Review of the Heat Pump Technologies and Applications

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Report Prepared by:
SUWIC, Sheffield University

Researcher: Dr. Hanning Li

Investigators: Professor Jim Swithenbank
Professor Vida N. Sharifi

Sheffield University Waste Incineration Centre (SUWIC)
Department of Chemical and Process Engineering
Sheffield University
Executive Summary

In accordance with the EPSRC Thermal Management Grant proposal, Sheffield University has conducted an extensive literature review on heat pump technologies and applications. This report presents the results obtained from this review work. Various sources of information were used in order to compile this report. These included websites, journal publications, reports and communications with manufacturers and industry.

Usage of heat pump technologies provides significant benefits to industrial processes, mainly increased energy efficiency and lowered air emissions. Heat pumps are generally classified into vapour compression heat pumps, adsorption heat pumps, and acoustic heat pumps.

The vapour compression heat pumps have been widely applied for process industry, such as drying, distillation, etc. The pump is mostly driven by electricity. In electric motor driven compression heat pump, however, fuel is converted to electrical energy at power plants and the waste heat is discharged to the environment, then electrical energy is converted to mechanical energy. In this process, energy is converted twice and heat loss is high. To improve energy efficiency, researchers are currently developing gas engine heat pumps that directly convert fuel to the energy required by heat pump through gas engine.

The vapour compression heat pumps require moving parts that cause complicated manufacture and installation, low reliability and high maintenance costs. The emerging technologies of adsorption and thermo-acoustic heat pumps avoid the usages of moving parts and harmful solutions. Both heat pumps are promising technologies for saving energy and environmental protection.

The main component in adsorption pump is adsorbent, i.e. gel, zeolites, porous alumina, activated carbons, metal chloride, etc. Recent research has resulted in development of new composite adsorbents to enhance the heat transfer by combing calcium chloride with expanded graphite (EG) and activated carbon fiber (ACF) for use in heat pumps. Reactor is mostly designed using metal heat exchanger tube coupled with metal fins cast to the tube.

Acoustic heat pumps investigated are currently based on standing-wave and travelling-wave systems. Some examples of recent R&D activities include thermoacoustic-Stirling heat engine for natural gas liquefaction at capacity of 500 gal/day in Praxair.

In addition to the above types of heat pumps, absorption and chemical heat pumps are also developed and used in process industry. The low performance of the absorption heat pump limits its applications. These days, absorption heat pump is mostly used in devices such as solar collectors. The most common combinations (refrigerant-absorbent) of the absorption heat pumps are i) ammonia-water and ii) water-lithium bromide. Research in chemical heat pumps has recently gained some attention, mainly due to heat source using low grade heat. The working fluids include methanol–formaldehyde, ethanol–acetaldehyde, i-propanol–acetone, n-butanol–butyraldehyde, etc.

Heat pump technologies have been used in process industry, e.g drying, distillation, etc. The investigation in drying food, fruit and agricultural products has found the
significant energy saving. The quality of dried products using heat pumps, like colour, flavour and preference have also been evaluated by several researchers. In distillation industry, three configurations of compression heat pumps have been used for energy saving. The heat pumps are mostly applied for separation of mixture with close boiling points, such as propylene-propane splitter and $C_4$ separation systems. Ethanol-water separation assisted by heat pump is becoming an attractive process to industry due to an increase demand for ethanol which can be used a fuel (e.g. in vehicles) to reduce CO$_2$ emission.

Various cost analysis studies have been carried out for heat pump application in process industries. These studies generally concluded that heat pump technologies significantly save energy and reduce operational costs. The location of heating source should be considered as part of capital costs calculations during the design stage.

The main topics covered in this review work include:

- Compression heat pump;
- Adsorption heat pump;
- Acoustic heat pump;
- Applications of heat pumps for drying processes;
- Applications of heat pumps for distillation processes;
- Economic evaluations of heat pump applications.

This report present the findings from the above review work.

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1 Introduction

Heat pumps are generally classified into vapour compression heat pumps, adsorption heat pumps and acoustic heat pumps. The vapour compression heat pumps have been widely used in process industry, such as drying, distillation. The pump is mostly driven by electricity. Gas engine driven heat pumps are also being considered by various industries, due to their increased energy efficiency and utilization of waste heat. The vapour compressor heat pumps require moving parts that cause complicated manufacture and installation, low reliability and high maintenance costs. The adsorption and acoustic pumps avoid the usages of moving parts and harmful solutions. Both adsorption and acoustic pumps are promising technologies for saving energy. The main disadvantage of adsorption heat pump (comparing with compression heat pumps) is its low efficiency. The adsorbent selection and reactor design are currently being investigated to increase the efficiency. Acoustic heat pumps investigated are currently based on standing-wave and travelling-wave systems.

This report introduces operational mechanisms of three heat pumps and reviews their recent developments. Heat pumps used in drying and distillation processes are reviewed for various applications, such as food, fruit, wood, chemical separation processes. Economic aspect of each technology is also reviewed and the results are presented in this report.
2 Heat Pump

Naturally, heat flows from a place at higher temperature to another at lower temperature. Heat pumps, however, are able to force the heat flow in the reverse direction, using a relatively small amount of drive energy (electricity, fuel, or high-temperature waste heat). Thus heat pumps can transfer heat from natural heat sources, such as the air, ground, water, or industrial waste, to an industrial application. Heat pumps can also be used for cooling. Heat is then transferred in the opposite direction, from the application that is cooled, to surroundings at a higher temperature.

Thermodynamic heat pump and refrigeration cycles are the models for heat pumps and refrigerators. The difference between a heat pump and a normal air conditioner is that a heat pump can be used to heat a home as well as cool it. Even though the heat pump can heat, it still uses the same basic refrigeration cycle to do this. In other words a heat pump can change which coil is the condenser and which the evaporator. In cooler climates it is common to have heat pumps that are able only to heat the house, making the pumps simpler and cheaper, since cooling is rarely necessary.

2.1 Heat Pump Types

Almost all heat pumps currently in operation are either based on a vapour compression, or on an absorption or adsorption cycle. The heat pump is a machine that moves heat from one location (the 'heat source') to another location (the 'sink' or 'heat sink'). The heat source acquires energy and the heat sink releases energy, thus two devices are required to accomplish individual function. In the heat pump, working fluid, i.e. water, is required to transfer energy from the heat source to the heat sink.

In heat pumps, two devices, condenser and evaporator, are responsible for the heat source and the heat sink. A vapour compression heat pump utilizes mechanical works to accomplish condensing-evaporation cycle. Instead of mechanical work, an adsorption heat pump cycle utilizes different temperature levels to accomplish the cycle. In addition, absorption and chemical heat pumps in industry can be classified into adsorption one since their cycles are based on temperature levels. The detail descriptions of compression and adsorption heat pumps will be discussed in section 3 and section 4.

The major types of industrial heat pumps are compression heat pumps, including vapour compression heat pumps, and closed-cycle vapour compression heat pumps. A vapour compression system can be classified as open or semi-open compression heat pumps. In open systems, vapour from an industrial process is compressed to a higher pressure and temperature one, and condensed in the same process giving off heat. In semi-open systems, heat from the recompressed vapour is transferred to the process via a heat exchanger. In this process, the process fluid is used as working fluid of heat pumps. In closed-cycle vapour compression systems, working fluid is cycled separately from process fluid.

Recently, another type of heat pump, named as acoustic heat pump, is emerging in industrial development. An acoustic heat pump is composed of thermoacoustic engine and thermoacoustic heat pump, responsible for heat source and heat sink. This type of heat pump will be introduced in section 5.
2.2 Heat Sources

Heating and cooling is accomplished by moving a refrigerant through the heat pump's “indoor” and “outdoor” cycle. The refrigerant is used to heat or cool coils in the process cycle. An external heat exchanger is used to heat or cool the refrigerant. A medium, i.e. air or water, provides heat or cool to the external heat exchange, led to the term "Heat Source" Heat Pump.

The technical and economic performance of a heat pump is closely related to the characteristics of the heat source. An ideal heat source for heat pumps has a high and stable temperature during the heating season, is abundantly available, is not corrosive or polluted, has favourable thermophysical properties, and its utilisation requires low investment and operational costs. In most cases, however, the availability of the heat source is the key factor determining its use.

In general, ambient and exhaust air, soil and ground water are practical heat sources for small heat pump systems, while sea/lake/river water, rock (geothermal) and waste water are used for large heat pump systems.

- **Ambient air** is free and widely available, and it is the most common heat source for heat pumps. Air-source heat pumps, however, achieve on lower seasonal performance than water-source heat pumps. This is mainly due to the rapid fall in capacity and performance with decreasing outdoor temperature.

- **Ground water** is available with stable temperatures (4-10°C) in many regions. Open or closed systems are used to tap into this heat source. In open systems the ground water is pumped up, cooled and then reinjected in a separate well or returned to surface water. Open systems should be carefully designed to avoid problems such as freezing, corrosion and fouling. Closed systems can be direct expansion systems, with the working fluid evaporating in underground heat exchanger pipes. A major disadvantage of ground water heat pumps is the cost of installing the heat source. Additionally, local regulations may impose severe constraints regarding interference with the water usage and the possibility of soil pollution.

- **Ground-source systems** similar advantages as (ground) water-source systems, i.e. they have relatively high annual temperatures. Heat is extracted from pipes laid horizontally or vertically in the soil, and both direct expansion systems can be used. The thermal capacity of the soil varies with the moisture content and the climatic conditions. Due to the extraction of heat from the soil, the soil temperature will fall during the heating season.

- **Waste water and effluent** are characterised by a relatively high and constant temperature throughout the year. Examples of possible heat sources in this category are effluent from sewers (treated and untreated sewage water), industrial effluent, cooling water from industrial processes or electricity generation, condenser heat from refrigeration plants. Waste water and effluent serve as an ideal heat source for industrial heat pumps to achieve energy savings in industry.

2.3 Heat Pump Performances

As shown in Figure 2-1, all real refrigerators and heat pumps require work to get heat to flow from cold area to warm area. The heat delivered by a heat pump is
theoretically the sum of the heat extracted from the heat source and the energy needed to drive the cycle.

![Figure 2-1 Heat and work flowchart in Heat pump]

The steady-state performance of an electric compression heat pump is referred to as the coefficient of performance (COP). It is defined as the ratio of the heat delivered to hot reservoir to the work input in the system.

\[
\text{COP}_{\text{heating}} = \frac{Q_H}{W}
\]

For ideal COP:

\[
\text{COP}_{\text{heating}} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C}
\]

Similarly,

\[
\text{COP}_{\text{cooling}} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C}
\]

Figure 2-2 shows the COP for an ideal heat pump as a function of temperature lifts, where the temperature of the heat source is 0°C. Also shown is the range of actual COPs for various types and sizes of real heat pumps at different temperature lifts. For electric compression heat pumps, COP is normally ranged from 2.5 to 5.0. Industrial heat pumps often have a higher COP than heat pumps for buildings. Typical COP ranges for industrial heat pumps are given in Table 2-1.
Table 2-1 Typical COP of heat pumps for industry

<table>
<thead>
<tr>
<th>Heat pump type</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVR 10-30</td>
<td>10-30</td>
</tr>
<tr>
<td>Closed cycle, electric</td>
<td>3.0-8.0</td>
</tr>
</tbody>
</table>

For engine and thermally driven heat pumps the performance is described by the primary energy ratio (PER). It is defined as the ratio of the amount of primary energy (e.g. fuel) supplied to the amount of energy delivered as hot source. The energy supplied is the higher heating value (HHV) of the fuel supplied. For electrically driven heat pumps a PER can also be defined, by multiplying the COP with the power generation efficiency.

IEC Heat Pump Centre provides achievable PERs for different heat pump types at evaporation 0°C and condensing temperature 50°C, as shown in Table 2-2. University of Strathclyde, UK, has investigated the primary energy ratio of the three systems, as shown in Figure 2-3. The engine-driven heat pump provides almost twice as much heat per unit of fuel burned as does the electric heat pump.

Table 2-2: Typical PER range for heat pumps with different drive energies.

<table>
<thead>
<tr>
<th>Heat pump type</th>
<th>PER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine (compression)</td>
<td>0.8 - 2.0</td>
</tr>
<tr>
<td>Thermal (absorption)</td>
<td>1.0 - 1.8</td>
</tr>
</tbody>
</table>
Figure 2-3. Primary energy ratios for three heating systems.

The performance of heat pumps is affected by a large number of factors, including:
- the climate - annual heating and cooling demand and maximum peak loads;
- the temperatures of the heat source and heat distribution system;
- the auxiliary energy consumption (pumps, fans, supplementary heat for the system etc.);
- the technical standard of the heat pump;
- the sizing of the heat pump in relation to the heat demand and the operating characteristics of the heat pump;
- the heat pump control system.
3 Vapour Compression Heat Pumps

3.1 Principle of Operations

Currently, most of heat pumps used in industry are based on a vapour-compression cycle. Figure 3-1 provides a schematic diagram of a typical vapor-compression system. The main components in a heat pump system are the compressor, the expansion valve and two heat exchangers used as evaporator and condenser. The components are connected to form a closed circuit, as shown in Figure 3-1. A volatile liquid, known as the working fluid circulates through the four components.

In the evaporator the temperature of the liquid working fluid is kept lower than the temperature of the heat source, leading heat flowing from the heat source to the liquid, and the working fluid evaporates. Vapour from the evaporator is compressed to a higher pressure and temperature. The hot vapour then enters the condenser, where it condenses and gives off the heat. Finally, the high-pressure working fluid is expanded to the evaporator through the expansion valve. The working fluid is returned to its original state and once again enters the evaporator.

Figure 3-1 schematic diagram of vapour compression cycle

The thermodynamics of the cycle can be analyzed on a diagram as shown in Figure 3-2. In this cycle, a circulating refrigerant such as Freon enters the compressor as a vapor. The vapor is compressed at constant entropy and exits the compressor. The superheated vapor travels through the condenser which first cools and removes the superheat and then condenses the vapor into a liquid by removing the heat at constant pressure and temperature. The liquid refrigerant goes through the expansion valve where its pressure abruptly decreases, causing flash evaporation.

In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump. Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied. Electrically-driven heat pumps for heating buildings typically supply 100 kWh of heat with just 20-40 kWh of electricity. Many industrial heat pumps can...
achieve even higher performance, and supply the same amount of heat with only 3-10 kWh of electricity.

![Thermodynamic cycle of heat pump operation](image)

Because heat pumps consume less primary energy than conventional heating systems, they are important technologies for reducing gas emissions that harm the environment, such as carbon dioxide (CO2), sulphur dioxide (SO2) and nitrogen oxides (NOx). However, the overall environmental impact of electric heat pumps depends on how the electricity is produced. Heat pumps driven by electricity from, for instance, hydropower or renewable energy reduce emissions more significantly than if the electricity is generated by coal, oil or gas-fired power plants.

### 3.2 Heat Pump Working Fluids

In heat pump technology, closed-cycle compression type heat pump requires a working fluid. Traditionally, the most common working fluids for heat pumps are "Freon", a trade name for a family of haloalkane refrigerants. These refrigerants, i.e. CFC, were commonly used due to their superior stability and safety properties: they were non-flammable and non-toxic. Unfortunately, these chlorine-bearing refrigerants contain chlorine element which does severe damage to the ozone layer that shields the Earth's surface from the Sun's strong UV radiation. CFC refrigerants in common include R-11 and R-12. Newer refrigerants that have reduced ozone depletion effect include HCFCs (R-22, used in most homes today) and HFCs (R-134a, used in process industry) have replaced most CFC use. HCFCs in turn are being hydrofluorocarbons (HFCs), such as R-410A, which lack chlorine. However, CFCs, HCFCs, and HFCs all have large global warming potential.

Newer refrigerants are currently the subject of research, such as supercritical carbon dioxide, known as R-744. These have similar efficiencies compared to existing CFC
and HFC based compounds, and have many orders of magnitude lower global warming potential.

In chemical processing, cold storage, food processing and district heating and cooling, R134a, R404A, R507, and R717 are used in large heat pump equipment, typically 25 kW to 30 MW.

Natural working fluids used in industry are substances, naturally existing in the biosphere, including are ammonia (NH₃), carbon dioxide (CO₂), air and water. They generally have negligible global environmental drawbacks. They are therefore long-term alternatives to the CFCs. Some of the natural working fluids are flammable or toxic. The safety implications of using such fluids may require specific system design and suitable operating and maintenance routines.

### 3.3 Compressor

The most common compressors used in heat pump system are reciprocating, rotary screw, centrifugal, and scroll compressors. Industrial vapour compression type heat pumps often use the process fluid itself as working fluid in an open cycle. These heat pumps are generally referred to as mechanical vapour re-compressors. The compressor is usually driven by an electric motor. An electric motor drives the compressor (see Figure 3-3a) with very low energy losses. The overall energy efficiency of the heat pump strongly depends on the efficiency by which the electricity is generated. The electric motor driven compressor is a mature technology, which can be reached at high efficiency with suitable refrigerant.

![Figure 3-3a](image1)

(A) electric-motor-driven

![Figure 3-3b](image2)

(b) gas combustion-driven

Figure 3-3 Closed cycle vapour compression heat pump

In electric motor driven compression heat pump, fuel is converted to electrical energy at power plants and the waste heat is discharged to the environment, then electrical energy is transmitted to the heat pumps and is converted to mechanical energy by motor of the heat pumps. In this process, energy is converted twice and heat loss is high. If fuel conversion can be directly converted to the energy required by heat pump, energy efficiency can become higher. A gas engine heat pump, as shown in Figure 3-3b, is designed by this concept. Many investigators are developing integration of gas
engine with heat pump system to achieve the higher efficiency. Following introduces the recent development of gas engine driven compressors or heat pumps

### 3.4 Gas Engine Driven Heat Pumps

A gas engine heat pump (GEHP) is driven by a gas fuelled internal combustion engine instead of an electric motor. A GEHP system mainly consists of two parts: (i) the HP itself, which includes an open compressor, a condenser, an expansion valve and an evaporator, and (ii) the gas engine system (Zhang et al., 2005).

The distinctive part of GEHPs is the gas engine system. Normally their heat efficiency is not very high (about 30–45%). But waste heat can be recovered in GEHPs. Therefore the considerable difference of GEHP systems from conventional electrical heat pump systems is its heat recovery and resulted energy efficiency. Heat recovery in GEHPs from waste heat of fuel combustion is approximately 80% (Li et al., 2005) and this heat is gained by utilizing the energy of exhaust gas and the waste heat released by engine. The utilization could be made generally by two ways: (i) it is transferred directly to air and heated air is used in heating process, and (ii) it is transferred to water and water heating process is done (Hepbasli et al., 2009).

Hepbasli et al. (2009) reviewed GEHP systems for residential and industrial applications. In their studies, development of GEHP systems was briefly given and the operation of these systems was described. This section introduces some recent development of gas engine driven heat pumps, mostly focused on experimental and industrial applications.

![Schematic diagram of GEHP](image)

**Figure 3-4** Schematic diagram of GEHP: 1. natural gas engine, 2. compressor, 3. four-way valve, 4. plate heat exchanger, 5. supply water pump, 6. expansion valve, 7. finned-tube heat exchanger, 8. heat radiator, 9. gas-to-water heat exchanger, 10, 13. three-way valve, 11. water-to-water heat exchanger, 12. cooling water pump.

Zhang et al. (2005) conducted the heating performance of a gas engine driven heat pump. Figure 3-4 shows the system used for testing the performance. The whole system consists of two parts: the heat pump system and the gas engine system. The heat pump itself is no different from the ordinary electrical heat pump. The gas engine is modified from a gasoline engine, as shown in Fig. 3-5. Their results indicated that the system PER decreases from 1.65 to 1.1 when the engine speed
increases from 1000 RPM to 3500 RPM at the constant temperature of 7 °C. This means that the GEHP is more energy saving when it works in low speed. The engine power efficiency is higher in the medium speed range, while the total energy efficiency decreases with the increase of engine speed. At the constant engine speeds of 2000 RPM, the system PER increases from 1.1 to 1.4 with the increase of temperature from -15 to 15 °C, mainly due to the increase of the heat pump efficiency with temperature.

Yagyu et al. (1997, 2000) designed and tested the performance of a gas engine driven Stirling heat pump. The developed machine was a three cylinder one, consisting of two Stirling sub-systems, one a power producer and one a heat pump. Figure 3-6 shows a concept of the prototype machine. Figure 3-7 shows a heat flow diagram of the three-cylinder heat pump. The heat pump comprises two 2-cylinder Stirling subsystems: one between high and medium temperature (H-M); one between medium and low temperature (M-L). The M-L subsystem acts as a heat pump and the H-M sub-system serves as a power producer which assists with extra shaft power. The downstream heat of the H-M sub-system is waste heat of the sub-system and utilized as an additional heating output. They tested the system using gasified methanol as fuel. The thermal efficiency is 32 % of the fueled gas HHV by using gasified methanol as fuel. The exhaust gas heat is 37 % of the fueled gas HHV. They estimated the total COP as 1.9 (on a HHV basis) and stated that COP would be improved to 2.42 (HHV) in CFC-free environment.
Li et al. (2007) designed a hybrid-power gas engine-driven heat pump (HPGHP) system, as shown in Figure 3-8. The system mainly comprises three parts: the power system, the refrigerant system and the water cycle system. The power system includes the internal combustion engine (ICE), a power distributing device, a motor, battery packs as well as a power control module, etc. The refrigerant system consists of a compressor, an indoor heat exchanger (IHE), an outdoor heat exchanger (OHE), an expansive valve and a four-way valve, etc. The jacket heat exchanger (JHE) and the exhaust heat exchanger (EHE) are important parts of the water cycle system which reclaims the waste heat from the exhaust and jacket in the ICE. They performed thermal efficiencies and concluded that maximum and minimum thermal efficiencies of a conventional GEHP system were 33% and 22%, respectively, while those of novel HPGHP system were 37% and 27%, respectively.

Figure 3-8 The structure of the parallel HPGHP system (Ying-Lin et al., 2007).

Sun (2007) studied and tested the performance of a combined heat and cold system driven by a gas industrial engine as a prototype named by CHCSDGE. The schematic diagram of the CHCSDGE prototype is shown in Figure 3-9. A gas industrial engine was supplied from Caterpillar Manufacturer Company. An open screw compressor, supplied from Wuhan New World Refrigeration Industrial Co. Ltd., was driven by the gas engine. A plate heat exchanger (PHE) was used to recover waste heat from the jacket coolant and a shell and tube heat exchanger (STHE) was used to recover waste heat from the exhaust gas. The experimental results demonstrated that the capacity in the cycle of the prototype was about 467.1 kW and the recovered heat was about 148.7 kW at the speed of 1800 rpm and 323.7 kW of consumed natural gas. The
refrigerating capacity and heat recovered from the gas industrial engine of the prototype reduced but the energy utilization ratio increased with the reduction of the gas engine speed in the range of 1350–1800 rpm. In order to attain a high efficiency, the speed of the gas industrial engine was preferably regulated at partial load.

Kim et al. (2009) experimentally investigated the heating capacity of heat pump using heat recovered from a gas engine. Figure 3-10 shows the schematic experimental apparatus for the system using heat recovered from the gas engine generator. Figure 3-11 shows the schematic of the second experimental apparatus for evaluating the effect of increasing the heating capacity of an EHP when the total recovered heat from the gas engine generator is only supplied to the sub-evaporator. They concluded that supplying the recovery heat to the sub-evaporator increases heating capacity by 52% and heating COP by 26%; and supplying the recovery heat to the discharge line HEX leads to an increase of heating capacity by 16% and an increase of heating COP by 26%. The recovery heat supplied to the sub-evaporator would gain a higher efficiency.

Figure 3-10 Schematic of experimental apparatus for evaluating the heating capacity of an EHP using the heat recovered from the gas engine generator.

Figure 3-11 Schematic of the second experimental apparatus for evaluating the effect of increasing the heating capacity of an EHP when the total recovered heat from the gas engine generator is only supplied to the sub-evaporator.
4 Adsorption Heat Pumps

4.1 Adsorption Heat Pumps

A basic adsorption heat pump cycle consists of four main parts: an adsorber, which is a container filled with an adsorbent (such as zeolite, active carbon, silica gel, etc.); a condenser; an evaporator; and an expansion valve. Basically, adsorption heat pump operates by cycling adsorbate between adsorber, condenser, and evaporator (Demir et al. 2008). In the adsorption heat pump cycle, adsorption phenomena play the same role of mechanical power, so that the working fluid can be circulated in the cycle without any mechanical power.

The adsorption heat pump cycle can be classified into two separate processes, adsorption and desorption processes. Figure 4-1 shows an impression of a basic adsorption-desorption cycle. Initially the whole assembly is at low pressure and temperature, the adsorbent contains a large concentration of refrigerant and the other vessel contains refrigerant gas (a). The adsorbent vessel (generator) is then heated, driving out the refrigerant and raising the system pressure. The desorbed refrigerant condenses as a liquid in the second vessel, rejecting heat (b). This is part of the useful heat output of a heat pump. Finally the generator is cooled back to ambient temperature, reasorbing the refrigerant and reducing the pressure. The reduced pressure above the liquid in the second vessel causes it to boil, absorbing heat and producing the cooling product. The heat rejected by the generator forms the other part of the useful heat output of the heat pump. The cycle is discontinuous since useful cooling only occurs for one half of the cycle. Two such systems can be operated out of phase to provide continuous cooling.

Figure 4-1 Basic adsorption cycle

Figure 4-2 shows transfer configuration of adsorption heat pump cycle. As mentioned above, the adsorption heat pump cycle can be considered as two separate cycles. The first cycle is a heat pump in which the working fluid is vaporized in evaporator by taking heat \( Q_L \) from the low-level temperature source and releasing \( Q_a \) heat to the first intermediate temperature source. This cycle represents adsorption process. The second cycle is a heat engine, which receives heat \( Q_z \) from the high-temperature source and releases heat \( Q_c \) to the second intermediate temperature source. The transfer of heat \( Q_c \) to the second intermediate temperature source occurs during the condensation of working fluid in condenser. This cycle represents desorption process. The adsorption heat pump cycle works between three temperatures levels (Fig. 4-2) whereas a vapour compression cycle works between two temperature levels and needs a mechanical power.
In an adsorption heat pump cycle, the work obtained in the heat engine is employed to run the heat pump. The temperatures of intermediate sources (Tc and Ta) are generally close to each other. Thus, three temperature (T_{Z}, T_{L}, and Tc or Ta) levels can be considered for an adsorption heat pump and the ideal coefficient of performance of an adsorption heat pump cycle can be obtained as (Demir et al. 2008):

For cooling:
\[
\text{COP}_{\text{ref}} = \frac{Q_{L}}{Q_{Z}} = \frac{1 - (T_{C}/T_{Z})}{(T_{C}/T_{L}) - 1}.
\]

For heating:
\[
\text{COP}_{h} = \frac{Q_{C}}{Q_{Z}} = 1 + \frac{1 - (T_{C}/T_{Z})}{(T_{C}/T_{L}) - 1}.
\]

4.2 Adsorbents

Adsorption is a surface phenomenon occurring at the interface of two phases: solid phase and fluid adsorbed on the solid surface, known as adsorbent and adsorbate. Adsorption is a physical process generally referred to as physical adsorption caused by Van der Waals forces, or a chemical process referred to as chemical adsorption, involving valency forces. Regardless of the type of sorption involved, heat of adsorption is involved. The heat of adsorption is usually small in physical adsorption and large in chemical adsorption. Adsorbent substances can be recovered to original conditions by a desorption process under the application of heat.

Briefly, adsorption characteristics of adsorbents are determined by the adsorption isotherms, for the amount a substance adsorbed. Generally, heat of adsorption is experimentally determined using the calorimetric method. Table 4-1 shows the heats of adsorption for some adsorbent/adsorbate pairs. The performance of adsorbents used in physical adsorption is governed largely by surface properties, such as surface area, micro-pores and macro-pores, size of granules in powders, crystals or in pellets.

Adsorbents generally grouped into `hydrophilic' and `hydrophobic'. Adsorbents having special affinity with polar substances like water are termed `hydrophilic'.

---

Figure 4-2 Heat transfer configuration of ideal adsorption heat pump cycle.
These include silica gel, zeolites and porous or active alumina. Non-polar adsorbents, termed 'hydrophobic', have more affinity for oils and gases than for water. These substances include activated carbons, polymer adsorbents and silicalites.

Table 4-1 Heat of adsorption of some adsorbent/adsorbate pairs (Srivastava and Eames, 1998)

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Adsorbate</th>
<th>Heat of adsorption (kJ kg⁻¹)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica gel</td>
<td>Methyl alcohol</td>
<td>1000–1500</td>
<td>Not suitable above 200°C</td>
</tr>
<tr>
<td></td>
<td>H₂O</td>
<td>2800</td>
<td>Used mostly for desiccant cooling</td>
</tr>
<tr>
<td>Activated alumina</td>
<td>H₂O</td>
<td>3000</td>
<td>Natural zeolites have lower values than synthetic zeolites</td>
</tr>
<tr>
<td>Zeolite (Various grades)</td>
<td>H₂O</td>
<td>3300–4200</td>
<td>Reacts at approx. 100°C</td>
</tr>
<tr>
<td></td>
<td>NH₃</td>
<td>4000–6000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>800–1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH₃OH</td>
<td>2300–2600</td>
<td></td>
</tr>
<tr>
<td>Charcoal</td>
<td>C₂H₄</td>
<td>1000–1200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NH₃</td>
<td>2000–2700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H₂O</td>
<td>2300–2600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH₃OH</td>
<td>1800–2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₃H₆OH</td>
<td>1200–1400</td>
<td></td>
</tr>
</tbody>
</table>

4.2.1 Commercial hydrophilic solid adsorbents

Commercial hydrophilic solid adsorbents mostly refer to Silica gel, Activated alumina, Zeolites and metal chloride.

Silica gel (SiO₂.xH₂O) is prepared from pure silica and chemically bonded water (about 5%). If it is overheated and loses this water, its adsorption capacity is lost and therefore it is generally used in temperature applications under 200°C. It is available in various pore sizes, and the smaller the pore size the greater is the surface area per unit mass, which is typically 650 m²/g. Silica gel grades with the finest pores have a molecular sieve effect similar to those of Zeolites. Silica gel has a large capacity for adsorbing water, especially at high vapour pressures. Silica gels, ranging from pore sizes 2 to 3 nm (Type A) to about 0.7 nm (Type B) are mostly used in commercial applications. Type A is used for general drying and Type B for relative humidities greater than 50%. Heat of adsorption of water vapour on silica gel is predominantly due the heat of condensation of water (Srivastava and Eames, 1998)

Activated alumina is aluminium oxide in a porous form prepared by dehydration of aluminium hydrates (mostly Al₂O₃.3H₂O) to about 6% moisture level and having surface area ranging between 150 and 500 m²/g with pore sizes ranging from 1.5 to 6 nm. It is generally useful as a drying agent and adsorbent for polar organic substances.

Zeolites, also called molecular sieves, are aluminosilicate minerals and are naturally occurring. Many types of synthetic zeolites have been developed for special applications, i.e. molecular sieves of types 4A, 5A, 10X and 13X. These substances have cavity volumes in the range of 0.05 to 0.30 cm³/g. However, they may be heated to about 500°C without damage occurring to their adsorption and regeneration properties. Type 4A (NaA), is used for drying and separation of hydrocarbon mixtures. Type 5A (or CaA) is used to separate some cyclic hydrocarbons. Type 10X (or CaX) and 13X (or NaX) adsorb quite a wide range of adsorbates because of their larger diameter of inlet necks of their pores.
Metal chloride is a very widely available adsorbent for heat pumps. Wang et al. (2009) conducted the adsorption tests using working pairs alkaline-earth metal chlorides as adsorbents and ammonia as refrigerant. The study shows that the adsorbents of CaCl₂, SrCl₂ provide better adsorption capability associated with ammonia when compared to that of MgCl₂, BaCl₂. The results show that the refrigeration capacity of the unit adsorbent of CaCl₂/CaSO₄ is 1.26 times higher than that of CaCl₂, and SrCl₂/CaSO₄ is 1.6 times higher than that of SrCl₂ at 100°C.

4.2.2 Commercial hydrophobic solid adsorbents

Activated carbons are made by pyrolyzing and carbonising source materials, such as coal, lignite, wood, nut shells and synthetic polymers, at high temperatures (700 to 800°C). Activated carbons are available in many forms including powders, microporous, granulated, molecular sieves and carbon fibres. Generally, the activated carbon in the powdered form (15 to 25 mm particles) is used for adsorption of liquids and in granulated (sieved granules of 4 to 20 mesh or about 3 mm to 0.8 mm diameter) or pellet forms for air purification and gas separation. Activated carbon in microporous forms has molecular sieving ability and is widely used for separation of nitrogen and oxygen in air. Activated carbon fibres (diameter of 7 to 15 mm) are used for air and water purification.

4.2.3 Recent development of composite adsorbents

Heat transfer in a reactor used for gas–solid reaction is generally poor and its effective thermal conductivity is generally in the range of 0.1–0.2 W/(m K). Therefore, enhancement of heat transfer in the reactor is important for developing gas–solid heat pumps with high performance. One of enhancing heat transfer is preparation of composite reactant of adsorbent combined with heat transfer promoter with high thermal conductivity. Composite adsorbents made from metallic foams, zeolites and natural graphite have good prospects in improving the heat transfer rates in the adsorbent beds, consequently increasing heat pump system performance. Table 4-2 summarized some composites according to the kind of heat transfer promoter.

<table>
<thead>
<tr>
<th>Heat transfer promoter</th>
<th>Preparation technique</th>
<th>Reaction couple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded graphite</td>
<td>Simple mixing</td>
<td>CaCl₂/NH₄ [1]</td>
</tr>
<tr>
<td></td>
<td>Impregnation of aqueous solution of salt into EG, dehydration and calcination</td>
<td>CaCl₂/CH₃OH [2]</td>
</tr>
<tr>
<td></td>
<td>Impregnation of aqueous solution of salt into compressed EG, dehydration and calcination</td>
<td>CaCl₂/CH₃NH₂ [3]</td>
</tr>
<tr>
<td>Carbon fiber</td>
<td>Mixing activated carbon with compressed EG using resin as a binder</td>
<td>MgCl₂/H₂O [8]</td>
</tr>
<tr>
<td></td>
<td>Impregnation of aqueous solution of salt into fiber and dehydration</td>
<td>MnCl₂/H₂O [9]</td>
</tr>
<tr>
<td></td>
<td>Insertion of carbon fiber brush into bed</td>
<td>Zeolite/H₂O [10]</td>
</tr>
<tr>
<td>Metal foam (Cu, Ni)</td>
<td>Formation of an intercalation compound</td>
<td>Activated carbon/CO₂ [9]</td>
</tr>
<tr>
<td></td>
<td>Impregnation of a suspension of ads, compression and calcination</td>
<td>Activated carbon/CH₃OH [10]</td>
</tr>
<tr>
<td>Aluminum hydroxide</td>
<td>Mixing, compression and calcination</td>
<td>Zeolite/H₂O [12]</td>
</tr>
<tr>
<td>Metal fin or tube</td>
<td>Insertion of fins into bed</td>
<td>Co/Fe/H₂O [13]</td>
</tr>
<tr>
<td></td>
<td>Integration of reactant with heat exchanger by coating fin tubes with an adsorbent layer</td>
<td>Silica gel/H₂O [14]</td>
</tr>
<tr>
<td></td>
<td>Forming monolithic carbon discs and insertion into aluminum fins</td>
<td>Zeolite/ H₂O [15]</td>
</tr>
<tr>
<td></td>
<td>Activated carbon/ NH₃ [16]</td>
<td></td>
</tr>
</tbody>
</table>

Expanded graphite is normally used as material for promoting heat transfer. The common preparation procedure is to impregnate an aqueous solution of inorganic salt into expanded graphite matrices. Using this method one can prepare a reactor bed whose effective thermal conductivity is up to 10 times larger than that of the bed
packed with untreated salt particles. In case of adsorbents like activated carbon that is insoluble in water, resin is used as a binder to bond the adsorbent with expanded graphite. Following summarizes some recent reports of carbon and expanded graphite based composites.

Wang et al. (2006) investigated the performance of activated carbon and a carbon composite as adsorbents for heat pumps. They concluded that for the physical adsorbents, consolidated activated carbon showed best heat transfer performance. For the composite adsorbents, the consolidated composite adsorbent, with mass ratio of 4:1 between CaCl2 and activated carbon, showed the highest cooling density when compared to the granular composite adsorbent and to the merely chemical adsorbent. Fujioka et al. (2008) investigated the enhancement of the heat transfer by combing calcium chloride with expanded graphite (EG) and activated carbon fiber (ACF) in a packed bed reactor for heat pumps. The effective thermal conductivity of EG composite bed was larger than that of the untreated calcium chloride bed. The effective thermal conductivity of ACF composite bed was lower than the untreated calcium chloride bed and. Li et al. (2009) studied the performance of composite adsorbent of CaCl2 and expanded graphite. The testing results show that the composite adsorbent treated by solution is more homogeneous than the simple mixed composite adsorbent. The treated composite adsorbent has a better mass transfer performance. Tokarev et al. (2010) developed a composite sorbent “31 wt.% CaCl2/ACF” and found that was an advanced material for adsorptive refrigeration. Zajaczkowski et al. (2010) developed and patented a new composite material for heat pumps. It is based on the composition of expanded graphite (EXG) and carbon fibers (CF). They concluded that high heat transfer capabilities of carbon fibers allow sorption composites with high transfer capabilities.

![Figure 4-3 Photographs of composite zeolite/foam aluminum.](image)

Besides expanded graphite composite, composite zeolite/foam aluminum also enhances heat and mass transfer for adsorption refrigeration. Hu et al. (2009) designed new composite zeolite/foam aluminum. The effective thermal conductivity of this composite material is 2.89 W/m K, much higher than that of a zeolite particles packed bed. Its adsorption performance is the same as that of zeolite particles according to the experiment results. Compared with the zeolite–water system, the composite
zeolite/foam aluminum–water system has much higher COP at short cycle time because of the enhancement of the heat transfer. Figure 4-3 shows the appearance of composite zeolite/foam aluminum.

Compared to enhancing heat transfer technology, silica gel technology attracted researchers on adsorbent regeneration at a relatively low temperature (below 100 °C, and typically about 85 °C). Liu et al. (2005) tested a developed silica gel adsorption water chiller to utilize low heat sources from 70 °C to 95°C. Tahat et al. (2001) studied experimentally a thermo-chemical energy-store using silica gel and water as a reversible pair using low grade thermal energy. They found the low specific energy storage capacity of adsorbent and consequently the large weight and volume of the apparatus. To improve the performance of silica gel, Yamamoto et al. (2003) and Huang et al. (2010) modified the inner pores of activated carbon by impregnating silica to achieve a high water vapour adsorption performance. In fact, this technique needs further investigating to meet the adsorption heat pump practical application (Huang et al., 2010).

Recently, composite sorbents have been prepared by impregnating salt inside a porous adsorbent matrix to improve the specific water sorption capacity. A new family of composite sorbents called selective water sorbents (SWSs) has been presented for sorption cooling and heat pumping. It is based on a porous host matrix (silica, alumina, etc.) and an inorganic salt (CaCl2, MgCl2, MgSO4, Ca(NO3)2, etc.) impregnated inside pores (Saha et al., 2009). Among the different SWSs, the “CaCl2 confined to silica gel” shows very high water sorption capacity (up to 0.8 g of water per 1 g of dry adsorbent). One important benefit is that the relatively low temperature (80–100 °C) required for regeneration yields this SWS very attractive for utilization of low grade heat sources, such as solar heat, industrial waste heat, or automotive exhaust gas. Restuccia et al. (2004) studied performances of SWSs for application in cooling. The results showed that this new material allows us reaching COP at 0.6 at low desorption temperature of 90-95 °C. Zhu et al. (2006) experimentally studied the sorption properties of the silica gel supported CaCl2 sorbent. The results showed that the sorption capacity of water on silica gel increased significantly after its impregnation with CaCl2. Its huge water sorption amount and high specific TES (thermal energy storage) capacity provided great potential in the application in the low grade heat storage. Daou et al. (2008) developed composite adsorbent S40 (microporous silica gel impregnated in 40% concentrated aqueous solution of calcium chloride) and obtained a maximum COP value of 0.62 in a single-bed system.

4.3 Development of Adsorbent Bed Design

The design of adsorbent bed is the difficulty of adsorption heat pumps. Adsorbent bed requires a special design for controlling heat and mass transfer. Theoretical studies have shown the influence of both heat and mass transfer kinetics on performance of adsorption heat pump system (Chahbani et al., 2004). Since thermal conductivity of adsorbents is generally low, heat is transferred slowly through the adsorbent bed as well as the periods of adsorption and desorption processes become longer. Many researchers have carried out the experimental studies to improve mass and heat transfer rates in adsorbent beds. In general, the adsorbent bed can be designed according to uncoated and coating type adsorbers.

4.3.1 Uncoated type adsorber
In this type of adsorbent bed, pellet, granule or fiber adsorbent is generally employed. Adsorbent is not treated and used as it is received from the manufacturer. The adsorbate moves in voids between particles (pellet or granule) and then adsorbed in the adsorbent. Fins can be employed in order to increase heat transfer rate in the bed; mass transfer rate through the bed is improved by creating voids in the bed. Some examples of uncoated type adsorbers are shown in Fig. 4-4. Fig. 4-4a depicts slim thin wall shell tube adsorber designed for improving heat transfer rate by Gui et al. (2002). The activated carbon used as adsorbent which is placed among the tubes that are used for heating and cooling. The rib pieces on tubes increase heat transfer rate from the tubes to the activated carbon, since the contact area of heat transfer is increased. Saha et al. (2006) employed activated carbon fiber as adsorbent. Activated carbon fibers, having higher total pore volume, surface area and adsorption capacity, are packed tightly inside oxygen-free copper fins as shown in Fig. 4-4b. Critoph et al. (2000) developed prototype of a fast cycle adsorption refrigerator that is composed of laminate of monolithic carbon discs and aluminum fins as shown in Fig. 4-4c.

4.3.2 Coating type adsorber

In this type of adsorber, adsorbent is coated around a pipe, fin or in metal foam. This type of adsorbent bed generates high rates of heat and mass transfer.

Figure 4-4 Photograph of untreated type of adsorbent bed designs.

Figure 4-5 An advanced solid sorption chiller using SWS-1L

Restruccia et al. (2002) designed a coated stainless steel tube with adsorbent in bed. It consists of an adsorbent coating (zeolite-based) firmly bound to the metal of the
heat exchanger. This improves the global heat transfer coefficient and, consequently, the specific power of the system. Fig. 4-5 shows a sample. In this case, a stainless steel tube (type AISI 304, internal diameter 14 mm, thickness 0.4 mm) is coated with 4 mm of adsorbent.

The direct synthesis of thin zeolite coatings on the heat exchanger walls has been considered as a possible solution. The zeolite layers can be directly grown on the metal surface. In this case, the heat transfer across the interface should be strongly increased due to the close contact between the exchanger surface and the zeolite. Bonaccorsi et al. (2006) developed Zeolite 4A coated copper foams for heat pump applications. The copper foam obtained had a final density of 0.5 g/cm³ with an open porosity close to 70% and a maximum pore size of 0.5 mm. By two successive synthesis treatments, the copper foam surface was totally coated with a compact layer of zeolite 4A crystals firmly bonded to the substrate with 17% of zeolite. The water adsorption capacity of the zeolite/foam composite is comparable with that of a commercial zeolite 4A powder.

Regarding the heat and mass transfer augmentation in an adsorber, several new modules combining silica gel particles with heat exchanging pipe were developed by several researchers. Kubota et al. (2008) developed a fin-type silica gel tube (FST), as shown in Fig. 4-6 (Kubota et al., 2008). The FST module is made up of copper tube (16 mm I.D., 400 mm in length) and copper circular fins cast to the tube. The module was wrapped by stainless steel mesh through which water vapour could easily penetrate into silica gel bed. The total weight of silica gel packed into each adsorber was 5.8 kg-dry basis. The advantage of this module included high heat transfer rate owing to the fins cast to the tube and high water vapour permeability into the packed bed through the stainless steel mesh. It was estimated that the adsorber would achieve twice higher cooling output than that with un-optimized modules.

Hirota et al. (2008) developed a FST module is made up of a copper heat exchanger tube (I.D.: 16 mm; height: 400 mm) and copper fins cast to the tube, as shown in Fig. 4. Silica gel (Fuji Silysia Chemical Ltd.) with an average particle size of 412 µm is packed between the fins and wrapped by a stainless net. Figure 4-7 shows the module they used in the investigation.
Wang and Zhang (2009) investigated an adsorption heat pump with multi-cooling tubes. Each cooling tube is one self-contained adsorption cooling unit of which the adsorber, the condenser and the evaporator are all housed in one tube, as shown in Figure 4-8. The adsorber in the upside of the tube consists of silica gel, fins, metal mesh, spring and shell. The fins are annular, and their centre is the mass transfer channel surrounded by metal mesh and spring. The bottom of the cooling tube is the evaporator whose evaporating surface is coated with a porous layer to enhance heat transfer. Fig. 4-9 is the schematic diagram of the designed AHP (adsorption heat pump) with multicooling tubes. In the AHP, the all adsorption cooling tubes is divided into two groups, Adsorber A and Adsorber B. The working fluid used in the heat pipe is methanol. The cooling tubes of one group will be cooled to adsorb and yield refrigerating output while those of the other group are heated for desorption. The working status of Adsorber A and Adsorber B will switch after the previous process finishes. So, this AHP can be regarded as a two-bed adsorption cooling system.

Figure 4-8 Structure of cooling tube. Figure 4-9 Heat pump multi-cooling tubes.

4.4 Process Development

While reactor design has been developed, the processes for suitable reactors are also developed for testing and application. This section briefly introduces some process arrangement for adsorption heat pump applications.

Hirota et al. (2008) investigated a process of a suction-pump-assisted thermal and electrical hybrid adsorption heat pump. Fig. 4-10 is a schematic drawing of the lab-scale hybrid adsorption heat pump system with the silica gel–water system. This equipment consists of an adsorber, an evaporator/condenser, and a mechanical booster pump (MBP). The drawing of the adsorber is shown in Fig. 4-11. The adsorber has four separate chambers for varying the weight of the adsorbent. Four FST modules are installed in each chamber. The FST module is described by Figure 4-7. The MBP (ULVAC, Inc.; MBS-010 type) is used as a suction-pump for transporting water vapour. As the test observations, they found that the suction-
pump-assisted thermal and electrical hybrid adsorption heat pump was able to improve the adsorptivity by approximately 1.6 times as that of the thermally operated adsorption heat pump.

![Figure 4-10 Schematic drawing of the experimental apparatus](image)

Figure 4-11 Details of adsorber

Al-Ansari et al. (2001) developed water–zeolite adsorption heat pump for desalination process, as shown in Figure 4-12. The system includes the evaporator/condenser unit, two adsorption beds, feed preheaters, and a heat exchanger for the thermal fluid circulating between the adsorption and desorption beds. In the process, seawater was preheated and introduced into evaporator. The evaporation separated water and brine. The vapour of evaporated water entered secondary adsorber where cold water condensed water vapour into liquid water. The liquid water was pumped into first adsorber where steam as the heat source increased the temperature of the liquid water. The heated water in the first adsorber provided the heat to evaporator. After releasing heat, product water was flowed out. The adsorber plays the role of bottom condenser.
Figure 4-12 Single effect-evaporator driven by adsorption heat pump.

D.C. Wang et al. (2005) experimentally studied adsorption heat pumps using waste heat supplied at 110 °C, as shown in Figure 4-13. Activated carbon and methanol pairs were used in the adsorption pump. As a heat pumping cycle, its evaporator absorbs heat from the ambient through the cooling tower, at the same time the adsorber and the condenser release heat into the room through two fan coils. There are two adsorbers, a condenser, an evaporator, a heater and a cooler in this system. Each adsorber is filled with 26 kg activated carbon. The condenser and the cooler are plate type heat exchangers. The evaporator is a spray-type. The heater is an electric boiler with 44 kW power. When one adsorber is heated in desorption process, the other will be cooled in adsorption process.

Figure 4-13 Schematic diagram of the adsorption heat pump prototype

Wang et al. (2001) investigated adsorption heat pump using plate in heat exchangers or plate in shell and tube type heat exchangers as adsorbers. Carbon and methanol
were used as adsorption pair. In the system, two adsorbers are independently operated for heating or cooling, along with the heat recovery process, as shown in Figure 4-14. Each of two adsorbers has 26 kg carbon embedded. The plate fin type adsorber makes the heating and cooling for adsorbers quite rapid.

![Figure 4-14 Schematic drawing of the whole adsorption heat pump system.](image)

### 4.5 Absorption Heat Pumps

The absorption cycle is similar to the adsorption cycle, except for the method of selecting absorbent rather than adsorbent. In the absorption system, an absorber dissolves the refrigerant in a suitable liquid, a liquid pump which raises the pressure and a generator which, on heat addition, drives off the refrigerant vapor from the high-pressure liquid. In an absorption refrigerator, a suitable combination of refrigerant and absorbent is used. The most common combinations are ammonia (refrigerant) and water (absorbent), and water (refrigerant) and lithium bromide (absorbent).

![Figure 4-15 Absorption heat pump](image)

In absorption systems, compression of the working fluid is achieved thermally in a solution circuit which consists of an absorber, a solution pump, a generator and an expansion valve as shown in Figure 4-15. Low-pressure vapour from the evaporator is absorbed in the absorbent. This process generates heat. The solution is pumped to high pressure and then enters the generator, where the working fluid is boiled off with
an external heat supply at a high temperature. The working fluid (vapour) is condensed in the condenser while the absorbent is returned to the absorber via the expansion valve.

Heat is extracted from the heat source in the evaporator. Useful heat is given off at medium temperature in the condenser or in the absorber. In the generator high-temperature heat is supplied to run the process. A small amount of electricity may be needed to operate the solution pump.

4.6 Chemical Heat Pumps

In the absorption system, an absorber dissolves the refrigerant (i.e. ammonia) in a suitable liquid (i.e. water). The process is either physical absorption or absorption with chemical reactions. In various cases of absorption with chemical reactions, there is one case based on dehydrogenation of alcohols and hydrogenation of aldehydes or ketone, as shown below:

\[
\text{Alcohol} \leftrightarrow \text{Aldehyde (or Ketone) + Hydrogen}
\]

In the above reaction process, alcohol is decomposed into aldehyde and hydrogen by dehydrogenation reaction (endothermic). For this reaction to occur (at low temperature), heat could be supplied from a low temperature source. The hydrogenation reaction is exothermic and heat is released at a higher temperature, thus causing upgrading of heat for the applications. According to this principle, a chemical heat pump is developed to change the temperature levels of thermal energy, which is stored by chemical substances. These chemical substances play an important role in absorbing and releasing heat.

Research in chemical heat pumps recently has gained attention, mainly due to heat source using low grade heat. Most systems involved in investigation included methanol–formaldehyde-hydrogen, ethanol–acetaldehyde-hydrogen, i-propanol–acetone-hydrogen, n-butanol–butyraldehyde-hydrogen, etc. In these systems, the dehydrogenation reaction takes place in liquid phase at low-temperature (70–100 °C) and requires thermal energy; while the hydrogenation reaction is carried out in gas-phase at high-temperature (150–200 °C) as an exothermic reaction. Dehydrogenation reaction occurs at the boiling point of liquid phase and its temperature level is fixed by the equilibrium conditions at reaction pressure. The alcohol produced by hydrogenation reaction of aldehyde or ketone and hydrogen is recycled for dehydrogenation reaction. Since two reverse reactions running at different temperature levels are involved, at least two reactors and one heat exchanger are required in the system cycle.
5 Thermoacoustic Heat Pumps

During the past two decades, there has been an increasing interest in the development of thermoacoustic cooling and heating for a variety of commercial, military and industrial applications. Thermoacoustic (TA) uses high-amplitude sound waves in a mixture of harmless gases to create oscillations in pressure, temperature and displacement, which are used to pump heat. Although the temperature oscillations are small, research during the past two decades has shown that "Thermoacoustic" effects can produce powerful and efficient heat engines, including heat pumps and refrigerators. Thermoacoustic engines typically have no moving parts. Some have a single oscillating part, which needs no lubrication or sliding-seals that are subject to wear. Thus, these engines have the potential to be simple, reliable and cost less to operate. They can be mass-produced using current production methods and use harmless gases found naturally in the environment.

5.1 Thermoacoustic Systems

Thermoacoustics relates to the physical phenomenon that a temperature difference can create and amplify a sound wave and vice versa that a sound wave is able to create a temperature difference. A distinction is made between a thermoacoustic engine or prime mover (TA-engine) and a thermoacoustic heat pump (TA-heat pump). The first relates to a device creating an acoustic wave by a temperature difference while in the second an acoustic wave is used to create a temperature difference. Figure 3.1 shows the combination of a TA-engine, operating between a temperature difference between $T_{\text{high, engine}}$ and $T_{\text{low, engine}}$, and a TA-heat pump, operating between $T_{\text{high, heat pump}}$ and $T_{\text{low, heat pump}}$. These four temperature levels can, to some extent, be freely chosen to match the application.

Figure 5-1 Thermodynamic illustration of combination of a TA-engine and TA-heat pump

5.2 Thermoacoustic Engines

It is commonly accepted that oscillatory thermal expansion and contraction of a gas could create acoustic power and that the oscillatory thermal expansion and contraction could themselves be caused by the acoustic wave in a channel with a temperature gradient. In oscillatory thermal expansion and contraction, sound wave plays an
important role for the devices operated under gas oscillatory. As known, a sound wave is associated with changes in pressure, temperature and density of the medium through which the sound wave propagates. In addition, the medium itself is moved around an equilibrium position. These fluctuations are too small to be noticed in the sounds we hear everyday. However, the sound waves that are common in thermoacoustics are extreme in magnitude, resulting in noticeable fluctuations. Table 5-1 presents a comparison of parameters between a normal conversation and thermoacoustics. The difference is several orders of magnitude.

Table 5-1 Comparison between normal and thermoacoustic sound levels

<table>
<thead>
<tr>
<th></th>
<th>Normal conversation</th>
<th>Thermoacoustics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound level</td>
<td>60 dB</td>
<td>170 dB</td>
</tr>
<tr>
<td>Temperature fluctuation</td>
<td>0,00002 ºC</td>
<td>10ºC</td>
</tr>
<tr>
<td>Gas displacement (100 Hz)</td>
<td>0,00001 cm</td>
<td>4 cm</td>
</tr>
<tr>
<td>Gas velocity</td>
<td>0,0001 m/s</td>
<td>35 m/s (130 km/h)</td>
</tr>
</tbody>
</table>

In thermoacoustics, an acoustic wave is brought into interaction with a porous structure with a much higher heat capacity compared to the medium through which the sound wave propagates. This porous structure acts as a kind of heat storage.

To generate oscillatory thermal expansion and contraction under sound waves, most of research have been done on standing wave and travelling-wave systems, as well as cascading two systems into one system.

### 5.2.1 Standing-Wave engines

Figure 5-2 shows a principle process of standing-wave engine. As a typical parcel of the gas oscillates along the axis of the channel, it experiences changes in temperature, caused by adiabatic compression and expansion of the gas by the sound pressure and by heat exchange with the solid wall of the channel. A cycle results from the coupled pressure, temperature, position, and heat oscillations. The time phasing between gas motion and gas pressure is such that the gas moves hotward while the pressure is rising and coolward while the pressure is falling. The time phasing is a standing acoustic wave with a simple resonator such as a closed-closed $\lambda/2$ or a closed-open $\lambda/4$ resonator, where $\lambda$ is the acoustic wavelength. For the highest efficiency, the tradeoffs among viscous, thermal-relaxation, and thermal conduction losses usually put the stack and its heat exchangers at a location in the wave where $z \sim 5\rho a$, where $z$ is the magnitude of the specific acoustic impedance and $\rho$ and $a$ are the gas density and sound speed.

![Figure 5-2 The standing-wave engine process. A parcel of gas oscillating horizontally in a channel. At this instant of time, it moves left (small arrow) and absorbs heat from the channel walls (large arrows).](image)
The process shown in Fig. 5-2 occurs in a single channel, and the temperature gradient is maintained by a heat source outside of one end of the tube and a heat sink to atmospheric air along and in the other end of the tube. For standing-wave engines, the process occurs in many channels in parallel, all of which contribute to the acoustic power generation. Such a set of parallel channels, called a stack. This allowed filling a large-diameter tube with small channels, creating a large volume of strong thermo-acoustic power production, while leaving the rest of the resonator open and relatively low in dissipation. Heat exchangers at the ends of the stack are needed for efficient delivery and extraction of the large amounts of heat needed by a stack. Figure 5-3 shows an example of such an engine (Wollan, 2002), which produced acoustic powers up to 17 kW and operated at an efficiency as high as 18%.

Figure 5-3 Schematic and photo of a powerful standing-wave thermoacoustic engine, built at Cryenco in Denver, CO to supply acoustic power to an orifice pulse tube refrigerator. In the photo, the engine (also shown in the schematic) is at the left (background) and the refrigerator is in the foreground. The resonator is essentially \( \lambda/2 \), with pressure oscillations in the engine and refrigerator 180° out of phase and similar in magnitude.

5.2.2 Travelling-Wave engines

A simple, dead-ended resonator in standing-wave engine cannot provide the ambient power injection. A design of generator is necessary. In Stirling engine, as shown in Figure 5-4a, two pistons oscillating with the correct relative time phasing carry a gas in two heat exchangers and a regenerator through a cycle of pressurization, motion from ambient to hot, depressurization, and motion from hot to ambient. By using sound wave, the Stirling engine’s pistons could be eliminated by imbedding the heat exchangers (2 and 3) and regenerator (1) in a suitable acoustic waveguide, as shown in Figure 5-4b.

The time phasing described above is that of a travelling acoustic wave, which carries acoustic power from ambient to hot. In contrast to standing-wave engines, acoustic power must be injected into the ambient end of a regenerator in order to create more acoustic power; the regenerator is an amplifier of acoustic power. For the highest efficiency, the tradeoffs among viscous and thermal losses usually put the regenerator and its heat exchangers around a location in the wave where \( z \sim 30\rho a \).
Figure 5-4 Stirling engines and travelling-wave engines

Figure 5-5 Thermoacoustic-Stirling hybrid engines, producing 1 kW of power at an efficiency of 30% without moving parts. The E’s show the circulation and flow of acoustic power.

Ceperley (1979) proposed a traveling-wave Stirling engine. The system is now referred to as a ThermoAcoustic Stirling Heat Engine (TASHE). Yazaki et al. (1998) demonstrated a traveling-wave engine very similar to that by Ceperley, with the path length around the toroidal waveguide nearly equal to 2 $\lambda$. At about the same time, de Blok (1998) and Backhaus and Swift (2000) invented a traveling-wave engine with the heat exchangers. Figure 5-5 shows the Los Alamos demonstration of that concept. The conversion of heat to acoustic power occurs in the regenerator between two heat
exchangers, which causes the gas in the channels of the regenerator to move toward the hot heat exchanger while the pressure is high and toward the main ambient heat exchanger while the pressure is low. With a wire screen or parallel-plate regenerator, the engine of Figure 5-5 has produced acoustic power of 710 W or 1750 W, respectively, each with an efficiency of 30%.

5.2.3 Cascaded Standing-Wave and Travelling-Wave engines

The traditional Stirling engine in Figure 5-4a has high efficiency, but its moving parts (requiring tight seals between the pistons and their surrounding cylinders) compromise reliability and thus is responsible for high fabrication costs. The thermoacoustic-Stirling hybrid engine (Fig. 5-4b) has reasonably high efficiency and very high reliability, but the toroidal topology needed is responsible for high fabrication costs, for two reasons: It is difficult to provide flexibility in the toroidal pressure vessel to accommodate the thermal expansion of the hot heat exchanger and surrounding hot parts, and some structure or control must be provided. Finally, the stack-based standing-wave thermoacoustic engine (Fig. 5-3) is reliable and costs little to fabricate, but its efficiency is only about 2/3 that of a regenerator based system.

Figure 5-6 A cascade of one stack and two regenerators, with the necessary adjacent heat exchangers and thermal buffer tubes, should provide high efficiency in a simple, reliable package. The portion of the resonator shown in the figure is approximately $\lambda/2$ tall. "T_{bt}" is a thermal buffer tube, and "h_{x}" is a heat exchanger.

Cascading standing-wave and travelling-wave engines can provide a new solution. Figure 5-6 shows what one standing-wave engine and two travelling-wave engines are cascaded in series (Backhaus and Swift, 2002). All three engines will be within one
pressure maximum in the standing wave, with the stack at a location where \( z \sim 5\rho a \) (\( \rho \): density and \( a \): sound speed) and the regenerators at locations of higher than \( z \). The two cascaded regenerator units will provide great amplification of the small amount of acoustic power that will be created by the small stack unit. The linear topology simplifies thermal expansion problems. Hu et al. (2006) studied a cascade thermoacoustic engine at the length of 1.2 m and a frequency of 470Hz. They concluded that the performance of cascade engine was very sensitive to the length of the traveling-wave region.

5.3 Recent Development for Process Industry

5.3.1 Waste-heat driven engine

ECN, together with partners, developed a multiple regenerator system in which several regenerator units are applied within one TA-engine in order to generate sufficiency acoustic power from the relatively low waste heat temperatures. Figure 5-7 shows a TA-engine containing three regenerator units, which is already running at a waste heat temperature of 110ºC. This low starting temperature enables the application of waste heat for driving TA-engines. The acoustic energy is subsequently being used in a TA-heat pump to upgrade waste heat to usable process heat at the required temperature.

Figure 5-7 Waste-heat driven TA-engine
(Spoelstra and Tijani, 2005)

Figure 5-8 shows their applications. The TA-engine is located at the right side and generates acoustic power from a stream of waste heat stream at a temperature of 140ºC. The acoustic power flows through the resonator to the TA-heat pump. Waste heat of 140ºC is upgraded to 180ºC. The system can be applied into the existing utility system at an industrial site.
Besides upgrading waste heat, the ECN also develop this technology for upgrading industrial waste heat to process heat or cold in a cost effective way. They investigated a process on a scale of 5 kW heat. The system has a waste heat driven multi-stage engine and is coupled with a heat pump in a double Helmholtz resonator. The working medium is nitrogen and the system can be pressurized up to 18 bar. Although a first prototype of the application has been realised, the efficiencies are presently too low to enable a cost effective system. Much development work therefore lies ahead. In the longer term the expected size will be about 1 MW. Figure 5-9 shows a scale of such a system. ECN estimated the energy saving using this technology within the Netherlands about 16 PJ, which is comparable with the energy use of more than 150,000 households.
Important part of the research in this area is the TA-engine driven by a burner. Figure 5-10 shows a test installation of a TA-engine driven by a natural gas burner. This system has a thermal power of about 5 kW and is filled with Argon with 10 bar pressure. This system suffers from high heat losses due to the high temperature involved. However, it is one of the few systems in the world that runs on the heat input by a burner.

### 5.3.2 Thermoacoustic coolers for liquefaction

The research on the heat driven thermoacoustic cooler system has progressed over decades. In the early time, the heat driven thermoacoustic cooler is heat driven orifice pulse tube coolers which used the thermo-acoustic engine instead of the compressor.

Swift (1988) investigated a standing wave device TAD (ThermoAcoustic Driver). The use of a TAD to drive an OPTR (orifice pulse tube refrigerator), now known as a TADOPTR. The TADOPTR was first demonstrated in 1990 in a joint effort between NIST and Los Alamos National Laboratories. It reached a temperature of 90 K and was the first cryogenic refrigerator with no moving parts (Wolland et al., 2002). A schematic of the TADOPTR is shown in Figure 5-11. A much larger version of the TADOPTR has been developed to liquefy natural gas by burning a portion of the natural gas to provide the required heat source. A refrigeration power of about 2 kW at 120 K has been produced by this device, which operates at a frequency of 40 Hz using a resonance tube about 12 m long. The TAD and OPTR have Carnot efficiencies of about 30% and 23%, respectively.

![Figure 5-11. Schematic of ThermoAcoustically Driven Orifice Pulse Tube Refrigerator (TADOPTR)](image-url)
Figure 5-12. Schematic of ThermoAcoustic Stirling Heat Engine (TASHE)

Ceperley (1979) proposed a travelling-wave Stirling engine. The system is now referred to as a ThermoAcoustic Stirling Heat Engine (TASHE). The first system assembled achieved a Carnot efficiency of about 42%. A schematic of the system is shown in Figure 5-12. Instead of a stack of closely spaced plates, as used in the TAD, the TASHE uses a regenerator consisting of stacked stainless steel screen, just as in a cryocooler regenerator. Such a structure is easier to fabricate than a stack of closely spaced plates. For an ambient temperature of 300 K and a hot end at 900 K, 1 kW of acoustic power at ambient is amplified to 3 kW at the hot end. An adiabatic compliance tube (pulse tube) allows this 3 kW acoustic power at 900 K to be transformed to 3 kW acoustic power at 300 K. Of this 3 kW, 2 kW in an ideal case can perform useful work such as driving an OPTR. The other 1 kW is fed back to the ambient end of the regenerator through a phase-shift mechanism consisting of inerterance and compliance components.

In the development of industrial application, Praxair has been developing thermoacoustic liquefiers and refrigerators for liquefaction of natural gas and for other cryogenic applications (Wolland et al., 2002). The technology eliminated the need of electric power in multi-kW refrigeration. The liquefier development program is divided into two components: pulse tube refrigerators driven by combustion-powered thermoacoustic Stirling heat engines (TASHEs), and pulse tube refrigerators driven by linear motors. The linear-motor-driven technology will be limited to low-power refrigeration and liquefaction applications.

The project began with its 2001 acquisition from Chart, Inc. After the acquisition of the project, Praxair made extensive modifications. The refrigerators were kept intact, but the engine and burner were completely rebuilt, and a more sophisticated system for control and data acquisition was created. The resulting system is shown in Figure 5-13, and a simple block diagram is shown in Figure 5-14. Heat from a high-temperature heat source (combustion of natural gas) provides useful energy to the system, heat is removed from a load (methane, experiencing cooling and liquefaction) at cryogenic temperatures, and waste heat is rejected to ambient temperature. Thermoacoustic processes in 30-bar helium gas accomplish the energy conversions and transport.
The major thermoacoustic subsystems are: (1) an engine to generate high-intensity acoustic power from high-temperature heat; (2) a wave tube (a nearly half-wavelength resonator) to transport the acoustic power from the engine to the refrigerators and to determine the 40-Hz operating frequency; and (3) refrigerators to generate useful cryogenic refrigeration while consuming the acoustic power. The engine is a thermoacoustic-Stirling hybrid heat engine. The engine subsystem includes additional components to generate heat and transport it to the hot heat exchanger of the engine: a combustion chamber and a high-pressure, high-temperature, blower driven circulating-helium heat-transfer loop. The refrigerators are three inertance-enhanced orifice pulse tube refrigerators. Figure 5-15 shows the configuration of refrigerators and closed-loop methane circulating system. The three refrigerators are driven in parallel by the acoustic power delivered by the wave tube. They are linked in series by the methane circulation loop, so that the first refrigerator precools the incoming methane to about 180 K, the second refrigerator cools the methane to liquefaction temperature and partially liquefies it, and the third refrigerator further liquefies the methane. These three pulse tube refrigerators were designed to produce a total of 7 kW of refrigeration at methane liquefaction temperatures, so they are large, with regenerators of 20 cm diameter and pulse tubes of 10 cm diameter. All components are in line in each refrigerator. A closed-loop methane circulating system provides the load on the refrigerators. The system consists of a large storage tank, a circulating blower, and a heater enclosed in an insulated box.

Figure 5-13. Photograph of 500-gal/day system in Denver, with project leader John Wollan. (Arman et al., 2005)
As a conclusion, the multiple Stirling heat engine-driven pulse tube refrigerators run well and stably. The planned 20,000 gal/day thermoacoustic liquefier technology should be able to compete with existing natural-gas liquefiers of comparable capacity, in terms of both efficiency and cost.

5.3.3 Thermoacoustic engine driven by waste of combustion

Gardner and Howard (2009) investigated waste-heat-driven using waste gas generated from internal engine. The original contribution is the design and construction of a combined waste-heat driven thermoacoustic engine and heat-pump system that is directly powered by exhaust gases from a combustion engine. The pressure vessel contains Helium gas at a mean pressure of 1.6 MPa.

The thermoacoustic engine (prime-mover) is a device that can capture the exhaust-gas waste-heat from an internal-combustion engine, and convert the waste-heat to high-amplitude standing acoustic waves within a resonator. The acoustic waves power a standing-wave thermoacoustic heat-pump. Figure 5-16 is a sketch of the overall system. The exhaust-gas from an internal combustion engine is delivered to the thermoacoustic engine at the left-hand side of the sketch. A heat exchanger is used to extract heat from the gas stream and deliver it to the thermoacoustic engine. Adjacent to the hot heat exchanger within the thermoacoustic engine is the prime mover stack.
Figure 5-16 Sketch of the thermoacoustic prime mover and heat pump.

The stack is the heat storage constructed by seven stainless steel honeycomb disks of diameter 155 mm and thickness 12 mm. Oscillating gas parcels move heat from the hot heat exchanger to the stack; adjacent parcels absorb the heat causing the parcels to expand, doing work on the surrounding gas, and enhancing the oscillation pressure amplitude.

The pressure vessel is filled with Helium gas, which oscillates as a standing half-wave at the fundamental frequency of 315 Hz. The pressure vessel was approximately 1.5m long. The resonance frequency of the device was approximately 315Hz.

At the right hand end of the resonator tube shown in Figure 5-16 is a brass-shelled cold heat exchanger. This heat exchanger constitutes the beginning of the heat pump section.

A Mitsubishi Magna V6 engine was installed in engine tests. The heat from the exhaust gases of the engine were used as the source of waste-heat for the thermoacoustic engine. The temperature of the exhaust gas from the Mitsubishi engine is about 700°C. The acoustic system provided 6kW from this exhaust stream. Table 5-2 lists the predicted performance of the prime mover and heat-pump.

Table 5-2 the predicted performance of the prime mover and heat-pump

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>(Hz)</td>
<td>315</td>
</tr>
<tr>
<td>Input Power</td>
<td>(W)</td>
<td>5750</td>
</tr>
<tr>
<td>Hot Metal Temp</td>
<td>(K)</td>
<td>860</td>
</tr>
<tr>
<td>Amb. Metal Temp</td>
<td>(K)</td>
<td>311</td>
</tr>
<tr>
<td>Acoustic Power</td>
<td>(W)</td>
<td>500</td>
</tr>
<tr>
<td>Cold Metal Temp</td>
<td>(K)</td>
<td>230</td>
</tr>
<tr>
<td>Cooling Power</td>
<td>(W)</td>
<td>135</td>
</tr>
<tr>
<td>Engine % Carnot</td>
<td>(%)</td>
<td>12</td>
</tr>
</tbody>
</table>

5.3.4 Double-acting acoustic driver

Cool Sound Industries was established as a commercial platform to bring together the various technical disciplines required to successfully develop residential and commercial air conditioning applications. In 1996, Frank Wighard, the company's
founder, filed an initial patent on a double driver configuration that adapts thermoacoustic heat transfer process to air conditioning applications, as shown in Figure 5-17. He has since proposed numerous improvements to his basic design.

![Figure 5-17 Patent drawing of a Double-acting Acoustic Driver](image)

### 5.3.5 Solar energy

In 1998, the first solar energy powered standing wave thermoacoustic engine (shown in Figure 5-18) was built by Chen and Garrett from Pennsylvania State University (Chen et al., 2004). Sunlight was focused, by a 3-feet-diameter lens, to one end of a ceramic stack, which locates inside a one-end-open resonant tube. This ¼ wavelength resonant can emit the sound of 420 Hz, with an intensity of 120 dB at the point 1 m distance from the open end of the tube. This prototype proved the feasibility of thermoacoustic engines driven by solar energy, which is clean and environmentally benign. Maximal pressure ratios of 1.12 and 1.088 have been achieved in the experiments with nitrogen and helium as working fluids, respectively, with the corresponding operating frequency of 24 Hz and 70 Hz. The pressure wave is qualified in driving a Stirling-type pulse tube refrigerator.

![Figure 5-19 Garrett’s solar energy powered thermoacoustic engine](image)
6 Heat Pump Applications for Drying Process

Drying is one of the most energy intensive unit operations that account for up to 15% of all industrial energy utilizations (Chua et al., 2001). In many industrial drying processes, a large fraction of energy is wasted. Mujumdar (1987) reported that drying consumes up to 70% of the total energy in manufacturing wood products, 50% of the total energy consumption in the manufacturing of finished textile fabrics and over 60% of the total energy needed for farm corn production. Therefore, energy management is an essential part of drying process and efficient energy conservation contributes significantly to the overall operating cost.

Recently, there has been a great interest in utilizing heat pump drying for drying fruits, vegetables and biological materials (Hawlader, 2007). Heat pumps are devices for raising the temperature of low grade heat energy to a more useful level that generally consumes high grade energy. Using heat pumps in convective hot air dryers has been recognized as an ideal area for heat pump applications (Schmidt, 1998). Strommen et al. (2002) found that heat pump dryings consume 60–80% less energy than conventional dryers operating at the same temperature. This makes such dryers a feasible option for users who are not satisfied with high energy consumption of directly heated dryers.

This section reviews the applications and performances of heat pumps on drying processes. And some industrial cases are provided for case studies...

6.1 Types of Heat Pump Systems

Several types of heat pumps are available on the market for drying applications. In general, heat pumps used for drying can be classified, according to heating sources, into air source, ground source and chemical absorption heat pumps. Colak and Hepbasli (2009a) reviewed 53 tested results using heat pump technologies for drying. They are 48 using air source heat pumps, 4 ground source heat pumps and 1 chemical heat pump. Air source heat pump systems were mostly used in studies about heat pump drying.

6.1.1 Air source heat-pump drying systems

Schematic illustration of an air source heat pump drying system is illustrated in Figure 6-1. This system consists of mainly two subsystems; heat pump system and drying chamber. The main components of the heat pump system are an evaporator, a condenser, a compressor and an expansion valve. In this system, heat is extracted from the air. The heat is transferred to the refrigerant in the evaporator and released in condenser where air is heated and delivered to drying solid materials.
6.1.2 Ground source heat-pump drying systems

Despite many studies about heat pump drying systems have been done for a long years, ground source heat pump drying studies are quite limited. Schematic illustration of a ground source heat pump drying system is illustrated in Fig. 6-2.

This system consists of mainly three subsystems; (a) ground source heat exchanger (b) heat pump system, and (c) drying chamber. The main components of the heat pump system are an evaporator, a condenser, a compressor and an expansion valve. In this system, heat is extracted from the ground by the ground source heat exchanger, where a water-antifreeze solution is circulated. The heat is transferred to the refrigerant in the evaporator, upgraded in the heat pump cycle, and is supplied to the drying chamber. Here, heat is rejected to the drying air and this heated air enters the drying chamber (Colak and Hepbasli, 2005).
6.1.3 Chemical heat-pump drying systems

A chemical heat pump is proposed as one of the potentially significant technologies for effective energy utilization in drying. The chemical heat pump can store thermal energy such as the waste heat from dryer exhaust, solar energy, geothermal energy, etc. in the form of chemical energy via an endothermic reaction in a suitably designed reactor and release the energy at various temperature levels.

As reported by Ogura and Mujumdar (2000), the calcium oxide hydration/dehydration system is the most feasible for heat pump drying from viewpoints of temperature level, safety, corrosion and cost. The system applied CaO/H2O/Ca(OH)2 reaction operating in the heat enhancement and refrigeration modes. Figure 6-3 shows a schematic diagram of the chemical heat pump unit employed (Ogura et al. 2002).

![Figure 6-3 A chemical absorption heat pump dryer](image)

6.2 Type of Dryer

In general, batch shelf or tray dryers or kilns (for wood) are the most commonly used dryers in conjunction with heat pumps, other types may also be used (i.e., fluidized beds, rotary dryers). However, dryers that consume large amounts of drying air, e.g., flash or spray dryers, are not particularly suited for heat pump operation (Colak and Hepbasli, 2009b).

6.2.1 Batch dryer

Heat pump drying system more suitable for drying to batch operation than to continuous one because batch systems allow total recirculation with a very low air leakage rate, giving rise to high thermal efficiencies (Colak and Hepbasli, 2009b).

The feasibility of an air heat pump cycle for tumbler clothes dryers was investigated by Braun et al. (2002). As shown in Fig. 6-4, batch dryers (tumbler dryers) have been
especially used for clothes drying. This dryer offered up to a 40% improvement in energy efficiency over the electric dryer.

Figure 6-4 A schematic of a closed air cycle heat pump tumbler dryer.

6.2.2 Conveyor dryer

Continuous bed drying shows promising results over batch drying and can potentially be a better option for specialty crops. Very few studies have been done on heat pump assisted continuous bed dryers compared to heat pump assisted batch dryers (Colak and Hepbasli, 2009b).

A schematic illustration of this heat pump tunnel dryer is given in Fig. 6-5. This model was developed and applied for studying heat-sensitive products, agricultural products, and wet foam rubber (Colak and Hepbasli, 2009b).

Figure 6-5 A schematic of a heat pump tunnel dryer.
Adapa and Schoenau (2005) designed, developed and validated a prototype heat pump continuous bed dryer, which can be used for commercial production and processing of specialty crops. Block diagram of this system is given in Fig. 6-6.

![Block diagram of prototype heat pump conveyor dryer](image)

Figure 6-6 A block diagram of prototype heat pump conveyor dryer [28].

### 6.2.3 Fluidized bed dryer

Fluidized bed drying (FBD) has been applied for drying granular solids in the food, ceramic, pharmaceutical and agriculture industries (Colak and Hepbasli, 2009). Fluid-bed dryers can be made simple and, combined with a heat pump system: they might be competitive in the food industry and the pharmaceutical industry. A fluidized bed heat pump drying unit can be shown in Figure 6-7.

![Schematic of a fluidized bed heat-pump dryer](image)

Figure 6-7 A schematic of a fluidized bed heat-pump dryer (Colak and Hepbasli, 2009).

Colak and Hepbasli (2009) described recent development of heat pump assisted fluidized bed dryer. The system was used for investigating heat-sensitive product.
The investigation also involved in using air or inert gas as the drying medium at low temperature for drying. Meanwhile, Strommen and Jonassen (1996) and Alves-Filho and Strommen (1996) described the development of novel, counter-current heat pump fluidized bed dryers with high SMERs(specific moisture extraction rate) for the drying of heat-sensitive products.

6.3 Effects on Product Properties

Heat pumps have been used for drying of various products, such as fruits and vegetables, meat, paper, wood, timber, clothes, ceramics, chemical and biological materials.

Colak and Hepbasli (2009), having reviewed various dried agricultural products, concluded that the colour and aroma qualities of dried agricultural products using heat pumps were better than those products using conventional hot-air dryers. Following summarizes some significant results based on the review by Colak and Hepbasli (2009).

For drying banana, heat pump technology could save 44% of running cost and has favourable impact on the slice colour of the dried products. Apple slices dried by heat pump were perfect according to consumer preference. Air heat pump dried apples showed excellent colour and retention of Vitamin C. A heat pump drying was the best system for preservation of volatile compounds in sliced dried fruit followed by cabinet and tunnel dryer. For potato drying using heat pump, the percentage reductions in overall colour change were found to be 87%. Drying rectangular-shaped potato and apple slices as model composite food products were studied to find better drying performance compared to single apple or potato samples.

Drying onion slices using a heat pump could save energy about 30%, compared with conventional dryers. Drying ginger using heat pump resulted in that volatile constituents had been retained in higher concentrations than those subjected to freeze-drying.

Drying different herbs (Jew’s mallow, spearmint and parsley) using a heat pump increased the dryer productivity and reduced the energy consumption. The energy consumption for drying of malt with a coupled gas engine heat pump dryer could be reduced by 40%. Superheated steam dried (SSD) followed by a heat pump dried shrimp had much lower degree of shrinkage, higher degree of rehydration, better colours, less tough and softer, and more porous than single stage SSD shrimp.

The absorption heat pumps can be used for paper drying. An open absorption heat pump configuration was used to dehumidify and reheat air streams for convection drying. Some waste heat streams can be used for energy recovery using different heat pump systems with special emphasis on compression heat pump. Colak and Hepbasli (2009) also summarized the possibilities in heat pump drying of lumber from different softwoods and hardwoods, and poplar and pine timbers.

6.4 Industrial Cases

6.4.1 Lachine Steel Factory

Lachine Steel Factory is located in Lachine, Quebec, Canada. The drying process is built in 1996, used for sludge disposal. The sludge is contaminated with lead and zinc from the process and has high water content (50%). At beginning, three options were
reviewed for an effective way to drain the sludge for a more economic transfer. A gas dryer seemed very expensive and complex to both install and operate. A heated screw conveyor performed well but required further development. A heat pump appeared most advantageous with its high energy-efficiency and instant installation. It has been estimated that a more than 40% weight reduction in sludge is achieved with the system.

The heat pump system consists of a compressor, heat exchangers and ventilator. The heat source is ground source. The dry air is used for drying the sludge. The system operates in a closed loop. Once drained, the sludge is transferred to a landfill site.

Drive energy of heat pump is 123,600 (kWh/year) using ground as heating source. The efficiency for recovering thermal energy: 98%. The capital cost including installation is CAD 45,000 and energy cost is 0.037 (CAD/kWh). The annual CO2 emissions are 51 tons less than for a conventional gas dryer. By using heat pump, the company saves CAD 50,000 each year in transfer and landfill charges. Payback is taken about 1 year based on transfer and landfill charges.

A gas dryer is considered for an alternative system. Energy input is 420,000 (kWh/year) with efficiency for recovering thermal energy of 50%. Capital and installation costs are 100,000 and 20,000 (CAD). Maintenance cost is 7200/year (CAD) based on energy cost.

6.4.2 Christchurch

In 2000, a wood drying kiln in Christchurch, New Zealand, was started with the purpose to evaluate the technology and cost for potential commercial production and marketing purpose. In the drying process, the timber is loaded into the kiln, which is then preheated by a dryer to a required temperature. The dehumidification process is started and continued until the timber is dried.

The existing compressors were replaced with a new modular heat pump system in a closed cycle compression with a capacity of 2 x 15 (kW). The refrigerant is R134a. The heat pump has run well and reliably since the commissioning. The overall drying cycle average energy efficiency, or specific moisture extraction rate (SMER), is between 2-3 kg H2O/kWh.
7 Distillation Process

Distillation columns are the most widely used separation units in the petrochemical and chemical industries and they are well known for their high energy consumption. About 60% of energy used by chemical industry was for distillation (Mix et al., 1978). So reducing this energy consumption would provide a great benefit. Although there are other alternatives, the introduction of a heat pump technology to a distillation column has significant potential because the plant operation is usually simpler compared to other technologies of heat reduction (Annakou and Mizsey, 1995). In a heat pumping system used for distillation, the energy of the cold top stream is employed as energy supply for boiling the hot bottom stream.

7.1 Heat Pump Configurations in Distillation Processes

In distillation, the most frequently used types of heat pumps are the compression systems, including direct vapour recompression, external working fluid (closed cycle heat pump) and bottom flashing, as shown in Fig. 7-1.

Ranade and Chao (1990) have discussed the usages of the different kind of heat pumps. The vapour recompression seems to be the most economical solution, but the simplest way of introducing a heat pump into an existing process is the closed cycle system with working fluid. A design strategy for selecting a heat pump-assisted distillation system of closed cycle heat pump type is developed by Omideyi et al. (1984).

Figure 7-1 Heat pump-assisted distillation scheme.
Meszaros and Fonyo (1986) have presented a comprehensive strategy for heat pump assisted distillation process design and suggested that the feasibility of the heat integration with the rest of the process should be analyzed before considering heat pumping... Mizsey and Fonyo (1992) have studied energy integrated separation design enhanced by closed cycle heat pumping. They investigated the influence of relevant parameters, such as relative volatility, feed flow rate and tray pressure drop, on the system economy. They demonstrated that in a retrofitting case, where the existing equipment limits the energy integration possibilities, the use of heat pumping can significantly improve the efficiency of energy utilisation.

Danziger (1979) has studied distillation columns with vapour recompression. He concluded that vapour recompression was the most suitable method for separation of close boiling components. Based on his result, the energy saved by the application of a heat pump was over 80% compared to conventional distillation.

### 7.2 Separation of Mixtures with Closing Boiling Points

Propylene-propane (P-P) splitter and C4 separation systems have closing boiling points. This makes separations difficult and the separations usually take place in a superfractionator (Annakou and Mizsey, 1995). Direct vapour recompression is the most favourable heat pump system to use when dealing with P-P separation.

The most frequently used schemes of heat pump-assisted distillation are the single compressor scheme and the double compressor scheme (Figure 7-2 and Figure 7-3).

![Figure 7-2 Single compressor scheme.](image)

![Figure 7-3 Double compressor scheme.](image)

Quadri (1981) has discussed the process design and optimisation of P-P splitting. He compared the single and the double compressor heat pump schemes, and concluded that the single compressor scheme is about 50% cheaper than the double one. Parker (1978) has presented a different conclusion that the two heat pump compressor schema was cheaper than the single one. The different conclusions are due to assessment methods for two schemes. Annakou and Mizsey (1995) have investigated
The double compressor scheme in parallel arrangement, single compressor scheme and conventional column. The comparison of the double compressor scheme to the single compressor scheme showed practically the same. They both had lower annual total cost than the conventional column by about 37%.

Finelt (1979) has also studied a P-P splitter at three different pressures and has compared the single compressor heat pump system to that of the conventional column. He concluded that the total costs of a P-P splitter plant increase with decreasing column pressure because the reduced size of the column does not offset the increased cost required for the compressor. He also found that the optimum pressure of P-P splitter was in about 8.5 bar.

Fonyo and Benko (1998) studied various heat pumping processes for C4 separations. They compared 2 MHP (mechanical heat pump) and 2 AHP (absorption heat pump) with conventional distillation. The column examined has 66 theoretical trays, the feed enters in tray 44, and there is a side draw from tray 62 to the isomerisation reactor. The reflux ratio is 10.4, the reboiler and condenser duties were 12380 kW and 12360 kW, respectively. In the AHT scheme, a temperature and pressure elevation is required for technological reasons, the reflux ratio is also increased to 16, the reboiler and condenser duties were 16380 kW and 15730 kW, respectively. They concluded that in all cases the costs were lower when compared with conventional distillation. Mechanical pumps provide economic feasibility for C4 splitter at larger heat load and smaller column temperature difference. The absorption heat pumps were suitable for distillation processes with a larger column temperature difference, where mechanical heat pumps cannot be used.

Diez et al, (2009) studied i-butane/n-butane mixture separation using several heat pump assisted distillation processes and compared to conventional distillation. This conventional process, along with top vapour recompression, bottom flashing and absorption heat pumps, were simulated using the HYSYS software platform. Potential energy savings are shown by incorporating heat pumps for distillation of mixtures with close boiling points. They concluded that distillation with both top vapour recompression and bottom flashing heat pumps allowed reduction of operation (energy) costs by 33% and 32%, respectively. This improved the economic potential by 9% and 10%, respectively. Due to the large steam consumption, when compared to the conventional case, the absorption heat pump is not suitable for this system.

Meszaros and Meli (1994) studied the separation processes of 1-butene from C4 fractions using conventional, heat integrated and heat pump assisted distillations. With computer aided analysis, they concluded that a combination of heat integration and vapour recompression proves to be the most economical scheme for separating 1-butene.

### 7.3 Ethanol-Water Separation

In the last couple of decades it has become evident that many threats to the global environment, such as the accumulation of greenhouse gases and acid rains, are energy-related issues. Ethanol when used as motor fuel can substantially decrease CO2 emission, which is largely responsible for the greenhouse effect. Chemical plants are therefore expected to increase productivity and make ethanol a more competitive fuel. In order to achieve this aim, conventional ethanol–water distillation column should be redesigned to incorporate energy-saving devices. Heat pumping can be an economical energy integration technology in order to decrease consumption of
primary energy and to minimize negative impact of large cooling and heating demands to the environment. This section summarizes the development and application of heat pump technologies for ethanol-water separation process, to understand the feasibility in the realistic application.

Canales and Marquez (1992) have investigated a pilot-plant test for ethanol-water separation. Their results demonstrated the reduction in energy consumption as compared to conventional distillation, which ranged from 45 to 56%. Thermodynamic efficiency was higher as well, 16% against 6.5% which also indicates better energy utilization.

Karncharoenkulwong and Mungcharoen (1998) studied the simulation and steady-state operation of an ethanol–water vapour recompression pilot plant distillation column. They reported a remarkable energy reduction of 89.3% compared to conventional column and an improved thermodynamic efficiency from 11.3% to 13.3%.

Oliveira et al. (2001, 2002) presented a simulation study of ethanol–water distillation column with water-ethanol recompression and external heat pumps. Figure 7-4 shows the process diagrams of the simulated processes. The working fluids used in external heat pumps are R-11 and R-114. They concluded that the vapour recompression appears to be more economical in terms of energy consumption and to require less number of trays, while the external fluid heat pump system demands compressors of larger size, for the presently acceptable working fluids (i.e., R11 and R114 excluded). Their results and conclusions provide process engineer methods and knowledge about how much energy is consumed in the case of integrating the method to ethanol production.

Besides the evaluation to overall energy saving and efficiency, estimating the actual energy consumption at operation parameters also attracts attention by many investigators, because it is an important aspect towards the determination of the viability of the system in ethanol–water separation. Meili and Stuecheli (1987) have identified the different pressure drops that can affect the power requirement in vapour
recompression distillation columns but no calculations were made. Enweremadu (2008, 2009) studied the influences of various operation parameters on the total energy consumption in heat-pump assisted ethanol-water distillation. They selected parameters for studied including pressure increase across the compressor, column heat loss and the overall heat transfer coefficient of reboiler–condenser as an explicit function of Prandtl, Reynolds and Nusselt numbers. Results showed that when these parameters were included in the study, there was an increase in compressor power input and total energy consumption while the energy effectiveness reduced.

7.4 Other Separation Processes

In addition, there are some publications regarding heat pump applications for distillation processes in ethylbenzene-xylene and ethylbenzene/styrene separations. Ferre et al. (1985) applied a direct vapour recompression heat pump to an ethylbenzene/xylene separation and to an ethylbenzene/styrene separation; both cases reduced energy consumption. Diez et al. (2009) founded the possible significant energy saving in ethylbenzene/styrene separations. Significant savings should also be possible in processes with high energy consumption, such as separation of p-xylene from m-xylene and o-xylene, and separation of iso-pentane from n-pentane. They also concluded that an absorption heat pump is not suitable for this system.

There are also some distillation processes which employ both mechanical and absorption heat pumps which have been patented. Meszaros (1999) patented a distillation plant with a vapour recompression heat pump which could be used successfully to separate a mixture of i-butane/n-butane/c/t-2-butene. With the mechanical heat pump patented by Meili (2003), styrene can be separated from a mixture containing the more volatile ethylbenzene and small amounts of benzene and toluene. Erickson (1982) patented an absorption heat pump system which could be added to an ethyl chloride/dichoroethylene separation system.

7.5 Industrial Cases

As a part of propylene distribution system in the Shell site at Pernis near Rotterdam, Netherlands, a propylene-propane distillation column was built in 1995, using the vapour recompression with capacity of 50,200 kW. This was done to save energy, reduce the use of cooling water and increase the yield of distillation process. In the process, propylene is obtained by distillation separation of propylene and propane. In a conventional distillation the reboiler is heated by low pressure steam and the overhead vapours are cooled with cooling water. By using heat pump, the overhead top vapours are used to heat the bottom of the distillation column. The top vapours are compressed in an electrically driven two-stage centrifugal compressor to higher pressure and temperature. The splitter produces polymer grade propylene with a purity of min. 99.5 wt% (this used to be 90 wt %).

Heat pump drive energy (kWh/year) is 50 400 MWh/year. Energy outputs of heating and cooling are 401 600 MWh/year and 352 000 MWh/year. Energy cost 136 EUR/kW demand charge. Coefficient of performance (COP) is 14.9 if heating and cooling are added.

Payback is 2 years at a natural gas price of 0.11 EUR/m3 and an electricity price of 0.05 EUR/kWh an annual energy cost saving of 3.5 million EUR is estimated.
8 Economic Analysis

8.1 Compression Heat Pumps

Wright and Steward (1985) studied three heat pump systems installed and operated in three different process industries in Canada. These included an edible oils plant, Monarch Fine Foods in Rexdale, Ontario, a milk processing plant, Agrinove in Ste, Claire, Quebec and a lead smelter, Brunswick Mining and Smelting in Beledune, New Brunswick.

They published financial details of the three cases by giving capital investment of the installation, the value of the heat recovered by the system and the cost of the electricity used during one year of operation.

Table 8-1 Capital costs for the installations (all figures Canadian dollars)

<table>
<thead>
<tr>
<th></th>
<th>Monarch</th>
<th>Agrinove</th>
<th>Brunswick Smelting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Exchangers</td>
<td>8,200</td>
<td>7,284</td>
<td>2,600</td>
</tr>
<tr>
<td>Heat Pumps</td>
<td>$10,060*</td>
<td>50,880</td>
<td>29,200†</td>
</tr>
<tr>
<td>Water Pumps</td>
<td>12,664</td>
<td>—</td>
<td>3,105</td>
</tr>
<tr>
<td>Oil in Water Analyzer</td>
<td>13,860</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>3,894</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Total Equipment</td>
<td>$119,648</td>
<td>$58,164</td>
<td>$34,905</td>
</tr>
<tr>
<td>Mechanical</td>
<td>58,060</td>
<td>28,060</td>
<td>65,238</td>
</tr>
<tr>
<td>Electrical</td>
<td>14,317</td>
<td>6,243</td>
<td>—</td>
</tr>
<tr>
<td>Building</td>
<td>18,700</td>
<td>2,874</td>
<td>18,500</td>
</tr>
<tr>
<td>Total Installation</td>
<td>$91,017</td>
<td>$37,177</td>
<td>$83,738</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>9,327</td>
<td>1,500</td>
<td>7,300</td>
</tr>
<tr>
<td>Engineering</td>
<td>4,104</td>
<td>4,236</td>
<td>24,700</td>
</tr>
<tr>
<td>Total Investment</td>
<td>$224,096</td>
<td>$101,077</td>
<td>$150,643</td>
</tr>
</tbody>
</table>

*Includes fouling guard on evaporator.
†Includes two heat pumps.

Table 8-1 shows the capital expenses for three heat recovery installations. There is a very different in the capital investment for the three installations. The total investment costs for three units were $224,096 at Monarch Fine Foods, $150,643 at Brunswick Mining and Smelting, and 101,077 at Agrinove. The capital costs in three installations indicated that the expenditures on equipment were directly related to the rate of heat recovery in three installations. However, the installation costs were depended on the distance between heating source and heating sink, due to the pipeline construction was required. At Agrinove, short distance between them led to the relative low installation cost. The other two installations required considerable piping to connect the distance between hot source and boiler feed water make-up. A separated building was also required at these two plants while only one platform for mounting equipment was need at Agrinove. At Brunswick Mining and Smelting, the collection of the blast furnace cooling water and overall cooling circuit was more complicated and needed more engineering works. The payback times for Monarch Fine Foods, Agrinove and Brunswick Mining and Smelting were estimated of 2.29, 4.75 and 3.5 years.

As a conclusion, Wright and Steward (1985) suggested that heat pump should be considered a part of the process itself from a system operation point of view.
IEA Heat Pump Centre published several heat pump applications in process industry. Some of them included the costs. Following summarizes the published cost outcomes of installed compression heat pumps.

Located in Hoechst plant, Vlissingen, the Netherlands, there is a heat pump installed for distillation application. The installation was completed in 1982. The steam was used as refrigerant. There are two heat pump systems. One was the investment of EUR 295,000 with cost saving EUR 270,000/year; another one was the investment of EUR 155,000 with cost saving of EUR 725,000 per year. It was the payback in 1 year and 3 months.

Located in Umeå, Sweden, there is a heat pump installed for waste incineration application in 2000. The waste incineration was used for a district heating system with 750 GWH per year. Closed-cycle compression system was installed by 14 MW heat pumps with R134a as refrigerant. The equipment cost of heat pump was 3,000,000 CHF (~1,600,000 euro). The installation cost was 650,000,000 (~68,000,000). The maintenance cost was 60,000 CHF (~32,000 euro).

Lachine Steel Factory is located in Lachine, Quebec, Canada. There is a heat pump system installed in 1996 for the drying process which was used for sludge disposal. Drive energy of heat pump is 123 600 (kWh/year) using ground as heating source. The capital cost including installation is CAD 45 000 and energy cost is 0.037 (CAD/kWh. Payback is taken about 1 year based on transfer and landfill charges.

### 8.2 Chemical Heat Pumps

A chemical heat pump is designed based on reversible reaction mechanism, requiring two main units: an endothermic reactor (low-temperature heat is supplied) and an exothermic reactor (high-temperature heat is released). The reaction is generally described as dehydrogenation of alcohols and hydrogenation of aldehydes or ketone, as shown below:

\[ \text{Alcohol} = \text{Aldehyde (or Ketone)} + \text{Hydrogen} \]


Karaca et al. (2002) studied those heat pump systems based on dehydrogenation of alcohols and hydrogenation of aldehydes and a ketone. In these systems, the dehydrogenation reaction takes place in liquid phase at low-temperature (70–100 °C) and requires thermal energy; while the hydrogenation reaction is carried out in gas-phase at high-temperature (150–200 °C) as an exothermic reaction. Since two reverse reactions running at different temperature levels are involved, at least two reactors and one heat exchanger are used in the system cycle. Figure 8-1 shows the process flowchart of i-propanol–acetone–hydrogen system, expressed by following reversible reaction:

\[ C_3H_7OH = C_3H_6O + H_2 \quad \Delta H = +57.3 \text{ kJ/mol} \]

The process in Figure 8.1 is also used for the analysis of other systems. Annual total costs for systems are shown in Table 8-2.
As shown in Table 8.2, the economics of these heat pumps are almost the same ranging between 30.339 and 30.935 $/kW h. However, the M–F–H and E–AL–H chemical heat pumps are suitable for low heat duties; while the iP–A–H and nB–B–H chemical heat pumps are better for higher heat duties (Karaca et al., 2002). Based on the calculated results, they concluded that on the base of economic analysis, annual total costs for chemical heat pumps are more economical than the steam boiler. The waste-heat must be supplied to produce the benefits of the process.

Table 8-2 The results for chemical heat pumps with same heat duties as those of a steam boiler

<table>
<thead>
<tr>
<th>Chemical heat pump</th>
<th>η</th>
<th>Q_H (kW)</th>
<th>Q_L (kW)</th>
<th>G (kg/h)</th>
<th>x_AD</th>
<th>LTC × 10^{-3} $(/kW h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M–F–H</td>
<td>0.447</td>
<td>264</td>
<td>590</td>
<td>332</td>
<td>0.056</td>
<td>30.935</td>
</tr>
<tr>
<td></td>
<td>0.516</td>
<td></td>
<td>511</td>
<td>334</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>E–AL–H</td>
<td>0.373</td>
<td>649</td>
<td>1739</td>
<td>1774</td>
<td>0.224</td>
<td>30.501</td>
</tr>
<tr>
<td></td>
<td>0.405</td>
<td></td>
<td>1602</td>
<td>1797</td>
<td>0.435</td>
<td></td>
</tr>
<tr>
<td>iP–A–H</td>
<td>0.379</td>
<td>1782</td>
<td>4702</td>
<td>6541</td>
<td>0.245</td>
<td>30.344</td>
</tr>
<tr>
<td></td>
<td>0.530</td>
<td></td>
<td>1602</td>
<td>6566</td>
<td>0.674</td>
<td></td>
</tr>
<tr>
<td>nB–B–H</td>
<td>0.400</td>
<td>1766</td>
<td>4420</td>
<td>6766</td>
<td>0.265</td>
<td>30.339</td>
</tr>
<tr>
<td></td>
<td>0.437</td>
<td></td>
<td>4045</td>
<td></td>
<td>0.485</td>
<td></td>
</tr>
</tbody>
</table>
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