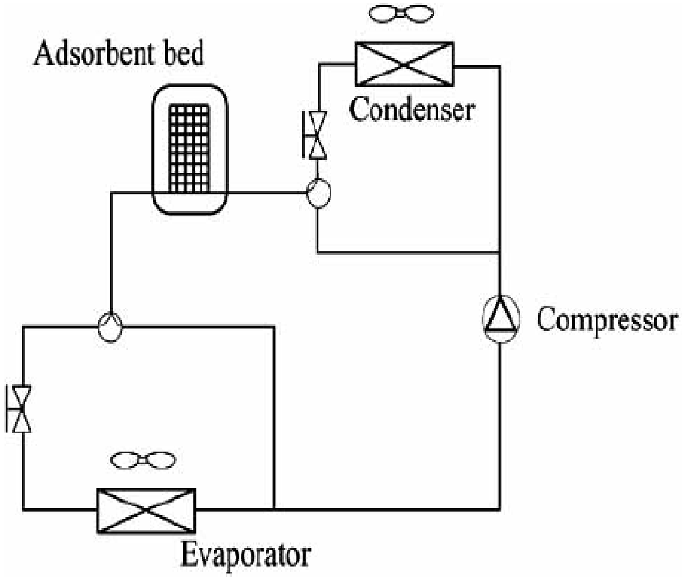

Figure 2.8 A refrigeration unit combining adsorption cycle with compressive cycle [18]

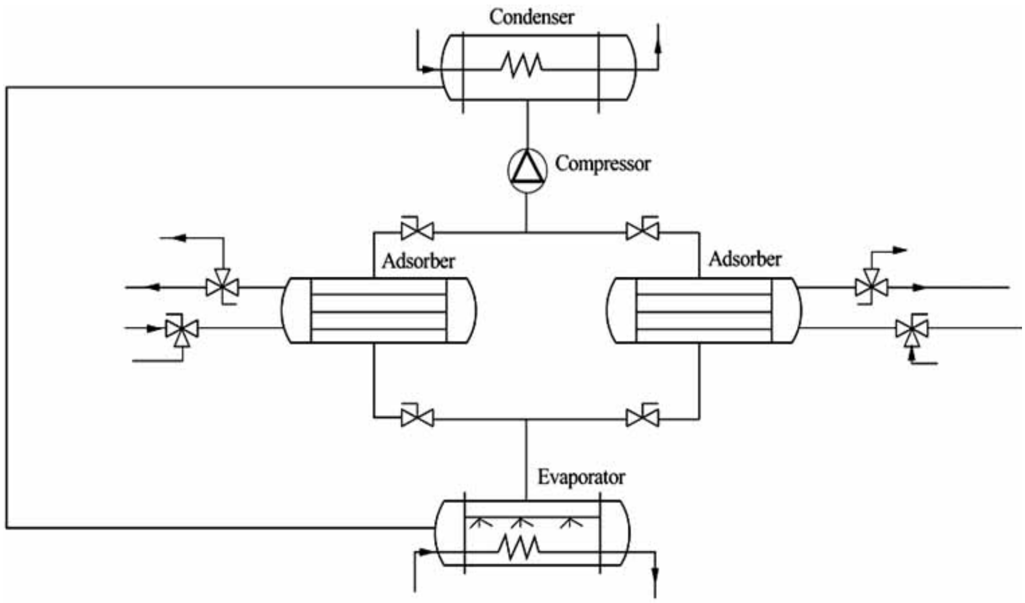

Figure 2.9 An adsorption heat pump with steam pressure machine

2.2.8 Industrial Adsorption Systems

The potential for the two-bed silica-gel–water adsorption chiller was evaluated by a number of researchers; Wang et al, Sakoda and Suzuki, Cho and Kim, Saha et al, Boelman et al, Boelman et al, and has already been commercialized in two Japanese adsorption chillers currently on the market for air-conditioning (Mycom, Nishiyodo and GBU) in which low driving temperatures as low as 70°C are used. Using the brand name "MYCOM", Mayekawa Mfg. Co., Ltd. are producing Silica-gel/water adsorption chillers (ADREF-models) with ranges between 35 and 350 kW for use in the air-conditioning industry. These units could be driven with low grade heat between 60 ˚C and 90 ˚C. Electrical power consumption of these units is normally 6% of chilling capacity and the weight/chilling output ratio is 0.2 tons/kW.

According to Justin Zhu from Jiangsu Shuangliang Air-Conditioning Equipment Co.,Ltd, the customers used these chillers in research projects in CCHP, solar energy system and in special agricultural projects. However, the manufacturer did not find the development of this chiller to be cost competitive. They paid more in copper tube, silicon dioxide and manufacturing cost, but COP is lower compared with other technology and hence, they stopped marketing this chiller from last year. They are currently working on the development of a new ammonia chiller, 3-5 kW. However, this is not on the market yet.

Hunan DY Refrigeration Co. Ltd, in China, used the DY adsorption refrigeration system linked to micro-gas turbine to get cooling from waste heat. Professor Dingyu Li is the inventor of DY Adsorption Refrigeration technology with the ability to be directly added to exhaust flues of a CHP plant. The adsorption system consists of a DY Generator, one ammonia tank, one condenser. DY are marketing the DY-HWS Refrigeration System powered by 90 °C heat energy (hot water, steam, oil, surplus heat and waste water in industry). Refrigeration capacities of 14 kW, 20 kW and 30 kW have been advertised with ability to give temperatures between -25 and 18 ˚C with heating temperature over 120 to 270 ˚C with COPs of 0.3 to 0.5.

Wang and Wang presented an assessment of the DY chemical reaction icemaker driven with the exhausted gas from a fishing vessel diesel engine exhaust. The ice maker is the refrigeration equipment mainly designed for fishing vessels with tonnage about 100 tons. It takes DY double salt as absorbent and ammonia as refrigerant. Based on chemical affinity, chemical reaction is mono variant and chemical changes occur which induce modification of the solid itself. It is powered by exhaust heat of diesel engine to make flake ice and there is no any increase in consumption of oil. The whole set of DY fishing vessel diesel engine exhaust icemaker includes one icemaker, one condenser and one DY generator system as shown in Figure 2.10. One DY generator system contains one DY generator, one ammonia tank. The method of chilling uses fresh water or seawater. Ice-making capacity with thickness about 1.5–2 mm is 33–38 kg/h with the ice temperature of -15 °C.

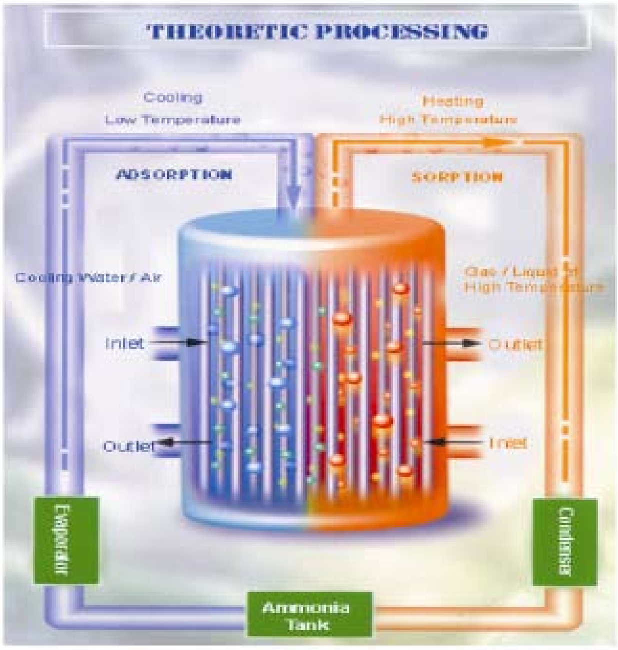

Figure 2.10 Principle of the DY refrigeration system

Classical vapour-compression technologies have reached a significant state of maturity up to now with wide use for this technology in the food retail and food production sectors. All of these systems consume precious fuel or electricity to achieve refrigeration. Along with a consideration for energy efficiency, increasing attention is being given also to the use of waste heat. Adsorption systems are heat-operated units that need little electricity, so they can utilize waste heat or renewable energies. Other advantages of solid sorption machines (noiseless, safety).

In comparison with the vapour compression refrigeration and absorption refrigeration systems, the adsorption refrigeration system has its drawbacks, such as low mass and heat transfer performance, expansion and agglomeration phenomenon for chemical adsorbent, low coefficient of performance (COP) and low specific cooling power. Besides the simple intermittent cycle and in order to provide steady refrigeration and improve the performance of adsorption refrigeration system. Some advanced cycles have been proposed and investigated, such as the multi-bed cycles, the thermal wave cycle, the forced convection cycle, the heat and mass recovery based on different adsorbent bed and different control strategies, heat pipe technologies hybrid.

Research has shown that solid-adsorption technology has a promising potential for competing with conventional absorption technology. Commercial solid adsorption systems are still limited for air-conditioning applications with only one commercially available system for sub zero temperatures. Up to now, lower temperature adsorption refrigeration systems are still under laboratory testing stages. Therefore, we find only laboratory experiments of adsorption machines in the open literature.