Department of Aeronautical Engineering Sem ;VII

SAEX1041- CRYOGENICS

UNIT- I

Cryogenics is the branch of physics that deals with the production and effects of very low temperatures. The Large Hadron Collider (LHC) is the largest cryogenic system in the world and one of the coldest places on Earth. All of the magnets on the LHC are electromagnets – magnets in which the magnetic field is produced by the flow of electric current. The LHC's main magnets operate at a temperature of 1.9 K (-271.3°C), colder than the 2.7 K (-270.5°C) of outer space.

The LHC's cryogenic system requires 40,000 leak-tight pipe seals, 40 MW of electricity – 10 times more than is needed to power a locomotive – and 120 tonnes of helium to keep the magnets at 1.9 K.

Extreme cold for exceptional performances

Magnets produce a magnetic field of 8.33 tesla to keep particle beams on course around the LHC's 27-kilometre ring. A current of 11,850 amps in the magnet coils is needed to reach magnetic fields of this amplitude. The use of superconducting materials – those that conduct electricity with no resistance – has proven to be the best way of avoiding overheating in the coils and of keeping them as small as possible.

Superconductivity could not happen without the use of cryogenic systems. The coils' niobium-titanium (NbTi) wires must be kept at low temperatures to reach a superconducting state. The LHC's superconducting magnets are therefore maintained at 1.9 K (-271.3°C) by a closed liquid-helium circuit.

Cryogenic techniques essentially serve to cool the superconducting magnets. In particle detectors they are also used to keep heavy gases such as argon or krypton in a liquid state, for detecting particles in calorimeters, for example.

Three steps to cooling

The layout of the LHC magnet cooling system is based on five "cryogenic islands" which distribute the cooling fluid and convey kilowatts of cooling power over several kilometres.

The entire cooling process takes weeks to complete. It consists of three different stages. During the first stage, helium is cooled to 80 K and then to 4.5 K. It is injected into the cold masses of the magnets in a second stage, before being cooled to a temperature of 1.9 K in the third and final stage.

During the first stage, some 10,000 tonnes of liquid nitrogen are used in heat exchangers in the refrigerating equipment to bring the temperature of the helium down to 80 K.

The helium is then cooled to 4.5 K (-268.7°C) using turbines. Once the magnets have been filled, the 1.8 K refrigeration units bring the temperature down yet further to 1.9 K (-271.3°C).

In total, the cryogenics system cools some 36,000 tonnes of magnet cold masses.

Tonnes of helium for the big chill

Helium was a natural choice of coolant as its properties allow components to be kept cool over long distances. At atmospheric pressure gaseous helium becomes liquid at around 4.2 K (-269.0°C). However, if cooled below 2.17 K (-271.0°C), it passes from the fluid to the superfluid state. Superfluid helium has remarkable properties, including very high thermal conductivity; it is an efficient heat conductor. These qualities make helium an excellent refrigerant for cooling and stabilising the LHC's large-scale superconducting systems.

Helium circulates in a closed circuit while the machine is in operation.

Liquid oxygenabbreviated **LOx**, **LOX** or **Lox** in the aerospace, submarine and gas industries—is one of the physical forms of elemental oxygen.

Physical properties

Liquid oxygen has a pale blue color and is strongly paramagnetic; it can be suspended between the poles of a powerful horseshoe magnet.[1] Liquid oxygen has a density of 1.141 g/cm^3 (1.141 kg/L or 1141 kg/m^3) and is cryogenic with a freezing point of 54.36 K (−218.79 °C; −361.82 °F) and a boiling point of 90.19 K (−182.96 °C; −297.33 °F) at 101.325 kPa (760 mmHg). Liquid oxygen has anexpansion ratio of 1:861 under 1 standard atmosphere (100 kPa) and 20 °C (68 °F), and because of this, it is used in some commercial and military aircraft as transportable source of breathing oxygen.

Because of its cryogenic nature, liquid oxygen can cause the materials it touches to become extremely brittle. Liquid oxygen is also a very powerful oxidizing agent: organic materials will burn rapidly and energetically in liquid oxygen. Further, if soaked in liquid oxygen, some materials such as coal briquettes, carbon black, etc., can detonate unpredictably from sources of ignition such as flames, sparks or impact from light blows. Petrochemicals, including asphalt, often exhibit this behavior.

The tetraoxygen molecule (O_4) was first predicted in 1924 by Gilbert N. Lewis, who proposed it to explain why liquid oxygen defiedCurie's law. Modern computer simulations indicate that although there are no stable O_4 molecules in liquid oxygen, O_2 molecules do tend to associate in pairs with antiparallel spins, forming transient O_4 units.

Liquid nitrogen has a lower boiling point at −196 °C (77 K) than oxygen's −183 °C (90 K), and vessels containing liquid nitrogen can condense oxygen from air: when most of the nitrogen has evaporated from such a vessel there is a risk that liquid oxygen remaining can react violently with organic material. Conversely, liquid nitrogen or liquid air can be oxygen-enriched by letting it stand in open air; atmospheric oxygen dissolves in it, while nitrogen evaporates preferentially.

Uses

In commerce, liquid oxygen is classified as an industrial gas and is widely used for industrial and medical purposes. Liquid oxygen is obtained from the oxygen found naturally in air by fractional distillation in a cryogenic air separation plant.

Liquid oxygen is a common cryogenic liquid oxidizer propellant for spacecraft rocket applications, usually in combination with liquid hydrogen, kerosene or methane. Liquid oxygen is useful in this role because it creates a high specific impulse.] It was used in the very first rocket applications like the V2 missile and Redstone, R-7 Semyorka,Atlas boosters, and the ascent stages of the Apollo Saturn rockets. Liquid oxygen was also used in some early ICBMs, although more modern ICBMs do not use liquid oxygen because its cryogenic properties and need for regular replenishment to replace boiloff make it harder to maintain and launch quickly. Many modern rockets use liquid oxygen, including the main engines on the now-retired Space Shuttle.

Liquid oxygen also had extensive use in making oxyliquit explosives, but is rarely used now due to a high rate of accidents

It is also used in the activated sludge processing in waste water treatment to maintain a high level of micro-organisms.

Portable container for transport of liquid oxygen

History

By 1845, Michael Faraday had managed to liquefy most gases then known to exist. Six gases, however, resisted every attempt at liquefaction and were known at the time as "permanent gases". They were oxygen, hydrogen, nitrogen, carbon monoxide, methane, and nitric oxide.

In 1877, Louis Paul Cailletet in France and Raoul Pictet in Switzerland succeeded in producing the first droplets of liquid air.

The first measurable quantity of liquid oxygen was produced by Polish professors Zygmunt Wróblewski and Karol Olszewski (Jagiellonian University in Kraków) on April 5, 1883.

Liquid hydrogen (LH2 or LH_2) is the liquid state of the element hydrogen. Hydrogen is found naturally in the molecular H_2 form.

To exist as a liquid, H_2 must be cooled below hydrogen's critical point of 33 K. However, for hydrogen to be in a fully liquid state without boiling at atmospheric pressure, it needs to be cooled to

20.28 K[3] (−423.17 °F/−252.87 °C). One common method of obtaining liquid hydrogen involves a compressor resembling a jet engine in both appearance and principle. Liquid hydrogen is typically used as a concentrated form of hydrogen storage. As in any gas, storing it as liquid takes less space than storing it as a gas at normal temperature and pressure. However, the liquid density is very low compared to other common fuels. Once liquefied, it can be maintained as a liquid in pressurized and thermally insulated containers.

Liquid hydrogen consists of 99.79% parahydrogen, 0.21% orthohydrogen.

In 1885 Zygmunt Florenty Wróblewski published hydrogen's critical temperature as 33 K; critical pressure, 13.3 atmospheres; and boiling point, 23 K.

Hydrogen was liquefied by James Dewar in 1898 by using regenerative cooling and his invention, the vacuum flask. The first synthesis of the stable isomer form of liquid hydrogen, parahydrogen, was achieved by Paul Harteck and Karl Friedrich Bonhoeffer in 1929.

Spin isomers of hydrogen

Room–temperature hydrogen consists mostly of the orthohydrogen form. After production, liquid hydrogen is in a metastable state and must be converted into the parahydrogen isomer form to avoid the exothermic reaction that occurs when it changes at low temperatures; this is usually performed using a catalyst like iron(III) oxide, activated carbon, platinized asbestos, rare earth metals, uranium compounds, chromium(III) oxide, or some nickel compounds.

Uses

It is a common liquid rocket fuel for rocket applications. In most rocket engines fueled by liquid hydrogen, it first cools the nozzle and other parts before being mixed with the oxidizer (usually liquid oxygen (LOX)) and burned to produce water with traces of ozoneand hydrogen peroxide. Practical H2–O2 rocket engines run fuel-rich so that the exhaust contains some unburned hydrogen. This reduces combustion chamber and nozzle erosion. It also reduces the molecular weight of the exhaust which can actually increasespecific impulse despite the incomplete combustion.

Liquid hydrogen can be used as the fuel for an internal combustion engine or fuel cell. Various submarines (Type 212 submarine, Type 214 submarine) and concept hydrogen vehicles have been built using this form of hydrogen (see DeepC, BMW H2R). Due to its similarity, builders can sometimes modify and share equipment with systems designed forLNG. However, because of the lower volumetric energy, the hydrogen volumes needed for combustion are large. Unless LH2 is injected instead of gas, hydrogen-fueled piston engines usually require larger fuel systems. Unless direct injection is used, a severe gas-displacement effect also hampers maximum breathing and increases pumping losses.

Liquid hydrogen is also used to cool neutrons to be used in neutron scattering. Since neutrons and hydrogen nuclei have similar masses, kinetic energy exchange per interaction is maximum (elastic collision). Finally, superheated liquid hydrogen was used in many bubble chamber experiments.

A massive hydrogen tank at Lewis Research Center in 1967

The product of its combustion with oxygen alone is water vapor (although if its combustion is with oxygen and nitrogen it can form toxic chemicals), which can be cooled with some of the liquid hydrogen. Since water is harmless to the environment, an engine burning it can be considered "zero emissions." Liquid hydrogen also has a much higher specific energy than gasoline, natural gas, or diesel.

The density of liquid hydrogen is only 70.99 g/L (at 20 K), a relative density of just 0.07. Although the specific energy is around twice that of other fuels, this gives it a remarkably low volumetric energy density, many fold lower.

Liquid hydrogen requires cryogenic storage technology such as special thermally insulated containers and requires special handling common to all cryogenic fuels. This is similar to, but more severe than liquid oxygen. Even with thermally insulated containers it is difficult to keep such a low temperature, and the hydrogen will gradually leak away (typically at a rate of 1% per day). It also shares many of the samesafety issues as other forms of hydrogen, as well as being cold enough to liquefy (and possibly solidify) atmospheric oxygen which can be an explosion hazard.

The triple point of hydrogen is at 13.81 K 7.042 kPa.

Cryogenic fuels are fuels that require storage at extremely low temperatures in order to maintain them in a liquid state. These fuels are used in machinery that operates in space (e.g. rocket ships and satellites) because ordinary fuel cannot be used there, due to absence of an environment that supports combustion (on earth, oxygen is abundant in the atmosphere, whereas in human-explorable space, oxygen is virtually non-existent). Cryogenic fuels most often constitute liquefied gases such as liquid hydrogen.

Some rocket engines use regenerative cooling, the practice of circulating their cryogenic fuel around the nozzles before the fuel is pumped into the combustion chamber and ignited. This arrangement was first suggested by Eugen Sänger in the 1940s. The Saturn Vrocket that sent the first manned missions to the moon used this design element, which is still in use today.

Quite often, liquid oxygen is mistakenly called cryogenic "fuel", though it is actually an oxidizer and not a fuel.

Russian aircraft manufacturer Tupolev developed a version of its popular Tu-154 design but with a cryogenic fuel system, designated the Tu-155. Using a fuel referred to as liquefied natural gas (LNG), its first flight was in 1989.

LIQUID NITROGEN

Liquid nitrogen is inert, colorless, odorless, noncorrosive, nonflammable, and extremely cold. Nitrogen makes up the major portion of the atmosphere (78.03% by volume, 75.5% by weight). Nitrogen is inert and will not support combustion; however, it is not life supporting. Nitrogen is inert except when heated to very high temperatures, where it combines with some of the more active metals, such as lithium and magnesium, to form nitrides. It will also combine with oxygen to form oxides of nitrogen and, when combined with hydrogen in the presence of catalysts, will form ammonia. Since nitrogen is noncorrosive, special materials of construction are not required to prevent corrosion. However, materials of construction must be selected to withstand the low temperature of liquid nitrogen. Vessels and piping should be designed to American Society of Mechanical Engineers (ASME) specifications or the Department of Transportation (DOT) codes for the pressures and temperatures involved. Although used more commonly in the gaseous state, nitrogen is commonly stored and transported as a liquid, affording a more cost-effective way of providing product supply. Liquid nitrogen is a cryogenic liquid. Cryogenic liquids are liquefied gases that have a normal boiling point below –130°F (–90°C). Liquid nitrogen has a boiling point of –320°F (–196°C). The temperature difference between the product and the surrounding environment, even in winter, is substantial. Keeping this surrounding heat from the product requires special equipment to store and handle cryogenic liquids. A typical system consists of the following components: a cryogenic storage tank, one or more vaporizers, and a pressure and temperature control system. The cryogenic tank is constructed like, in principle, a vacuum bottle. It is designed to keep heat away from the liquid that is contained in the inner vessel. Vaporizers convert the liquid nitrogen to its gaseous state.

A pressure control manifold controls the pressure at which the gas is fed to the process. Processes that use nitrogen as a liquid do not require the vaporizers and pressure control manifold.

LIQUID HELIUM

The chemical element **helium** exists in a liquid form only at the extremely low temperature of −269 °C (about 4 K or −452.2 °F). Its boiling point and critical point depend on which isotope of helium is present: the common isotope helium-4 or the rare isotope helium-3. These are the only two stable isotopes of helium. See the table below for the values of these physical quantities. The density of liquid helium-4 at its boiling point and a pressure of one atmosphere(101.3 kilopascals) is about 0.125 grams per cm^3, or about 1/8th the density of liquid water.

Liquefaction

Helium was first liquefied on July 10, 1908, by the Dutch physicist Heike Kamerlingh Onnes at the University of Leiden in theNetherlands.[2] At that time, helium-3 was unknown because the mass spectrometer had not yet been invented. In more recent decades, liquid helium has been used as a cryogenic refrigerant, and liquid helium is produced commercially for use insuperconducting magnets such as those used in magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR),Magnetoencephalography (MEG), and experiments in physics, such as low temperature Mössbauer spectroscopy.

Characteristics

The temperature required to produce liquid helium is low because of the weakness of the attractions between the helium atoms. Theseinteratomic forces in helium are weak to begin with because helium is a noble gas, but the interatomic attractions are reduced even more by the effects of quantum mechanics. These are significant in helium because of its low atomic mass of about four atomic mass units. The zero point energy of liquid helium is less if its atoms are less confined by their neighbors. Hence in liquid helium, its ground state energy can decrease by a naturally-occurring increase in its average interatomic distance. However at greater distances, the effects of the interatomic forces in helium are even weaker.

Because of the very weak interatomic forces in helium, this element would remain a liquid at atmospheric pressure all the way from itsliquefaction point down to absolute zero. Liquid helium solidifies only under very low temperatures and great pressures. At temperatures below their liquefaction points, both helium-4 and helium-3 undergo transitions to superfluids. Liquid helium-4 and the rare helium-3 are not completely miscible. Below 0.9 kelvin at their saturated vapor pressure, a mixture of the two isotopes undergoes a phase separation into a normal fluid (mostly helium-3) that floats on a denser superfluid consisting mostly of helium-4. This phase separation happens because the overall mass of liquid helium can reduce its thermodynamicenthalpy by separating.

At extremely low temperatures, the superfluid phase, rich in helium-4, can contain up to 6% of helium-3 in solution. This makes possible the small-scale use of the dilution refrigerator, which is capable of reaching temperatures of a few millikelvins.

Superfluid helium-4 has substantially different properties than ordinary liquid helium.

UNIT – II

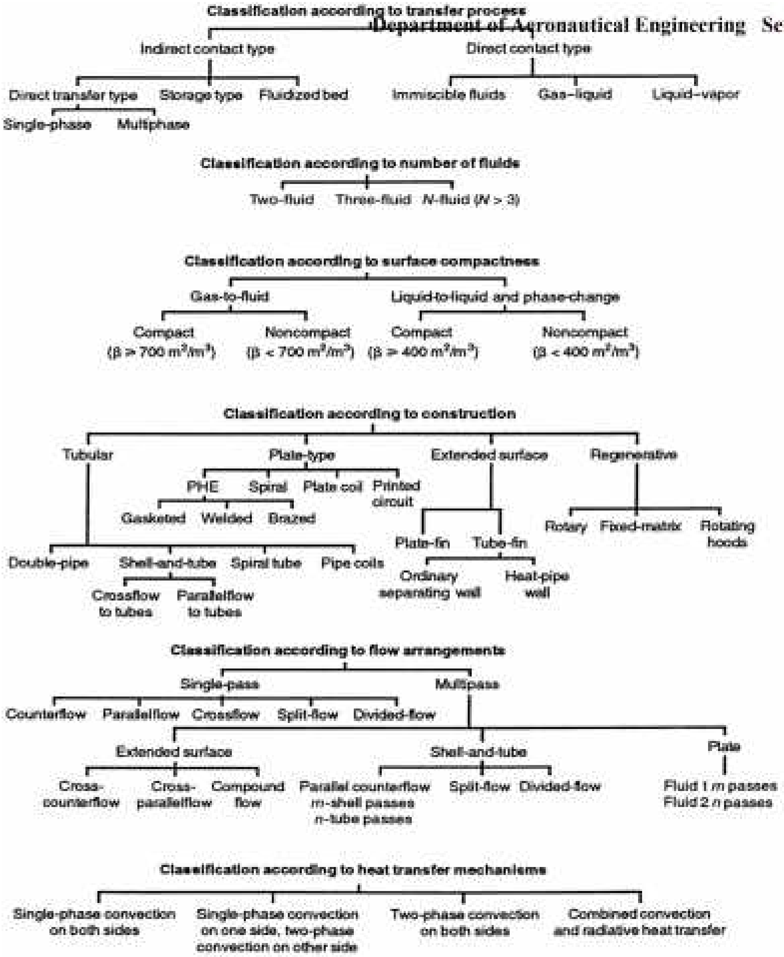
low-temperature physics, science concerned with the production and maintenance of temperatures much below normal, down to almost absolute zero, and with various phenomena that occur only at such temperatures. The temperature scale used in low-temperature physics is the Kelvin temperature scale, or absolute temperature scale, which is based on the behavior of an idealized gas (see gas laws; kinetic-molecular theory of gases). Low-temperature physics is also known as cryogenics, from the Greek meaning "producing cold." Low temperatures are achieved by removing energy from a substance. This may be done in various ways. The simplest way to cool a substance is to bring it into contact with another substance that is already at a low temperature. Ordinary ice, dry ice (solid carbon dioxide), and liquid air may be used successively to cool a substance down to about 80°K (about - 190°C). The heat is removed by conduction, passing from the substance to be cooled to the colder substance in contact with it. If the colder substance is a liquefied gas (see liquefaction), considerable heat can be removed as the liquid reverts to its gaseous state, since it will absorb its latent heat of vaporization during the transition. Various liquefied gases can be used in this manner to cool a substance to as low as 4.2°K, the boiling point of liquid helium. If the vapor over the liquid helium is continually pumped away, even lower temperatures, down to less than 1°K, can be achieved because more helium must evaporate to maintain the proper vapor pressure of the liquid helium. Most processes used to reduce the temperature below this level involve the heat energy that is associated with magnetization (seemagnetism). Successive magnetization and demagnetization under the proper combination of conditions can lower the temperature to only about a millionth of a degree above absolute zero. Reaching such low temperatures becomes increasingly difficult, as each temperature drop requires finding some kind of energy within the substance and then devising a means of removing this energy. Moreover, according to the third law of thermodynamics, it is theoretically impossible to reduce a substance to absolute zero by any finite number of processes.Superconductivity and superfluidity have traditionally been thought of as phenomena that occur only at temperatures near absolute zero, but by the late 1980s several materials that exhibit superconductivity at temperatures exceeding 100°K had been found. Superconductivity is the vanishing of all electrical resistance in certain substances when they reach a transition temperature that varies from one substance to another; this effect can be used to produce powerful superconducting magnets. Superfluidity occurs in liquid helium and leads to the tendency of liquid helium to flow over the sides of any container it is placed in without being stopped by friction or gravity.

Classification of Heat Exchangers

A variety of heat exchangers are used in industry and in their products. The objective of this chapter is to describe most of these heat exchangers in some detail using classification schemes. Starting with a definition, heat exchangers are classified according to transfer processes, number of fluids, degree of surface compactness, construction features, flow arrangements, and heat transfer mechanisms. With a detailed classification in each cate- gory, the terminology associated with a variety of these exchangers is introduced and practical applications are outlined. A brief mention is also made of the differences in design procedure for the various types of heat exchangers.

INTRODUCTION

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact. In heat exchangers, there are usually no external heat and work interactions. Typical applications involve heating or cooling of a fluid stream of concern and evaporation or condensation of single- or multicomponent fluid streams. In other applications, the objective may be to recover or reject heat, or sterilize, pasteurize, fractionate, distill, concentrate, crystallize, or control a process fluid. In a few heat exchangers, the fluids exchanging heat are in direct contact. In most heat exchangers, heat transfer between fluids takes place through a separating wall or into and out of a wall in a transient manner. In many heat exchangers, the fluids are separated by a heat transfer surface, and ideally they do not mix or leak. Such exchangers are referred to as direct transfer type, or simply recuperators. In con- trast, exchangers in which there is intermittent heat exchange between the hot and cold fluids—via thermal energy storage and release through the exchanger surface or matrix— are referred to as indirect transfer type, or simply regenerators. Such exchangers usually have fluid leakage from one fluid stream to the other, due to pressure differences and matrix rotation/valve switching. Common examples of heat exchangers are shell-and- tube exchangers,



automobile radiators, condensers, evaporators, air preheaters, and cooling towers. If no phase change occurs in any of the fluids in the exchanger, it is sometimes referred to as a sensible heat exchanger. There could be internal thermal energy sources in the exchangers, such as in electric heaters and nuclear fuel elements. Combustion and chemical reaction may take place within the exchanger, such as in boilers, fired heaters, and fluidized-bed exchangers. Mechanical devices may be used in some exchangers such as in scraped surface exchangers, agitated vessels, and stirred tank reactors. Heat transfer in the separating wall of a recuperator generally takes place by conduction. However, in a heat pipe heat exchanger, the heat pipe not only acts as a separating wall, but also facilitates the transfer of heat by condensation, evaporation, and conduction of the working fluid inside the heat pipe. In general, if the fluids are immiscible, the separating wall may be eliminated, and the interface between the fluids replaces a heat transfer surface, as in a direct-contact heat exchanger.

A heat exchanger consists of heat transfer elements such as a core or matrix containing the heat transfer surface, and fluid distribution elements such as headers, manifolds, tanks, inlet and outlet nozzles or pipes, or seals. Usually, there are no moving parts in a heat exchanger; however, there are exceptions, such as a rotary regenerative exchanger (in which the matrix is mechanically driven to rotate at some design speed) or a scraped surface heat exchanger.

The heat transfer surface is a surface of the exchanger core that is in direct contact with fluids and through which heat is transferred by conduction. That portion of the surface that is in direct contact with both the hot and cold fluids and transfers heat between them is referred to as the primary or direct surface. To increase the heat transfer area, appendages may be intimately connected to the primary surface to provide an extended, secondary, or indirect surface. These extended surface elements are referred to as fins. Thus, heat is conducted through the fin and convected (and/or radiated) from the fin (through the surface area) to the surrounding fluid, or vice versa, depending on whether the fin is being cooled or heated. As a result, the addition of fins to the primary surface reduces the thermal resistance on that side and thereby increases the total heat transfer from the surface for the same temperature difference. Fins may form flow passages for the individual fluids but do not separate the two (or more) fluids of the exchanger. These secondary surfaces or fins may also be introduced primarily for struc- tural strength purposes or to provide thorough mixing of a highly viscous liquid.

Not only are heat exchangers often used in the process, power, petroleum, transpor- tation, air-conditioning, refrigeration, cryogenic, heat recovery, alternative fuel, and manufacturing industries, they also serve as key components of many industrial products available in the marketplace. These exchangers can be classified in many different ways. We will classify them according to transfer processes, number of fluids, and heat transfer mechanisms. Conventional heat exchangers are further classified according to construc- tion type and flow arrangements. Another arbitrary classification can be made, based on the heat transfer surface area/volume ratio, into compact and noncompact heat exchan- gers. This classification is made because the type of equipment, fields of applications, and design techniques generally differ. All these classifications are summarized in Fig. 1.1 and discussed further in this chapter. Heat exchangers can also be classified according to the process function, as outlined in Fig. 1.2. However, they are not discussed here and the reader may refer to Shah and Mueller (1988). Additional ways to classify heat exchangers are by fluid type (gas–gas, gas–liquid, liquid–liquid, gas two-phase, liquid two-phase, etc.), industry, and so on, but we do not cover such classifications in this chapter.

JOULES THOMPSON EFFECT

- If a gas is allowed to expand through a fine nozzle or a porous plug, so that it issues from a region at a higher pressure to a region at a lower pressure there will be a fall in temperature of the gas provided the initial temperature of the gas should be sufficiently low.

- This phenomenon is called Joule – Thomson effect.

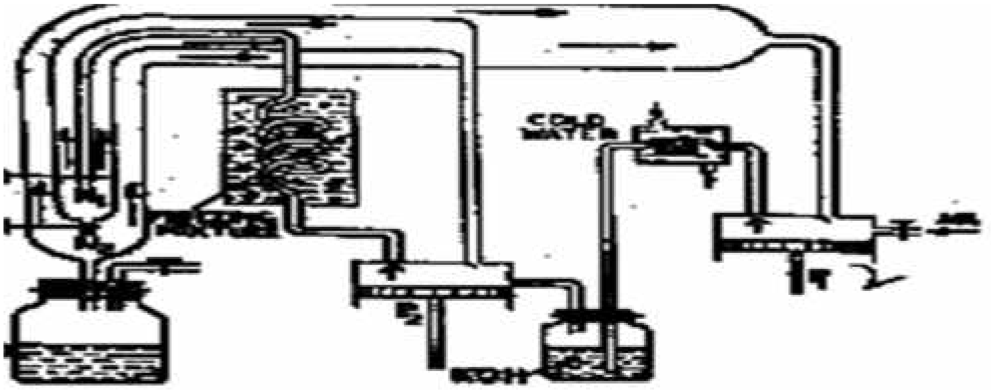
- The principle of regenerative cooling consists in cooling the incoming gas by the gas which has already undergone cooling due to Joule – Thomson effect.

- The pump P1 compresses air to a pressure of about 25 atmosphere and is passed through a tube surrounded by a jacket through which cold water is circulated.

- This compressed air is passed through KOH solution to remove CO_2 and water vapour.

- This air, free from CO2 and water vapour is compressed to a pressure of 200 atmospheres by the pump P2.

- This air passes through a spiral tube surrounded by a jacket containing a freezing mixture and the temperature is reduced to $-20^{o}C$



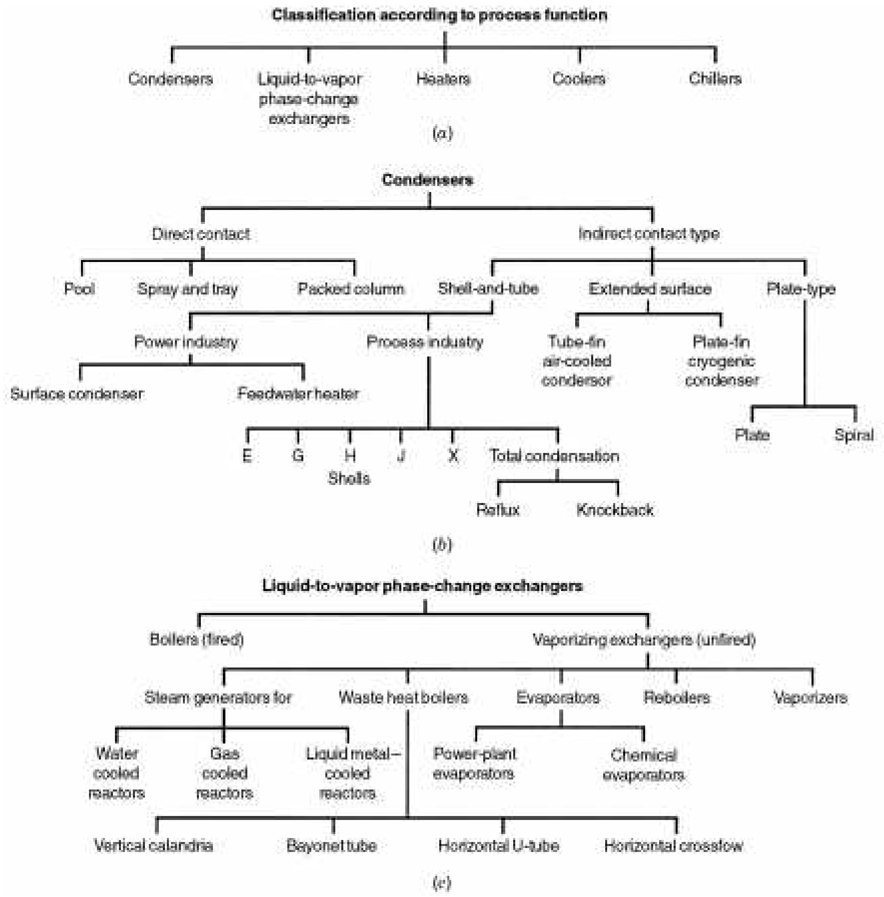


FIGURE 1.2 (a) Classification according to process function; (b) classification of condensers;

(c) classification of liquid-to-vapor phase-change exchangers.

Direct-Transfer Type Exchangers. In this type, heat transfers continuously from the hot fluid to the cold fluid through a dividing wall. Although a simultaneous flow of two (or more) fluids is required in the exchanger, there is no direct mixing of the two (or more) fluids because each fluid flows in separate fluid passages. In general, there are no moving parts in most such heat exchangers. This type of exchanger is designated as a recuperative heat exchanger or simply as a recuperator.{ Some examples of direct- transfer type heat exchangers are tubular, plate-type, and extended surface exchangers. Note that the term recuperator is not commonly used in the process industry for shell-

{ In vehicular gas turbines, a stationary heat exchanger is usually referred to as a recuperator, and a rotating heat exchanger as a regenerator. However, in industrial gas turbines, by long tradition and in a thermodynamic sense, a stationary heat exchanger is generally referred to as a regenerator. Hence, a gas turbine regenerator could be either a recuperator or a regenerator in a strict sense, depending on the construction. In power plants, a heat exchanger is not called a recuperator, but is, rather, designated by its function or application.

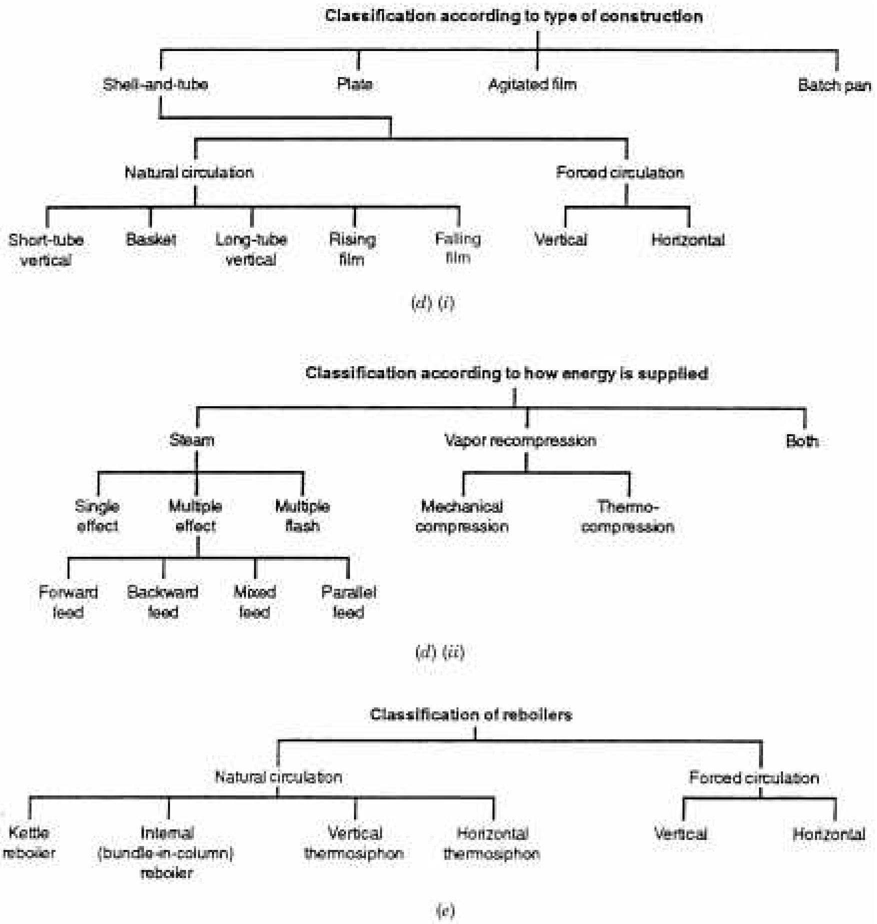


FIGURE 1.2 (d) classification of chemical evaporators according to (i) the type of construction, and (ii) how energy is supplied (Shah and Mueller, 1988); (e) classification of reboilers.

and-tube and plate heat exchangers, although they are also considered as recuperators. Recuperators are further subclassified as prime surface exchangers and extended-surface exchangers. Prime surface exchangers do not employ fins or extended surfaces on any fluid side.

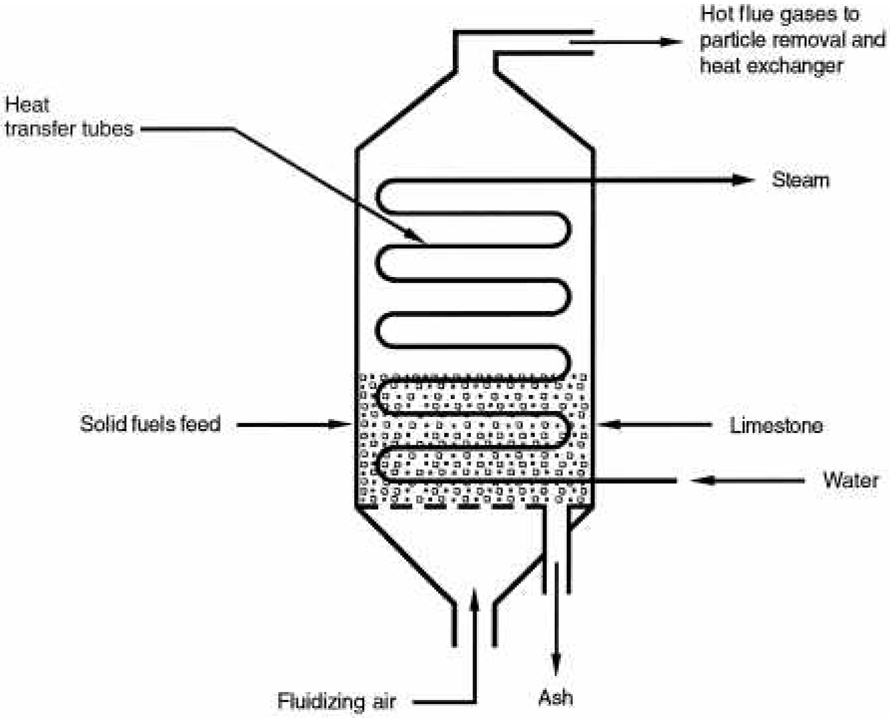
Plain tubular exchangers, shell-and-tube exchangers with plain tubes, and plate exchangers are good examples of prime surface exchangers. Recuperators consti- tute a vast majority of all heat exchangers.

Storage Type Exchangers. In a storage type exchanger, both fluids flow alter- natively through the same flow passages, and hence heat transfer is intermittent. The heat transfer surface (or flow passages) is generally cellular in structure and is referred to as a matrix (see Fig. 1.43), or it is a permeable (porous) solid material, referred to as a packed bed. When hot gas flows over the heat transfer surface (through flow passages), the thermal energy from the hot gas is stored in the matrix wall, and thus the hot gas is being cooled during the matrix heating period. As cold gas flows through the same passages later (i.e., during the matrix cooling period), the matrix wall gives up thermal energy, which is absorbed by the cold fluid. Thus, heat is not transferred continuously through the wall as in a direct-transfer type exchanger (recuperator), but the corre- sponding thermal energy is alternately stored and released by the matrix wall. This storage type heat exchanger is also referred to as a regenerative heat exchanger, or simply as a regenerator.{ To operate continuously and within a desired temperature range, the gases, headers, or matrices are switched periodically (i.e., rotated), so that the same passage is occupied periodically by hot and cold gases, as described further in Section 1.5.4. The actual time that hot gas takes to flow through a cold regenerator matrix is called the hot period or hot blow, and the time that cold gas flows through the hot regenerator matrix is called the cold period or cold blow. For successful operation, it is not necessary to have hot- and cold-gas flow periods of equal duration. There is some unavoidable carryover of a small fraction of the fluid trapped in the passage to the other fluid stream just after switching of the fluids; this is referred to as carryover leakage. In addition, if the hot and cold fluids are at different pressures, there will be leakage from the high-pressure fluid to the low-pressure fluid past the radial, peripheral, and axial seals, or across the valves. This leakage is referred to as pressure leakage. Since these leaks are unavoidable, regenerators are used exclusively in gas-to-gas heat (and mass) transfer applications with sensible heat transfer; in some applications, regenerators may transfer moisture from humid air to dry air up to about 5%.

For heat transfer analysis of regenerators, the "-NTU method of recuperators needs to be modified to take into account the thermal energy storage capacity of the matrix. We discuss the design theory of regenerators in detail in Chapter 5.

Fluidized-Bed Heat Exchangers. In a fluidized-bed heat exchanger, one side of a two-fluid exchanger is immersed in a bed of finely divided solid material, such as a tube bundle immersed in a bed of sand or coal particles, as shown in Fig. 1.3. If the upward fluid velocity on the bed side is low, the solid particles will remain fixed in position in the bed and the fluid will flow through the interstices of the bed. If the upward fluid velocity is high, the solid particles will be carried away with the fluid. At a ‘‘proper’’ value of the fluid velocity, the upward drag force is slightly higher than the weight of the bed particles. As a result, the solid particles will float with an increase in bed volume, and the bed behaves as a liquid. This characteristic of the bed is referred to as a fluidized condition. Under this condition, the fluid pressure drop through the bed remains almost constant, independent of the flow rate, and a strong mixing of the solid particles occurs. This results in a uniform temperature for the total bed (gas and par- ticles) with an apparent thermal conductivity of the solid particles as infinity. Very high heat transfer coefficients are achieved on the fluidized side compared to particle-free or dilute-phase particle gas flows. Chemical reaction is common on the fluidized side in many process applications, and combustion takes place in coal combustion fluidized beds. The common applications of the fluidized-bed heat exchanger are drying, mixing, adsorption, reactor engineering, coal combustion, and waste heat recovery. Since the

Regenerators are also used for storing thermal energy for later use, as in the storage of thermal energy. Here the objective is how to store the maximum fraction of the input energy and minimize heat leakage. However, we do not concentrate on this application in this book.



initial temperature difference $(T_{h;i} — T_{f;i})^{\{}$ is reduced due to fluidization, the exchanger effectiveness is lower, and hence "-NTU theory for a fluidized-bed exchanger needs to be modified (Suo, 1976). Chemical reaction and combustion further complicate the design of these exchangers but are beyond the scope of this book.

Direct-Contact Heat Exchangers

In a direct-contact exchanger, two fluid streams come into direct contact, exchange heat, and are then separated. Common applications of a direct-contact exchanger involve mass transfer in addition to heat transfer, such as in evaporative cooling and rectification; applications involving only sensible heat transfer are rare. The enthalpy of phase change in such an exchanger generally represents a significant portion of the total energy transfer. The phase change generally enhances the heat transfer rate. Compared to indirect-contact recuperators and regenerators, in direct-contact heat exchangers, (1) very high heat transfer rates are achievable, (2) the exchanger construction is relatively inexpensive, and (3) the fouling problem is generally nonexistent, due to the absence of a heat transfer surface (wall) between the two fluids. However, the applications are limited to those cases where a direct contact of two fluid streams is permissible. The design theory for these exchangers is beyond the scope of this book and is not covered. These exchangers may be further classified as follows.

Immiscible Fluid Exchangers. In this type, two immiscible fluid streams are brought into direct contact. These fluids may be single-phase fluids, or they may involve condensation or vaporization. Condensation of organic vapors and oil vapors with water or air are typical examples.

Gas–Liquid Exchangers. In this type, one fluid is a gas (more commonly, air) and the other a low-pressure liquid (more commonly, water) and are readily separable after the energy exchange. In either cooling of liquid (water) or humidification of gas (air) applications, liquid partially evaporates and the vapor is carried away with the gas. In these exchangers, more than 90% of the energy transfer is by virtue of mass transfer (due to the evaporation of the liquid), and convective heat transfer is a minor mechanism. A ‘‘wet’’ (water) cooling tower with forced- or natural-draft airflow is the most common application. Other applications are the air-conditioning spray chamber, spray drier, spray tower, and spray pond.

Liquid–Vapor Exchangers. In this type, typically steam is partially or fully condensed using cooling water, or water is heated with waste steam through direct contact in the exchanger. Noncondensables and residual steam and hot water are the outlet streams. Common examples are desuperheaters and open feedwater heaters (also known as deaeraters) in power plants.

CLASSIFICATION ACCORDING TO NUMBER OF FLUIDS

Most processes of heating, cooling, heat recovery, and heat rejection involve transfer of heat between two fluids. Hence, two-fluid heat exchangers are the most common. Three- fluid heat exchangers are widely used in cryogenics and some chemical processes (e.g., air separation systems, a helium–air separation unit, purification and liquefaction of hydro- gen, ammonia gas synthesis). Heat exchangers with as many as 12 fluid streams have been used in some chemical process applications. The design theory of three- and multifluid heat exchangers is algebraically very complex and is not covered in this book. Exclusively, only the design theory for two-fluid exchangers and some associated problems are presented in this book.

CLASSIFICATION ACCORDING TO SURFACE COMPACTNESS

Compared to shell-and-tube exchangers, compact heat exchangers are characterized by a large heat transfer surface area per unit volume of the exchanger, resulting in reduced space, weight, support structure and footprint, energy requirements and cost, as well as improved process design and plant layout and processing conditions, together with low fluid inventory.

A gas-to-fluid exchanger is referred to as a compact heat exchanger if it incorporates a heat transfer surface having a surface area density greater than about 700 m^2/m^3 (213 ft^2/ft^3){ or a hydraulic diameter D_h Ç 6 mm (^{1} in.) for operating in a gas stream and 400 m^2/m^3 (122 ft^2/ft^3) or higher for operating in a liquid or phase-change stream. A laminar flow heat exchanger (also referred to as a meso heat exchanger) has a surface area density greater than about 3000 m^2/m^3 (914 ft^2/ft^3) or 100 mm Ç D_h Ç 1 mm. The term micro heat exchanger is used if the surface area density is greater than about 15,000 m^2/m^3 (4570 ft^2/ft^3) or 1 mm Ç D_h Ç 100 mm. A liquid/two-phase fluid heat exchanger is referred to as a compact heat exchanger if the surface area density on any one fluid side is greater than about 400 m^2/m^3. In contrast, a typical process industry shell- and-tube exchanger has a surface area density of less than 100 m^2/m^3 on one fluid side with plain tubes, and two to three times greater than that with high-fin-density low-finned tubing. A typical plate heat exchanger has about twice the average heat transfer coefficient h on one fluid side or the average overall heat transfer coefficient U than that for a shell-and-tube exchanger for water/water applications. A compact heat exchanger is not necessarily of small bulk and mass. However, if it did not incorporate a surface of high-surface-area density, it would be much more bulky and massive. Plate-fin, tube-fin, and rotary regenerators are examples of compact heat exchangers for gas flow on one or both fluid sides, and gasketed, welded, brazed plate heat exchangers and printed-circuit heat exchangers are examples of compact heat exchangers for liquid flows. Basic flow arrangements of two-fluid compact heat exchangers are single-pass crossflow, counterflow, and multipass cross-counterflow (see Section 1.6 for details); for noncompact heat exchangers, many other flow arrangements are also used. The aforementioned last two flow arrangements for compact or noncompact heat exchangers can yield a very high exchanger effectiveness value or a very small temperature approach (see Section 3.2.3 for the definition) between fluid streams.

A spectrum of surface area density of heat exchanger surfaces is shown in Fig. 1.4. On the bottom of the figure, two scales are shown: the heat transfer surface area density Ø (m^2/m^3) and the hydraulic diameter D_h,{ (mm), which is the tube inside or outside diameter D (mm) for a thin-walled circular tube. Different heat exchanger surfaces are shown in the rectangles. When projected on the Ø (or D_h) scale, the short vertical sides of a rectangle indicate the range of surface area density (or hydraulic diameter) for the particular surface in question. What is referred to as Ø in this figure is either $Ø_1$ or $Ø_2$, defined as follows. For plate heat exchangers, plate-fin exchangers, and regenerators,

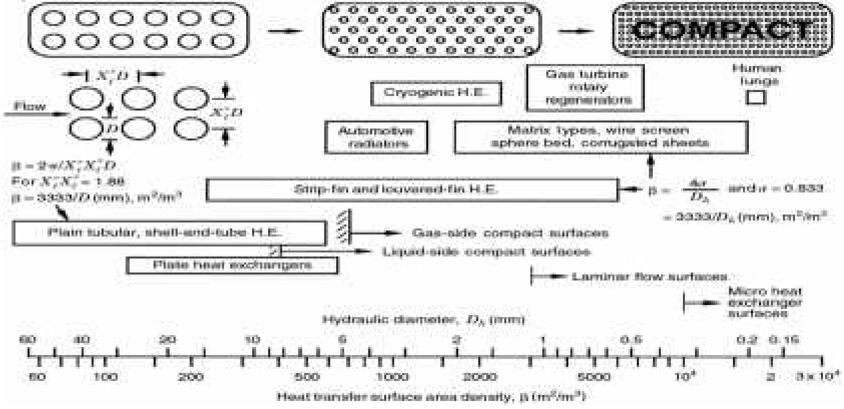


FIGURE 1.4 Heat transfer surface area density spectrum of exchanger surfaces (Shah, 1981).

Note that some industries quote the total surface area (of hot- and cold-fluid sides) in their exchanger specifications. However, in calculations of heat exchanger design, we need individual fluid-side heat transfer surface areas; and hence we use here the definitions of Ø and α as given above.

Based on the foregoing definition of a compact surface, a tube bundle having 5 mm (0.2 in.) diameter tubes in a shell-and-tube exchanger comes close to qualifying as a compact exchanger. As Ø or α varies inversely with the tube diameter, the 25.4 mm (1 in.) diameter tubes used in a power plant condenser result in a noncompact exchanger. In contrast, a 1990s automobile radiator [790 fins/m (20 fins/in.)] has a surface area density Ø on the order of 1870 m^2/m^3 (570 ft^2/ft^3) on the air side, which is equivalent to 1.8 mm (0.07 in.) diameter tubes. The regenerators in some vehicular gas turbine engines under development have matrices with an area density on the order of 6600 m^2/m^3 (2000 ft^2/ft^3), which is equivalent to 0.5 mm (0.02 in.) diameter tubes in a bundle. Human lungs are one of the most compact heat-and-mass exchangers, having a surface area density of about 17,500 m^2/m^3 (5330 ft^2/ft^3), which is equivalent to 0.19 mm (0.0075 in.) diameter tubes. Some micro heat exchangers under development are as compact as the human lung (Shah, 1991a) and also even more compact.

- Flexibility in distributing surface area on the hot and cold sides as warranted by design considerations
- Generally, substantial cost, weight, or volume savings.

The important design and operating considerations for compact extended-surface exchangers are as follows:

- Usually, at least one of the fluids is a gas having a low h value.
- Fluids must be clean and relatively noncorrosive because of low-D_h flow passages and no easy techniques for cleaning.
- The fluid pumping power (and hence the pressure drop) is often as important as the heat transfer rate.
- Operating pressures and temperatures are somewhat limited compared to shell-and-tube exchangers, due to joining of the fins to plates or tubes by brazing, mechanical expansion, and so on.
- With the use of highly compact surfaces, the resulting shape of the exchanger is one having a large frontal area and a short flow length; the header design of a compact heat exchanger is thus important for achieving uniform flow distribution among very large numbers of small flow passages.
- The market potential must be large enough to warrant the sizable initial manufacturing tooling and equipment costs.

Fouling is a major potential problem in compact heat exchangers (except for plate-and-frame heat exchangers), particularly those having a variety of fin geometries or very fine circular or noncircular flow passages that cannot be cleaned mechanically. Chemical cleaning may be possible; thermal baking and subsequent rinsing are possible for small units.[{] Hence, extended-surface compact heat exchangers may not be used in heavy fouling applications. Nonfouling fluids are used where permissible, such as clean air or gases, light hydrocarbons, and refrigerants.

Liquid-to-Liquid and Phase-Change Exchangers

Liquid-to-liquid and phase-change exchangers are gasketed plate-and-frame and welded plate, spiral plate, and printed-circuit exchangers. Some of them are described in detail in Section 1.5.2.

1.5 CLASSIFICATION ACCORDING TO CONSTRUCTION FEATURES

Heat exchangers are frequently characterized by construction features. Four major con- struction types are tubular, plate-type, extended surface, and regenerative exchangers. Heat exchangers with other constructions are also available, such as scraped surface exchanger, tank heater, cooler cartridge exchanger, and others (Walker, 1990). Some of these may be classified as tubular exchangers, but they have some unique features compared to conventional tubular exchangers. Since the applications of these exchangers are specialized, we concentrate here only on the four major construction types noted above.

Although the "-NTU and MTD methods (see end of Section 3.2.2) are identical for tubular, plate-type, and extended-surface exchangers, the influence of the following factors must be taken into account in exchanger design: corrections due to leakage and bypass streams in a shell-and-tube exchanger, effects due to a few plates in a plate exchanger, and fin efficiency in an extended-surface exchanger. Similarly, the "-NTU method must be modified to take into account the heat capacity of the matrix in a regenerator. Thus, the detailed design theory differs for each construction type and is discussed in detail in Chapters 3 through 5. Let us first discuss the construction features of the four major types.

1.5.1 Tubular Heat Exchangers

These exchangers are generally built of circular tubes, although elliptical, rectangular, or round/flat twisted tubes have also been used in some applications. There is considerable flexibility in the design because the core geometry can be varied easily by changing the tube diameter, length, and arrangement. Tubular exchangers can be designed for high pressures relative to the environment and high-pressure differences between the fluids. Tubular exchangers are used primarily for liquid-to-liquid and liquid-to-phase change (condensing or evaporating) heat transfer applications. They are used for gas-to-liquid and gas-to-gas heat transfer applications primarily when the operating temperature and/ or pressure is very high or fouling is a severe problem on at least one fluid side and no other types of exchangers would work. These exchangers may be classified as shell-and- tube, double-pipe, and spiral tube exchangers. They are all prime surface exchangers except for exchangers having fins outside/inside tubes.

1.5.1.1 Shell-and-Tube Exchangers. This exchanger, shown in Fig. 1.5, is generally built of a bundle of round tubes mounted in a cylindrical shell with the tube axis parallel to that of the shell. One fluid flows inside the tubes, the other flows across and along the tubes. The major components of this exchanger are tubes (or tube bundle), shell, front- end head, rear-end head, baffles, and tubesheets, and are described briefly later in this subsection. For further details, refer to Section 10.2.1.

A variety of different internal constructions are used in shell-and-tube exchangers, depending on the desired heat transfer and pressure drop performance and the methods employed to reduce thermal stresses, to prevent leakages, to provide for ease of cleaning, to contain operating pressures and temperatures, to control corrosion, to accommodate highly asymmetric flows, and so on. Shell-and-tube exchangers are classified and con- structed in accordance with the widely used TEMA (Tubular Exchanger Manufacturers Association) standards (TEMA, 1999), DIN and other standards in Europe and else- where, and ASME (American Society of Mechanical Engineers) boiler and pressure vessel codes. TEMA has developed a notation system to designate major types of shell-and-tube exchangers. In this system, each exchanger is designated by a three-letter combination, the first letter indicating the front-end head type, the second the shell type, and the third the rear-end head type. These are identified in Fig. 1.6. Some common shell-and-tube exchangers are AES, BEM, AEP, CFU, AKT, and AJW. It should be emphasized that there are other special types of shell-and-tube exchangers commercially available that have front- and rear-end heads different from those in Fig. 1.6. Those exchangers may not be identifiable by the TEMA letter designation.

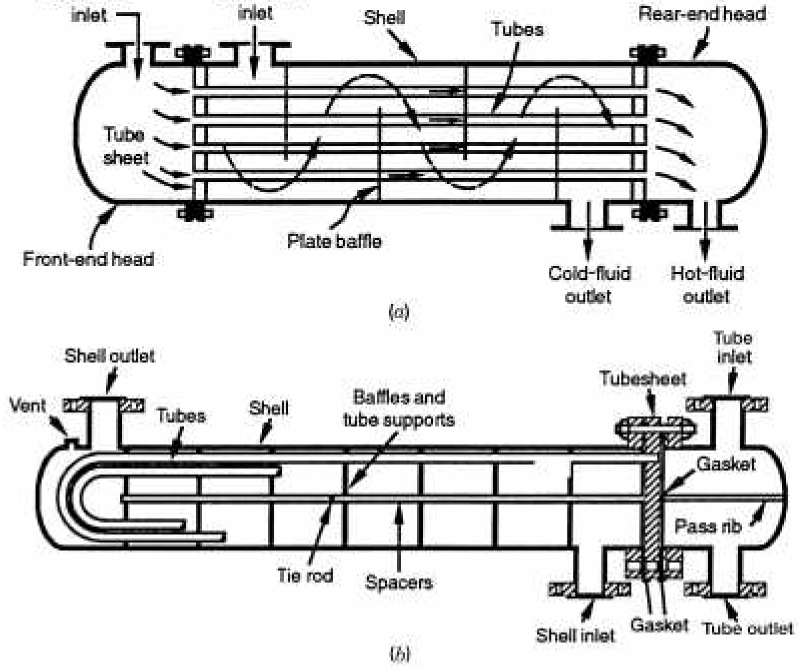


FIGURE 1.5 (a) Shell-and-tube exchanger (BEM) with one shell pass and one tube pass; (b) shell- and-tube exchanger (BEU) with one shell pass and two tube passes.

The three most common types of shell-and-tube exchangers are (1) fixed tubesheet design, (2) U-tube design, and (3) floating-head type. In all three types, the front-end head is stationary while the rear-end head can be either stationary or floating (see Fig. 1.6), depending on the thermal stresses in the shell, tube, or tubesheet, due to temperature differences as a result of heat transfer.

The exchangers are built in accordance with three mechanical standards that specify design, fabrication, and materials of unfired shell-and-tube heat exchangers. Class R is for the generally severe requirements of petroleum and related processing applications. Class C is for generally moderate requirements for commercial and general process applications. Class B is for chemical process service. The exchangers are built to comply with the applicable ASME Boiler and Pressure Vessel Code, Section VIII (1998), and other pertinent codes and/or standards. The TEMA standards supplement and define the ASME code for heat exchanger applications. In addition, state and local codes applicable to the plant location must also be met.

The TEMA standards specify the manufacturing tolerances for various mechanical classes, the range of tube sizes and pitches, baffling and support plates, pressure classification, tubesheet thickness formulas, and so on, and must be consulted for all these details. In this book, we consider only the TEMA standards where appropriate, but there are other standards, such as DIN 28 008.

Tubular exchangers are widely used in industry for the following reasons. They are custom designed for virtually any capacity and operating conditions, such as from high vacuum to ultrahigh pressure [over 100 MPa (15,000 psig)], from cryogenics to high temperatures [about 11008C (20008F)] and any temperature and pressure differences between the fluids, limited only by the materials of construction. They can be designed for special operating conditions: vibration, heavy fouling, highly viscous fluids,

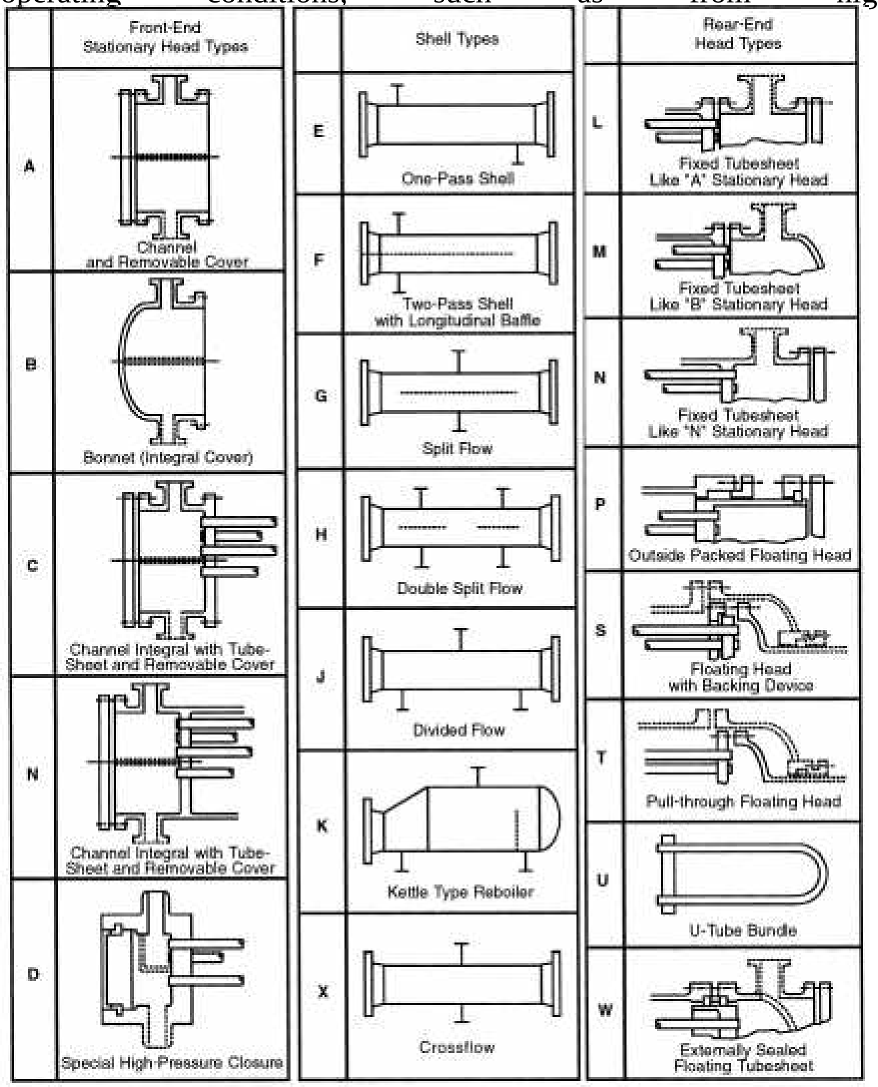


FIGURE 1.6 Standard shell types and front- and rear-end head types (From TEMA, 1999).

erosion, corrosion, toxicity, radioactivity, multicomponent mixtures, and so on. They are the most versatile exchangers, made from a variety of metal and nonmetal materials (such as graphite, glass, and Teflon) and range in size from small [0.1 m^2 (1 ft^2)] to supergiant [over 10^5 m^2 (10^6 ft^2)] surface area. They are used extensively as process heat exchangers in the petroleum-refining and chemical industries; as steam generators, condensers, boiler feedwater heaters, and oil coolers in power plants; as condensers and evaporators in some air-conditioning and refrigeration applications; in waste heat recovery applications with heat recovery from liquids and condensing fluids; and in environmental control.

Next, major components of shell-and-tube exchangers are briefly described.

Tubes. Round tubes in various shapes are used in shell-and-tube exchangers. Most common are the tube bundles{ with straight and U-tubes (Fig. 1.5) used in process and power industry exchangers. However, sine-wave bend, J-shape, L-shape or hockey sticks, and inverted hockey sticks are used in advanced nuclear exchangers to accommodate large thermal expansion of the tubes. Some of the enhanced tube geometries used in shell-and-tube exchangers are shown in Fig. 1.7. Serpentine, helical, and bayonet are other tube shapes (shown in Fig. 1.8) that are used in shell-and-tube exchangers. In most applications, tubes have single walls, but when working with radioactive, reactive, or toxic fluids and potable water, double-wall tubing is used. In most applications, tubes are bare, but when gas or low-heat-transfer coefficient liquid is used on the shell side, low-height fins (*low fins*) are used on the shell side. Also, special high-flux-boiling surfaces employ modified low-fin tubing. These are usually integral fins made from a thick-walled tube, shown in Fig. 1.9. Tubes are drawn, extruded, or welded, and they are made from metals, plastics, and ceramics, depending on the applications.

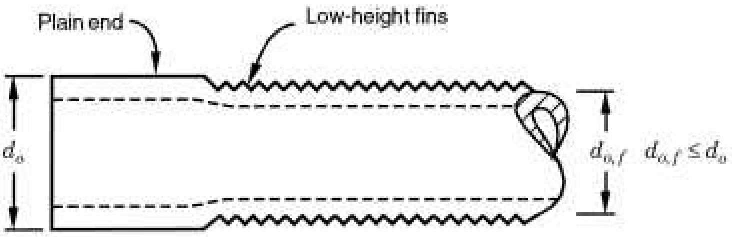


FIGURE 1.9 Low-finned tubing. The plain end goes into the tubesheet.

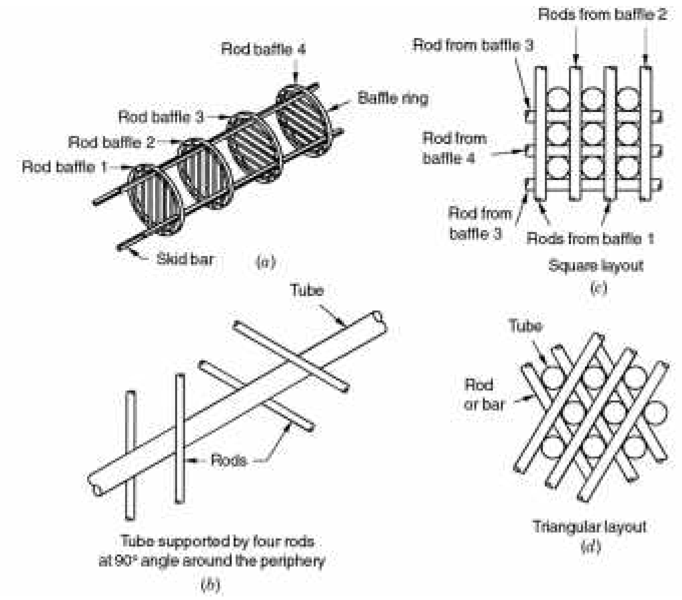


FIGURE 1.11 (*a*) Four rod baffles held by skid bars (no tubes shown); (*b*) tube in a rod baffle exchanger supported by four rods; (*c*) square layout of tubes with rods; (*d*) triangular layout of tubes with rods (Shah, 1981).

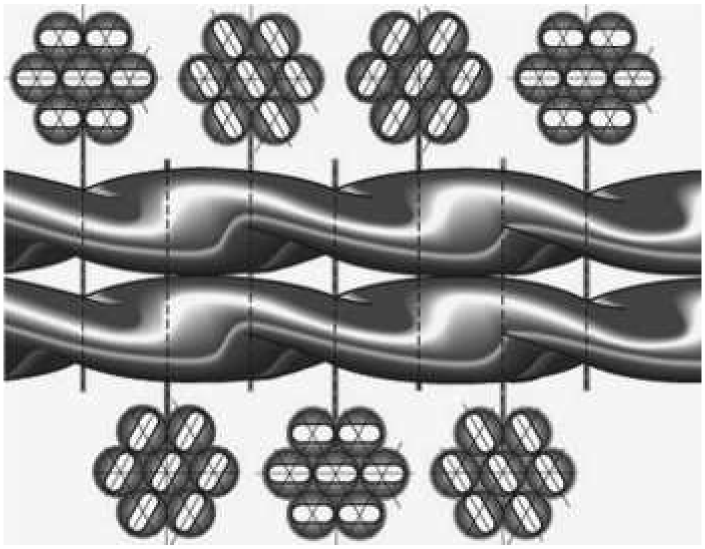
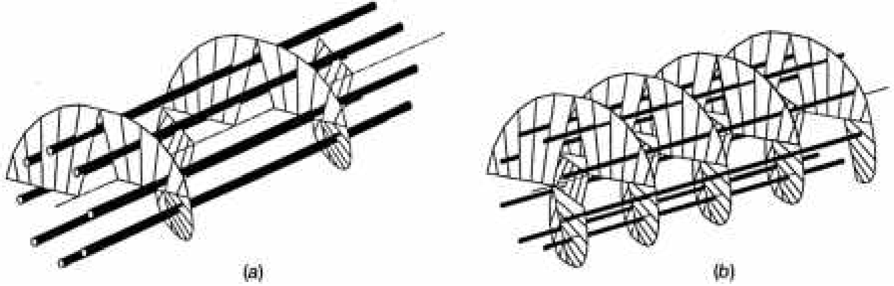


FIGURE 1.12 Twisted tube bundle for a shell-and-tube exchanger. (Courtesy of Brown Fintube Company, Houston, TX.)

FIGURE 1.13 Helical baffle shell-and-tube exchanger: (*a*) single helix; (*b*) double helix. (Courtesy of ABB Lumus Heat Transfer, Bloomfield, NJ.)

tubesheet through a clearance between the tube hole and tube, the tube-to-tubesheet joints are made by many methods, such as expanding the tubes, rolling the tubes, hydraulic expansion of tubes, explosive welding of tubes, stuffing of the joints, or welding or brazing of tubes to the tubesheet. The leak-free tube-to-tubesheet joint made by the conventional rolling process is shown in Fig. 1.14.



Double-Pipe Heat Exchangers. This exchanger usually consists of two con- centric pipes with the inner pipe plain or finned, as shown in Fig. 1.15. One fluid flows in the inner pipe and the other fluid flows in the annulus between pipes in a counterflow direction for the ideal highest performance for the given surface area. However, if the application requires an almost constant wall temperature, the fluids may flow in a parallelflow direction. This is perhaps the simplest heat exchanger. Flow distribution is no problem, and cleaning is done very easily by disassembly. This con- figuration is also suitable where one or both of the fluids is at very high pressure,

Good heat transfer pressure drop	No	Yes	Yes	Yes
High shell-side heat transfer coefficient	Yes	No	No	Yes
Tube-side	With inserts	With	Include	With
Suitable for very exchanger	No	Yes	Yes	No
Tends to have low	No	Yes	Yes	Yes
Can be cleaned mechanically	Yes, with square	Yes	Yes	Yes, with square

Low flow-induced vibration	With special designs	Yes	Yes	With helix
Can have low-finned tubes	Yes	Yes	Yes	Yes

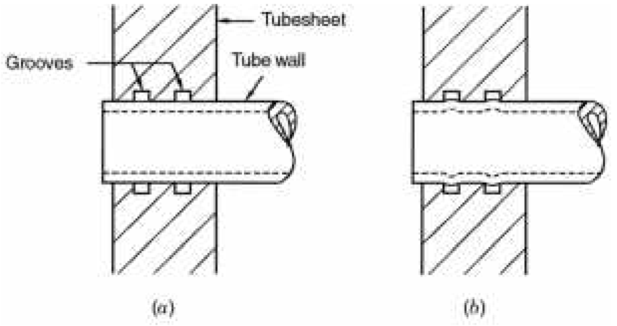


FIGURE 1.14 Details of a leak-free joint between the tube and tube hole of a tubesheet: (*a*) before tube expansion; (*b*) after tube expansion.

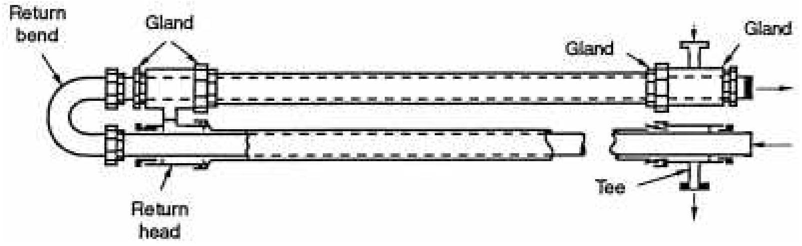


FIGURE 1.15 Double-pipe heat exchanger.

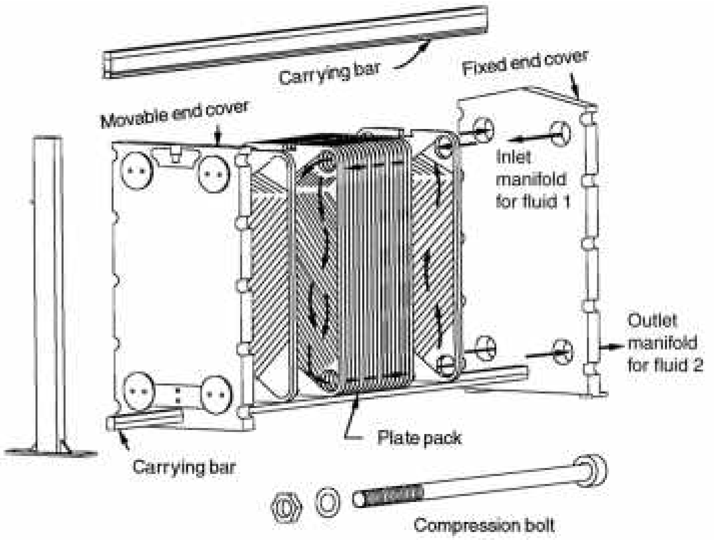
because containment in the small-diameter pipe or tubing is less costly than containment in a large-diameter shell. Double-pipe exchangers are generally used for small-capacity applications where the total heat transfer surface area required is 50 m^2 (500 ft^2) or less because it is expensive on a cost per unit surface area basis. Stacks of double-pipe or multitube heat exchangers are also used in some process applications with radial or longitudinal fins. The exchanger with a bundle of U tubes in a pipe (shell) of 150 mm (6 in.) diameter and above uses segmental baffles and is referred to variously as a *hairpin* or *jacketed U-tube exchanger*.

Spiral Tube Heat Exchangers. These consist of one or more spirally wound coils fitted in a shell. Heat transfer rate associated with a spiral tube is higher than that for a straight tube. In addition, a considerable amount of surface can be accommodated in a given space by spiraling. Thermal expansion is no problem, but cleaning is almost impossible.

Plate-Type Heat Exchangers

Plate-type heat exchangers are usually built of thin plates (all prime surface). The plates are either smooth or have some form of corrugation, and they are either flat or wound in an exchanger. Generally, these exchangers cannot accommodate very high pressures,temperatures, or pressure and temperature differences. Plate heat exchangers (PHEs)[{] can be classified as gasketed, welded (one or both fluid passages), or brazed, depending on the leak tightness required. Other plate-type exchangers are spiral plate, lamella, and platecoil exchangers. These are described next.

Gasketed Plate Heat ExchangersBasic Construction. The plate-



and-frame or gasketed plate heat exchanger (PHE) con- sists of a number of thin rectangular metal plates sealed around the edges by gaskets and held together in a frame as shown in Fig. 1.16. The frame usually has a fixed end cover (headpiece) fitted with connecting ports and a movable end cover (pressure plate, follower, or tailpiece). In the frame, the plates are suspended from an upper carrying bar and guided by a bottom carrying bar to ensure proper alignment. For this purpose, each plate is notched at the center of its top and bottom edges. The plate pack with fixed and movable end covers is clamped together by long bolts, thus compressing the gaskets and forming a seal. For later discussion, we designate the resulting length of the plate pack as L_{pack}. The carrying bars are longer than the compressed stack, so that when the movable end cover is removed, plates may be slid along the support bars for inspection and cleaning.ach plate is made by stamping or embossing a corrugated (or wavy) surface pattern on sheet metal. On one side of each plate, special grooves are provided along the per- iphery of the plate and around the ports for a gasket, as indicated by the dark lines in Fig. 1.17. Typical plate geometries (corrugated patterns) are shown in Fig. 1.18, and over 60 different patterns have been developed worldwide. Alternate plates are assembled.

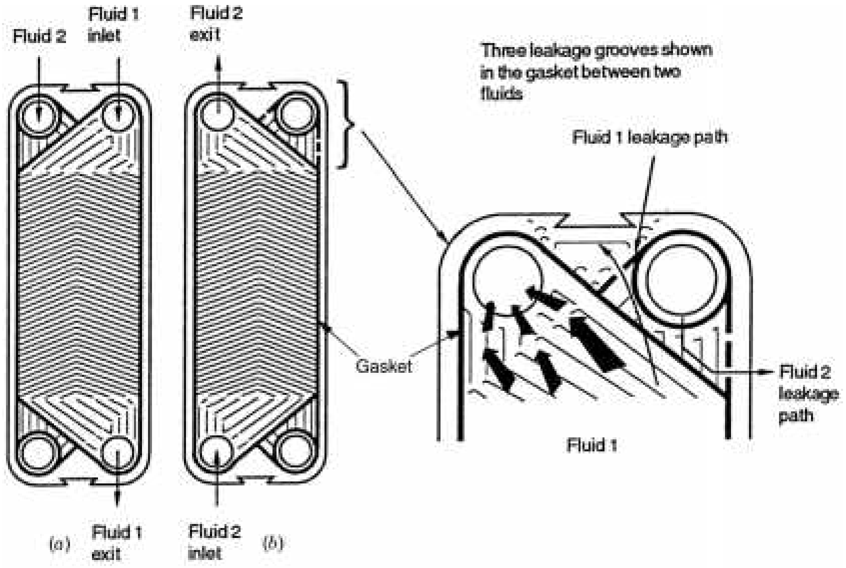


FIGURE 1.17 Plates showing gaskets around the ports (Shah and Focke, 1988).

that the corrugations on successive plates contact or cross each other to provide mechanical support to the plate pack through a large number of contact points. The resulting flow passages are narrow, highly interrupted, and tortuous, and enhance the heat transfer rate and decrease fouling resistance by increasing the shear stress, producing secondary flow, and increasing the level of turbulence. The corrugations also improve the rigidity of the plates and form the desired plate spacing. Plates are designated as *hard* or *soft*, depending on whether they generate a high or low intensity of turbulence.

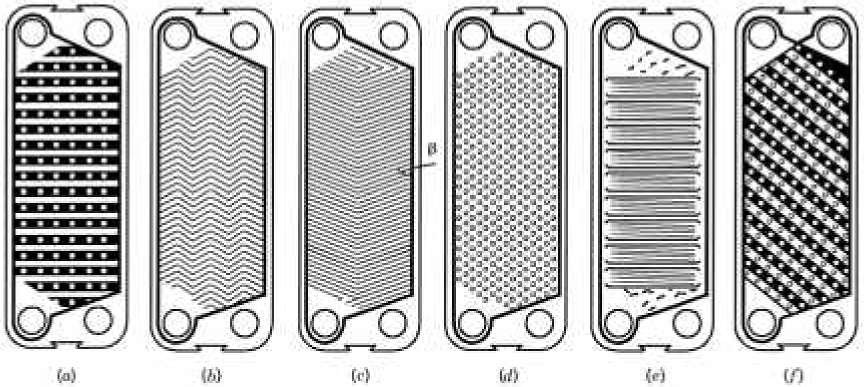


FIGURE 1.18 Plate patterns: (*a*) washboard; (*b*) zigzag; (*c*) chevron or herringbone;

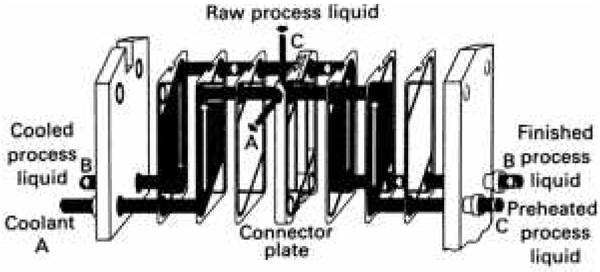
(d) protrusions and depressions; (*e*) washboard with secondary corrugations; (*f*) oblique washboard (Shah and Focke, 1988).

Sealing between the two fluids is accomplished by elastomeric molded gaskets [typically, 5 mm (0.2 in.) thick] that are fitted in peripheral grooves mentioned earlier (dark lines in Fig. 1.17). Gaskets are designed such that they compress about 25% of thickness in a bolted plate exchanger to provide a leaktight joint without distorting the thin plates. In the past, the gaskets were cemented in the grooves, but now, snap-on gaskets, which do not require cementing, are common. Some manufacturers offer special interlocking types to prevent gasket blowout at high pressure differences. Use of a double seal around the port sections, shown in Fig. 1.17, prevents fluid intermixing in the rare event of gasket failure. The interspace between the seals is also vented to the atmosphere to facilitate visual indication of leakage (Fig. 1.17). Typical gasket materials and their range of applications are listed in Table 1.2, with butyl and nitrile rubber being most common. PTFE (polytetrafluoroethylene) is not used because of its viscoelastic properties.

Each plate has four corner ports. In pairs, they provide access to the flow passages on either side of the plate. When the plates are assembled, the corner ports line up to form distribution headers for the two fluids. Inlet and outlet nozzles for the fluids, provided in the end covers, line up with the ports in the plates (distribution headers) and are connected to external piping carrying the two fluids. A fluid enters at a corner of one end of the compressed stack of plates through the inlet nozzle. It passes through alternate channels{ in either series or parallel passages. In one set of channels, the gasket does not surround the inlet port between two plates (see, e.g., Fig. 1.17*a* for the fluid 1 inlet port); fluid enters through that port, flows between plates, and exits through a port at the other end. On the same side of the plates, the other two ports are blocked by a gasket with a double seal, as shown in Fig. 1.17*a*, so that the other fluid (fluid 2 in Fig. 1.17*a*) cannot enter the plate on that side.{ In a 1 pass–1 pass} two-fluid counterflow PHE, the next channel has gaskets covering the ports just opposite the preceding plate (see, e.g., Fig. 1.17*b*, in which now, fluid 2 can flow and fluid 1 cannot flow). Incidentally, each plate has gaskets on only one side, and they sit in grooves on the back side of the neighboring plate. In Fig. 1.16, each fluid makes a single pass through the exchanger because of alternate gasketed and ungasketed ports in each corner opening. The most conventional flow arrangement is 1 pass–1 pass counterflow, with all inlet and outlet connections on the fixed end cover. By blocking flow through some ports with proper gasketing, either one or both fluids could have more than one pass. Also, more than one exchanger can be accommodated in a single frame. In cases with more than two simple 1-pass–1-pass heat exchangers, it is necessary to insert one or more intermediate headers or connector plates in the plate pack at appropriate places (see, e.g., Fig. 1.19). In milk pasteurization applications, there are as many as five exchangers or sections to heat, cool, and regenerate heat between raw milk and pasteurized milk.

Typical plate heat exchanger dimensions and performance parameters are given in Table 1.3. Any metal that can be cold-worked is suitable for PHE applications. The most

660 m^2/m^3 (37 to 200 ft^2/ft^3).



large flow rates but relatively small temperature drops or rises (6T) on each fluid side. Of the two looped patterns, the U-arrangement (Fig. 1.65*a*) is usually preferred over the Z-arrangement (Fig. 1.65*b*) since it allows all connections to be made on the same side of the frame. This eliminates the need for disconnecting pipework for maintenance and cleaning purposes.

A complex flow arrangement results by combining Z-arrangements in series with a generally identical number of thermal plates in each pass. Although only three such flow arrangements are shown in Fig. 1.65*c*–*e*, many other combinations are possible (see, e.g., Table 3.6). Primarily, these arrangements are used when there is a significant difference in the flow rates of the two fluid streams and the corresponding available pressure drops. Generally, the fluid, having very low permissible pressure drop, goes through the single pass; the other fluid goes through multiple passes in order to utilize the available pressure drop and pumping power. Also, if the flow rates are significantly different, the fluid having the lower flow rate goes through n (> 1) passes such that in each pass the heat capacity rates of both fluid streams are about equal. This would produce approximately equal heat transfer coefficients on each fluid side, resulting in a balanced exchanger (hA values approximately the same). Multipass arrangements always have ports located on fixed and movable end plates.

In the series flow arrangement (Fig. 1.65 *f*), each flow passage represents a pass. The series arrangement is used for small fluid flow rates that must undergo a large temperature difference. It is used for very close temperature approaches. Because of many flow reversals, a significant portion of the available pressure drop is wasted in reversals (i.e., the pressure drop in the series flow arrangement is extremely high). The manifold-

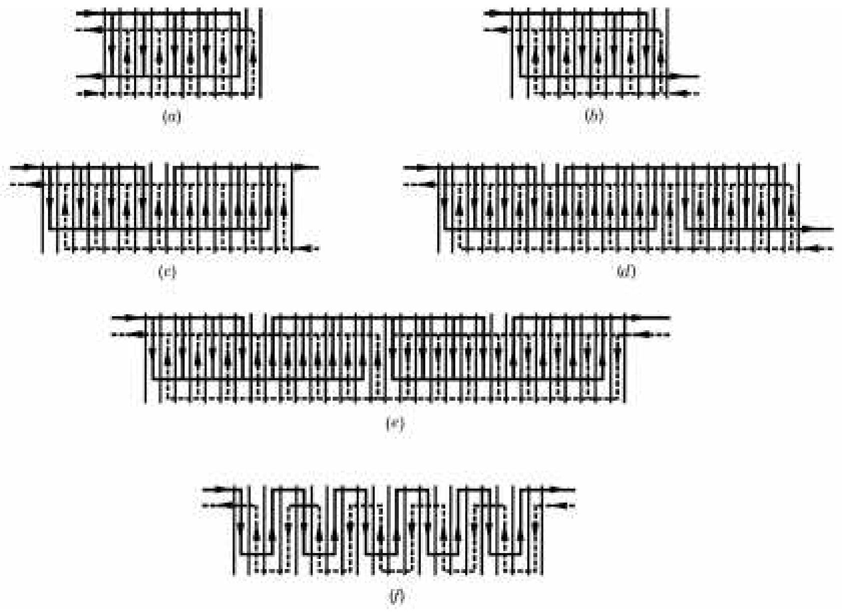


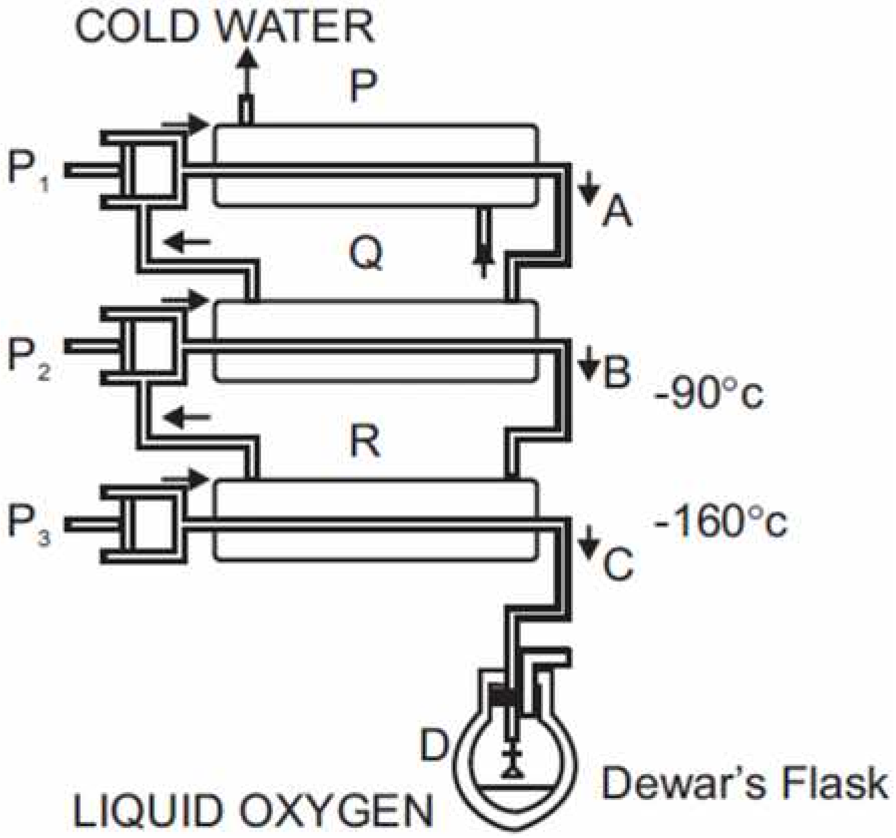
FIGURE 1.65 Single- and multipass plate heat exchanger arrangements. Looped or single-pass arrangements: (*a*) U arrangement; (*b*) Z arrangement. Multipass arrangements: (c) 2 pass – 1 pass,

(*d*) 3 pass – 1 pass, (*e*) 4 pass – 2 pass, and (*f*) series flow.

induced flow maldistribution (see Section 12.1.3) found in the looped pattern is nonexistent in the series flow arrangement. The series flow is not as effective as pure counterflow because each stream flows parallel to the other fluid stream on one side and counter on the other side. In most pasteurizers, a large section is in series flow.

Cascade Process - Liquefaction of oxygen:

The critical temperatures for oxygen -119°C and critical pressure is 49.7 atm. Principle: When a liquid is allowed to evaporate under reduced pressure, it produces high cooling. The apparatus arrangement used in this process is shown in the figure. It consists of three narrow tubes. A,B and C enclosed by three outer jackets P, Q and R respectively. The narrow tubes and the outer jackets are linked with the compression pumps P_1 , P_2 and P_3 as shown in the figure. The methyl chloride gas of critical temperature 145° C is compressed by the pump P_1 through the tube A. It is cooled by the cold water circulating in the jacket P. Here the methyl chloride reaches the temperature lower than its critical temperature. Then it is liquefied under high pressure. The liquid methyl chloride is collected in the jacket Q and evaporates under reduced pressure lowering the temperature to -90° C.



The ethylene gas of critical temperature 10° C is compressed by the pump P_2 through the tube B. It is cooled to -90° C by liquid methyl chloride. Then it is liquefied under high pressure. The liquid ethylene is collected in the jacket R and evaporates under reduced pressure lowering the temperature to -160° C. The oxygen gas of critical temperature - 119° C is compressed to 50 atmospheric pressure by the pump P_3 and passed through the tube C. It is cooled to - 160° C by liquid ethylene in R. Then it is liquefied and the liquid oxygen is collected in the Dewar flask D.

Magnetic refrigeration is a cooling technology based on the **magnetocaloric effect**. This technique can be used to attain extremely low temperatures, as well as the ranges used in common refrigerators. Compared to traditional gas-compression refrigeration, magnetic refrigeration is safer, quieter, more compact, has a higher cooling efficiency, and is more environmentally friendly because it does not use harmful, ozone-depleting coolant gases.[1][2][3]

The effect was first observed by French physicist P. Weiss and Swiss physicist A. Piccard in 1917.[4] The fundamental principle was suggested by P. Debye (1926) and W. Giauque (1927).[5] The first working magnetic refrigerators were constructed by several groups beginning in 1933. Magnetic refrigeration was the first method developed for cooling below about 0.3K

The magnetocaloric effect

The magnetocaloric effect (MCE, from *magnet* and *calorie*) is a magneto-thermodynamic phenomenon in which a temperature change of a suitable material is caused by exposing the material to a changing magnetic field. This is also known by low temperature physicists as *adiabatic demagnetization*. In that part of the refrigeration process, a decrease in the strength of an externally applied magnetic field allows the magnetic domains of a magnetocaloric material to become disoriented from the magnetic field by the agitating action of the thermal energy (phonons) present in the material. If the material is isolated so that no energy is allowed to (re)migrate into the material during this time, (i.e., an adiabatic process) the temperature drops as the domains absorb the thermal energy to perform their reorientation. The randomization of the domains occurs in a similar fashion to the randomization at the curie temperature of aferromagnetic material, except that magnetic dipoles overcome a decreasing external magnetic field while energy remains constant, instead of magnetic domains being disrupted from internal ferromagnetism as energy is added.

One of the most notable examples of the magnetocaloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature increases when it enters certain magnetic fields. When it leaves the magnetic field, the temperature drops. The effect is considerably stronger for the gadolinium alloy Gd 2).Praseodymium alloyedwith nickel (PrNi) has such a strong magnetocaloric effect that it has allowed scientists to approach to within one milliKelvin, one thousandth of a degree of absolute zero.[7]

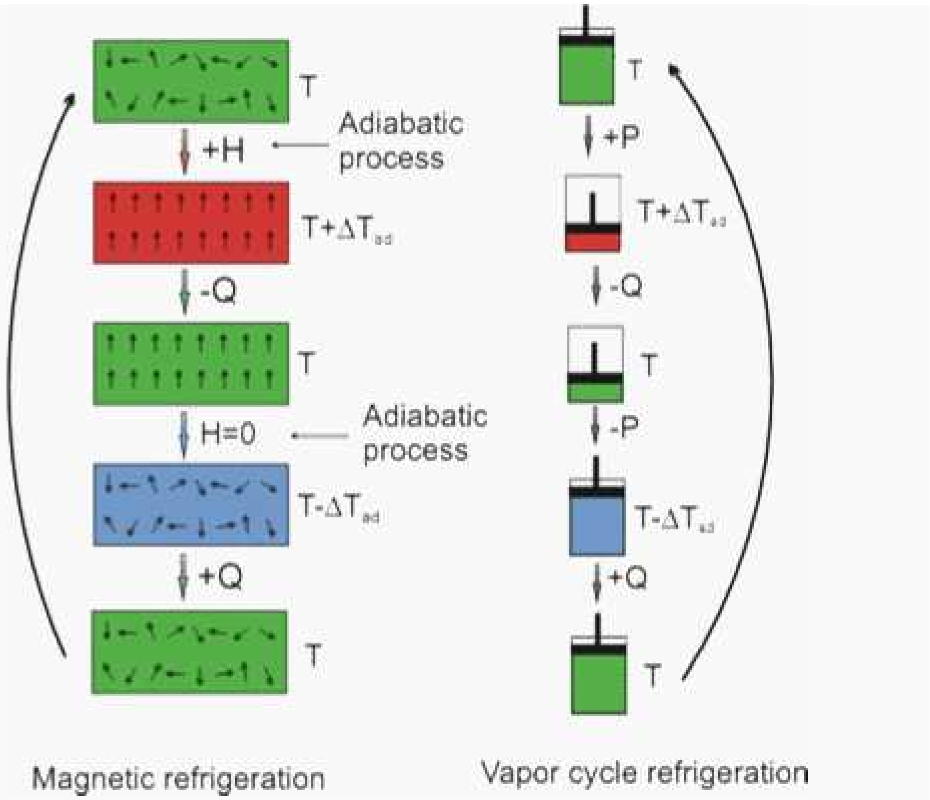
Equation

The magnetocaloric effect can be quantified with the equation below: where T is the temperature, H is the applied magnetic field, C is the heat capacity of the working magnet (refrigerant) and M is the magnetization of the refrigerant.

From the equation we can see that magnetocaloric effect can be enhanced by:

- applying a large field
- using a magnet with a small heat capacity
- using a magnet with a large change in magnetization vs. temperature, at a constant magnetic field

Thermodynamic cycle[edit]



Analogy between magnetic refrigeration and vapor cycle or conventional refrigeration. H = externally applied magnetic field; Q = heat quantity; P = pressure; ΔT_{ad} = adiabatic temperature variation

The cycle is performed as a refrigeration cycle that is analogous to the Carnot refrigeration cycle, but with increases and decreases in magnetic field strength instead of increases and decreases in pressure. It can be described at a starting point whereby the chosen working substance is introduced into a magnetic field, i.e., the magnetic flux density is increased. The working material is the refrigerant, and starts in thermal equilibrium with the refrigerated environment.

- *Adiabatic magnetization:* A magnetocaloric substance is placed in an insulated environment. The increasing external magnetic field (+H) causes the magnetic dipoles of the atoms to align, thereby decreasing the material's magnetic entropy and heat capacity. Since overall energy is not lost (yet) and therefore total entropy is not reduced (according to thermodynamic laws), the net result is that the substance is heated ($T + \Delta T_{ad}$).

- *Isomagnetic enthalpic transfer:* This added heat can then be removed (-Q) by a fluid or gas — gaseous or liquid helium, for example. The magnetic field is held constant to prevent the dipoles from reabsorbing the heat. Once sufficiently cooled, the magnetocaloric substance and the coolant are separated (H=0).
- *Adiabatic demagnetization:* The substance is returned to another adiabatic (insulated) condition so the total entropy remains constant. However, this time the magnetic field is decreased, the thermal energy causes the magnetic moments to overcome the field, and thus the sample cools, i.e., an adiabatic temperature change. Energy (and entropy) transfers from thermal entropy to magnetic entropy, measuring the disorder of the magnetic dipoles.[8]
- *Isomagnetic entropic transfer:* The magnetic field is held constant to prevent the material from reheating. The material is placed in thermal contact with the environment to be refrigerated. Because the working material is cooler than the refrigerated environment (by design), heat energy migrates into the working material (+Q).

Once the refrigerant and refrigerated environment are in thermal equilibrium, the cycle can restart.

Applied technique

The basic operating principle of an adiabatic demagnetization refrigerator (ADR) is the use of a strong magnetic field to control the entropy of a sample of material, often called the "refrigerant". Magnetic field constrains the orientation of magnetic dipoles in the refrigerant. The stronger the magnetic field, the more aligned the dipoles are, corresponding to lower entropy and heat capacitybecause the material has (effectively) lost some of its internal degrees of freedom. If the refrigerant is kept at a constant temperature through thermal contact with a heat sink (usually liquid helium) while the magnetic field is switched on, the refrigerant must lose some energy because it is equilibrated with the heat sink. When the magnetic field is subsequently switched off, the heat capacity of the refrigerant rises again because the degrees of freedom associated with orientation of the dipoles are once again liberated, pulling their share of equipartitioned energy from the motion of the molecules, thereby lowering the overall temperature of a system with decreased energy. Since the system is now insulated when the magnetic field is switched off, the process is adiabatic, i.e., the system can no longer exchange energy with its surroundings (the heat sink), and its temperature decreases below its initial value, that of the heat sink.

The operation of a standard ADR proceeds roughly as follows. First, a strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. The heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and the magnetic field is switched off, increasing the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of the heat sink. In practice, the magnetic field is decreased slowly in order to provide continuous cooling and keep the sample at an approximately constant low temperature. Once the field falls to zero or to some low limiting value determined by the properties of the refrigerant, the cooling power of the ADR vanishes, and heat leaks will cause the refrigerant to warm up.

Working materials

The magnetocaloric effect (MCE) is an intrinsic property of a magnetic solid. This thermal response of a solid to the application or removal of magnetic fields is maximized when the solid is near its magnetic ordering temperature. Thus, the materials considered for magnetic refrigeration devices should be magnetic materials with a magnetic phase transition temperature near the temperature region of interest.[9] For refrigerators that could be used in the home, this temperature is room temperature. The temperature change can be further increased when the order-parameter of the phase transition changes strongly within the temperature range of interest.[1]

The magnitudes of the magnetic entropy and the adiabatic temperature changes are strongly dependent upon the magnetic ordering process. The magnitude is generally small in antiferromagnets, ferrimagnets and spin glass systems but can be much larger for ferromagnets that undergo a magnetic phase transition. First order phase transitions are characterized by a discontinuity in the magnetization changes with temperature, resulting in a latent heat.[9] Second order phase transitions do not have this latent heat associated with the phase transition that was about 50% larger than that reported for Gd metal, which had the largest known magnetic entropy change at the time.[10] This giant magnetocaloric effect (GMCE) occurred at 270K, which is lower than that of Gd (294K).[3] Since the MCE occurs below room temperature these materials would not be suitable for refrigerators operating at room temperature.[11] Since then other alloys have also demonstrated the giant magnetocaloric effect. These include Gadolinium and its alloys undergo second-order phase transitions that have no magnetic or thermal hysteresis. However, the use of rare earth elements makes these materials very expensive.

Heusler alloys are also promising candidates for magnetic cooling applications because they have Curie temperatures near room temperature and, depending on composition, can have martensitic phase transformations near room temperature. These materials exhibit the magnetic shape memory effect and can also be used as actuators, energy harvesting devices, and sensors. When the martensitic transformation temperature and the Curie temperature are the same (based on composition) the magnitude of the magnetic entropy change is the largest. In February 2014, GE announced the development of a functional Ni-Mn-based magnetic refrigerator.

The development of this technology is very material-dependent and will likely not replace vapor-compression refrigeration without significantly improved materials that are cheap, abundant, and exhibit much larger magnetocaloric effects over a larger range of temperatures. Such materials need to show significant temperature changes under a field of two tesla or less, so that permanent magnets can be used for the production of the magnetic field.

Paramagnetic salts

The original proposed refrigerant was a paramagnetic salt, such as cerium magnesium nitrate. The active magnetic dipoles in this case are those of the electron shells of the paramagnetic atoms.

Eventually paramagnetic salts become either diamagnetic or ferromagnetic, limiting the lowest temperature that can be reached using this method.

Nuclear demagnetization

One variant of adiabatic demagnetization that continues to find substantial research application is nuclear demagnetization refrigeration (NDR). NDR follows the same principles, but in this case the cooling power arises from the magnetic dipoles of the nucleiof the refrigerant atoms, rather than their electron configurations. Since these dipoles are of much smaller magnitude, they are less prone to self-alignment and have lower intrinsic minimum fields. This allows NDR to cool the nuclear spin system to very low temperatures, often 1 µK or below. Unfortunately, the small magnitudes of nuclear magnetic dipoles also makes them less inclined to align to external fields. Magnetic fields of 3 teslas or greater are often needed for the initial magnetization step of NDR.

In NDR systems, the initial heat sink must sit at very low temperatures (10–100 mK). This precooling is often provided by the mixing chamber of a dilution refrigerator or a paramagnetic salt.

Commercial development

Research and a demonstration proof of concept in 2001 succeeded in applying commercial-grade materials and permanent magnets at room temperatures to construct a magnetocaloric refrigerator

On August 20, 2007, the Risø National Laboratory (Denmark) at the Technical University of Denmark, claimed to have reached a milestone in their magnetic cooling research when they reported a temperature span of 8.7 K. They hoped to introduce the first commercial applications of the technology by 2010.

As of 2013 this technology had proven commercially viable only for ultra-low temperature cryogenic applications available for decades. Magnetocaloric refrigeration systems are composed of pumps, motors, secondary fluids, heat exchangers of different types, magnets and magnetic materials. These processes are greatly affected by irreversibilities and should be adequately considered. At year-end, Cooltech Applications announced that its first commercial refrigeration equipment would enter the market in 2014. At the 2015Consumer Electronics Show in Las Vegas, a consortium of Haier, Astronautics Corporation of America and BASF presented the first cooling appliance.BASF claim of their technology a 35% improvement over using compressors

Current and future uses

Thermal and magnetic hysteresis problems remain to be solved for first-order phase transition materials that exhibit the GMCE.

One potential application is in spacecraft.

Vapor-compression refrigeration units typically achieve performance coefficients of 60% of that of a theoretical ideal Carnot cycle, much higher than current MR technology. Small domestic refrigerators are however much less efficient.

In 2014 giant anisotropic behaviour of the magnetocaloric effect was found in HoMn at 10 K. The anisotropy of the magnetic entropy change gives rise to a large rotating MCE offering the possibility to build simplified, compact, and efficient magnetic cooling systems by rotating it in a constant magnetic field.

History

The effect was discovered using nickel in 1917 by French physicist Pierre Weiss and Auguste Piccard. Originally, the cooling effect was less than 0.5 K/T.

Major advances first appeared in the late 1920s when cooling via adiabatic demagnetization was independently proposed by Peter Debye in 1926 and chemistry Nobel Laureate William F. Giauque in 1927.

It was first demonstrated experimentally by Giauque and his colleague D. P. MacDougall in 1933 for cryogenic purposes when they reached 0.25 K.

In 1997, the first near room-temperature proof of concept magnetic refrigerator was demonstrated by Karl A. Gschneidner, Jr. by theIowa State University at Ames Laboratory. This event attracted interest from scientists and companies worldwide who started developing new kinds of room temperature materials and magnetic refrigerator designs.

A major breakthrough came 2002 when a group at the University of Amsterdam demonstrated the giant magnetocaloric effect in MnFe(P,As) alloys that are based on abundant materials.

Refrigerators based on the magnetocaloric effect have been demonstrated in laboratories, using magnetic fields starting at 0.6 T up to 10 T. Magnetic fields above 2 T are difficult to produce with permanent magnets and are produced by a superconducting magnet (1 T is about 20,000 times the Earth's magnetic field).

UNIT III

There are essentially only four physical processes that are used to produce cryogenic temperatures and environments: **heat** conduction, evaporative cooling, cooling by rapid expansion (the Joule-Thompson effect), and adiabatic demagnetization. The first two are well known in terms of everyday experience. The third is less well known but is commonly used in ordinary refrigeration and air conditioning units, as well as cryogenic applications. The fourth process is used primarily in cryogenic applications and provides a means of approaching absolute zero.Heat conduction is familiar to everyone. When two bodies are in contact, heat flows from the higher temperature body to a lower temperature body. Conduction can occur between any and all forms of **matter**, whether gas, liquid, or solid, and is essential in the production of cryogenic temperatures and environments. For example, samples may be cooled to cryogenic temperatures by immersing them directly in a cryogenic liquid or by placing them in an atmosphere cooled by cryogenic refrigeration. In either case, the sample cools by conduction of heat to its colder surroundings.

The second physical process with cryogenic applications is evaporative cooling, which occurs because atoms or molecules have less energy when they are in the liquid state than when they are in the vapor, or gaseous, state. When a liquid evaporates, atoms or molecules at the surface acquire enough energy from the surrounding liquid to enter the gaseous state. The remaining liquid has relatively less energy, so its temperature drops. Thus, the temperature of a liquid can be lowered by encouraging the process of **evaporation**. The process is used in cryogenics to reduce the temperature of liquids by continuously pumping away the atoms or molecules as they leave the liquid, allowing the evaporation process to cool the remaining liquid to the desired temperature. Once the desired temperature is reached, pumping continues at a reduced level in order to maintain the lower temperature. This method can be used to reduce the temperature of any liquid. For example, it can be used to reduce the temperature of liquid nitrogen to its freezing point, or to lower the temperature of liquid helium to approximately 1K (-458°F [-272°C]).

The third process makes use of the Joule-Thompson effect, and provides a method for cooling gases. The Joule-Thompson effect involves cooling a pressurized gas by rapidly expanding its **volume**, or, equivalently, creating a sudden drop in **pressure**. The effect was discovered in 1852 by James P. Joule and William Thompson, and was crucial to the successful liquefaction of hydrogen and helium.

ABSTRACT: The sub-cooling of cryogenic propellants contained in tanks is an important and effective method for bringing down the lift-off mass of launch vehicle and thus the performance of the rocket engine is greatly improved. This paper presents the technical and experimental studies conducted on cryogenic liquids such as Liquid Oxygen, Liquid Nitrogen, and Liquid Hydrogen using helium bubbling method. The influence of cooled Helium on the degree of sub-cooling and the variation in flow rate of Helium gas admitted are discussed. The experimental and theoretical studies indicate that the sub-cooling technique using helium injection is a very simple method and can be very well adopted in propellant tanks used for ground and launch vehicle applications.

1.INTRODUCTION: The cryogenic propellants namely Liquid Hydrogen and Liquid Oxygen are filled in the propellant tanks. The mass of tank shall be as less as possible in order to limit the total lift-off mass of launch vehicle to a minimum value. This keeps the specific impulse of the cryogenic Engine to a higher value. The helium gas injected inside the propellants contained in the tank, reduces the temperature of the propellant. The density of the propellants is increased which ultimately reduces the volume of tank. Yesteryears, several experiments are conducted on the helium injection cooling. Larsen and Clarke have achieved best results of the experiments by injecting helium gas inside the oxygen tanks. Schmidt has achieved sub cooling of Liquid Hydrogen by similar technique of helium injection[2]. Cleary et al have sub cooled liquid oxygen by injected helium with various injection flow rates[3]. The basic principle behind sub cooling of cryogenic propellants is diffusion mass transfer. When a helium bubble passes through Liquid Nitrogen, the liquid Nitrogen surrounding the bubble will spontaneously evaporate and diffuses into the bubble due to diffusion mass transfer. This mass diffusion occurs due to pressure differential across the helium bubble. The evaporation of liquid takes away the latent heat from the bulk liquid, there by the temperature of bulk liquid Nitrogen is reduced. In the launch vehicle, the sub cooling of propellants can be done either prior to prepressurization or after pre-pressurization of tanks. If it is done before pre-pressurization, the warm up of liquid takes place during pre-pressurization period. Hence it is preferred to carry out sub-cooling after pre-pressurization. The experimental studies have been carried out on Liquid Nitrogen (LN2), Liquid oxygen (LOX) and Liquid Hydrogen (LH2) to predict the influence of different factors like helium injection temperature, helium injection flow rate. The numerical and experimental studies conducted to analyse the rate of sub cooling and the behavior of sub cooling shows that the rate of sub cooling increases with decrease in injection helium temperature and increase in helium flow rate. Also the helium injection pattern play a major role in achieving higher sub-cooling rate. Circumferential injection yields better results than axial injection. In the paper, analytical and experimental methods have been used to study the sub cooling behavior of Liquid Oxygen, Liquid Nitrogen and Liquid Hydrogen which are normally being used as cryogenic liquids in ground and launch vehicle applications.

2. MATHEMATICAL MODEL: The schematic diagram of helium injection cooling system is shown in fig 1. The very basic principle of sub cooling of cryogenic liquids by helium injection is diffusional mass transfer. Since the injected helium gas is pure, the difference in the partial pressure of Nitrogen in helium bubble and the vapour pressure of liquid Nitrogen causes diffusional mass transfer of Nitrogen vapour into the helium bubble. The diffusion of Nitrogen into the helium bubbles continues until thermodynamic phase equilibrium is reached. The diffusion process brings the cooling of bulk liquid caused by the vaporization of surrounding liquid. The phenomenon of diffusion taking place during helium injection is explained in fig 2 In order to clearly define the partial pressure at the interface surface, imaginary surfaces ‘a’ and ‘b’ are defined. As helium bubble raises just above the injection point and when it travels liquid Nitrogen gets evaporated into helium gas stream. At ‘a’ surface mole fraction of Nitrogen XN2,a while at ‘b’ surface, gas phase quantity of Nitrogen is present. When helium gas is injected into liquid Nitrogen, the partial pressure of Nitrogen vapour at the ‘b’ surface would differ significantly from that of bulk gas which causes diffusional mass transfer according to Fick’s law of diffusion. Performance Studies on Sub-cooling of Cryogenic Liquids Used for Rocket Engine T.Sinto, MurugadosssUg student

St.Anne’s college of engg & tech Department of mechanical Interface of LN2 & GHe The total vaporization rate of liquid Nitrogen m LN2 is expressed as the addition of two forms of vaporization taking place. One due to heat transfer between gas bubble and liquid Nitrogen m LN2,⍰ and the other due to pure diffusion m LN2$diff$ as given in Eqn(1). The amount of vaporization due to the heat transfer from the helium bubble to Liquid Nitrogen is normally negligible. The rate at which the bulk liquid Nitrogen energy change is given in Eqn(2) where Q gi is the heat transfer rate from the gas bubble to the liquid Nitrogen interface, m LN2⍰fg is the latent heat transfer rate by phase change of liquid Nitrogen and Q amb is the heat transfer rate into liquid Nitrogen from ambient. The liquid Nitrogen vaporization due to heat transfer m LOX,⍰ can be related to Q gi is shown in Eqn(3). Substituting Eqn(1) & (3) into the energy balance equation, Eqn(2) the vaporization due to heat transfer m LOX,⍰ is now cancelled. Therefore the vaporization due to diffusion m LO, is the main drive for cooling. Liquid Nitrogen sub cooling by helium injection can be characterised by diffusion driven evaporative cooling. m LN2 = m LN2,⍰+m LN2,$diff$ (1) Where m LN2 is the mass flow rate of LN 2 , m LN2,□ is the evaporation rate of LN 2 due to heat flux and m LN2,$diff$ is the evaporation rate of LN 2 due to diffusion. m LN2$cpLN$2$dTLN$2dt = Q gi−m LN2⍰fg+Q amb (2) Where $cpLN$2 is the specific heat of LN 2 , TLN2 is the temperature of LN 2 , t is the time, ⍰fg is the late heat of evaporation, gi is the heat transfer rate from the gas bubble to the LN 2 and amb is the heat transfer rate into liquid Nitrogen from ambient. Q gi = m LN2⍰fg (3) here hfg is the latent heat transfer rate by phase change of LN 2 . In the theoretical studies conducted three limiting cases can be arrived in terms of heat and mass transfer aspects. First case is instantaneous heat and mass transfer in which the bulk liquid and gas are always in thermodynamic phase equilibrium state. This approach gives maximum sub cooling rate and the second case is finite heat transfer and instantaneous mass transfer. In this case the temperature of bulk liquid and gas are different due to finite heat transfer. However due to the assumption of infinite mass transfer rate, the partial pressure of the itrogen vapour at the ‘b’ surface remains equal to that of the bulk gas. The third case is finite heat and mass transfer. Though the finite heat and mass transfer is the most realistic description of the phenomenon, the finite heat transfer and instantaneous diffusional mass transfer model gives satisfactory agreement with experimental data for small bubbles and gas with high diffusion coefficient such as helium. In the case of finite heat transfer and instantaneous diffusional mass transfer model, liquid Nitrogen evaporation rate $m\ LN2$ is calculated with the prescribed heat transfer coefficients (gas to interface $?gi$, liquid to interface $?gi$, net bubble surface Area (As) and interface temperature (Ti) for a given system as given in eqn(4). $m\ LN2 = As\ ?gi\ Tg- Ti -?(Ti- TLN2)$ hfg Liquid Nitrogen has finite vaporization rate depending on the net bubble surface area and the relevant heat transfer coefficients. Since thermodynamic phase equilibrium in bubble requires the partial pressure of Nitrogen in the bubble to be equal to the saturated vapour pressure of liquid Nitrogen at particular temperature of liquid the difference between the partial pressure of the Nitrogen in the bubble and the vapour pressure of the liquid nitrogen propels the generated vapour into the bubble without degradation. The transferred Nitrogen vapour mixes with helium gas instantaneously. 3.

EXPERIMENTAL SETUP: The schematic diagram of the experimental setup is given in fig 3. It consists of a Super Insulated Dewar of 1000 liters capacity in which the test liquid to be sub cooled is filled. The Dewar has an inner vessel of diameter 900 mm and shell height 1030 mm welded with semi-elliptical dishes at its top and bottom. The vacuum level of Super Insulated Dewar is maintained at 1x10-4 mbar. Axial temperature LN2 GHe distribution is measured with 4 numbers of RTD type temperature sensors. The Dewar has provision for filling the cryogenic liquids inside the tank, a vent circuit with electro pneumatic valve for remotely venting the vapours, pressurization circuit with GN2/GHe for pressurization of Dewar and helium injection circuit for injecting helium inside the Dewar. Helium gas at constant volume flow rate was injected through submerged nozzles (4 nos). Each nozzle has 10 holes of 2mm diameter each. For varying the helium gas flow rate the upstream helium supply pressure was varied. The volume flow rate of helium supply gas is measured by differential pressure transmitter. The heat–inleak of Dewar was calculated from the measured Liquid Nitrogen temperature for ambient condition where Liquid Nitrogen exists at saturated condition (77.36 K at 1.0 bar,a) and the heat in leak value was 220W.

4.EXPERIMENTAL PROCEDURE: Liquid Nitrogen is filled inside the Dewar by operating the Electro pneumatic valve. During filling process, the vent valve is kept open until the filling is completed upto 90% level of tank. Measurement of pressure is done by a pressure transducer. Before starting the experiments, the heat in leak of the tank is calculated from the increase in LN2 temperature and the resulting pressure increment over time. As seen from fig.5, larger helium injection rate brings out more amount of cooling. The reason is larger helium injection increases the helium gas fraction in the bubbles and accordingly lowers the GO2 fraction which increases the Liquid side heat transfer and net cooling. In the case 25 g/s injection rate the measured LOX temperature reaches as low as 75K at 4000 sec. The theoretical results and experimental results almost matches well. The curve with diamond marks in fig 6 is the case of finite heat transfer and instantaneous mass transfer. The curve with triangle marks is the case of instantaneous heat and mass transfer for comparison. This curve indicates the maximum sub cooling of Liquid Oxygen. The case of finite heat transfer and instantaneous mass transfer shows much better agreement with experimental data. The finite heat transfer model looks very useful for helium injection application.

5.PARAMETERS FOR ANALYSIS AND EXPERIMENTS: The difference in the Nitrogen partial pressure in helium bubble P GN2,b and the vapour pressure of Liquid Nitrogen Psat(TLN2) is the main source of diffusion driven evaporative cooling. Two methods are conceived to increase the difference and the net diffusion-driven evaporation. First method is to increase the vapour pressure. The maximum vapour pressure that Liquid Nitrogen can attain is the saturation vapour pressure corresponding to the saturation temperature of Liquid Nitrogen. Since the vapour increases with Liquid Nitrogen temperature, saturated Liquid nitrogen is more susceptible to helium injection cooling than sub-cooled one. Second method is to decrease the partial pressure of nitrogen in helium bubble. To decrease the partial pressure of nitrogen, high volume rate of helium is preferred. However, if the injected helium temperature is higher than Liquid Nitrogen, the high mass flow accompanies high energy influx which vaporizes Liquid Nitrogen by heat transfer between the warm helium and Liquid Nitrogen. This heat induced vaporization subsequently increases gaseous nitrogen partial pressure in helium bubbles. We have to consider, therefore the net effect of helium flow rate. To effectively lower the partial pressure of nitrogen in helium bubble at high helium flow rate, low temperature helium can be utilized. Theoretically if the injected helium has the same temperature with the liquid nitrogen, the vaporization due to heat transfer is zero and all the injected helium is used to lower the gaseous nitrogen partial pressure in bubbles. The variation range of main parameters for experiments and analysis is given in Table- 1, 2 & 3. No Parameter Paramete r Reference variation 1 Pressure of Dewar, Psys in bar,a 1.0 2 Helium injection flow rate (g/s) 15, 20, 25 3 Injection helium temperature THe, 85, 150, 295 To obtain 85K, 150K helium (K) is cooled in LN2 bath \ No Parameter Paramet er Reference variation 1 Pressure of Dewar, Psys in bar,a 1.0 2 Helium injection flow rate (g/s) 15, 20, 25 3 Injection helium temperature THe, 85, 150, 295 To obtain 85K, 150K helium (K) is cooled in LN2 bath No Parameter Paramete r Reference variation 1 Pressure of Dewar, Psys in bar,a 1.0 2 Helium injection flow rate (g/s) 30, 35, 40 3 Injection helium temperature THe 85, 150, 295 To obtain 85K, 150K helium (K) is cooled in LN2 bath

CONCLUSION: A very detailed Study has been carried out analytically and experimentally to find the effect of cooling Liquid Nitrogen, Liquid Oxygen and Liquid Hydrogen at atmospheric condition by varying the inlet temperature and injection flow rate of helium gas. In the case of Liquid Nitrogen and Liquid Oxygen as the helium supply temperature is lowered the sub cooling rate increases, where as in the case of Liquid Hydrogen it is unaffected. It is noticeable that the vaporization due to the vapour side heat transfer and Liquid side heat transfer is more or less same. Therefore for Liquid Hydrogen the cooling is unaffected. Initially saturated Liquid Nitrogen sub cooling is easily achieved regardless of injected helium temperature.

The finite heat transfer and instantaneous diffusion mass transfer model is applied for the analysis. The experimental results and theoretical model results are closely matching. Thus lowering injected helium temperature is an effective means for lowering gaseous nitrogen partial pressure in helium bubble. Also the nozzle Patten plays a major role in cooling rate. It is noticeable that instead of having the nozzles along the axis if it is placed radically it gives a stirring effect to the bulk liquid and more surface area contact takes places. This increases the cooling rate.

UNIT IV

Today, there is a big interest in using renewable vehicle fuels and one option is to use biogas. Biogas is produced when organic material is decomposed under anaerobic conditions and in this report biogas is referred to as landfill gas and digester gas. The main constituents are methane, CH4, and carbon dioxide, CO2, usually with a higher part of CH4 (around 60-70 %). To be able to use the raw biogas as a vehicle fuel it must be purified and upgraded, which means that impurities and CO2 respectively, are removed. There are a number of available upgrading technologies and the two most commonly used in Sweden are water scrubbing and PSA. The produced biogas can be injected into the gas grid or compressed to around 200 bar for use as vehicle fuel. However, in Sweden the gas grid is limited to the southwest coast and the biogas production plants are often situated far away from the end users. Therefore, compressed biogas (CBG) is distributed on mobile CBG storages, which is a very inefficient way to deliver gas since a huge share of steel is transported in comparison to the amount of gas. One solution to this problem is to use cryogenic technology, meaning that low-temperature processes (<-150 °C) and equipment are used, to produce liquid biogas, LBG. LBG is more than 600 times space efficient compared to biogas at atmospheric pressure (around 3 times more space efficient compared to CBG). There are two main ways to produce LBG and these are cryogenic upgrading technology and conventional upgrading technology connected with a small-scale liquefaction plant. In the cryogenic upgrading technology differences in condensation temperatures are used to separate impurities and CO2 from CH4. Using this technology also results in a clean liquid CO2 product, LCO2, that could be used in external applications. In the following text the different technical solutions for the production of LBG will be presented and analysed. Focus lies upon energy consumption but other important factors are environmental aspects and technical solutions. The analysis is based on energy balances and the primary energy concept is used to enable comparisons between different energy carriers. Included in the energy balances are the recovery of waste heat, CH4 losses and the use of LCO2 in external processes. 1.1 Aim The aim of this master thesis is to evaluate the energy balances for cryogenic and commercial upgrading technologies for the production of LBG. The evaluations are made in a system perspective and included in the system are purification, upgrading and liquefaction of biogas, distribution and fuelling. 1.2 Method Cryogenic technology and the production of LBG is not yet an everyday occurrence but the technology is on the way to commercialisation. Since there is little experience of the technology there is not much written about it. There are however three reports from the Swedish Gas Centre (SGC) that deal with cryogenic technology and LNG as an option for Sweden. These reports have been a starting point in the work with this thesis, but all three have a more economical approach. 4 The early work was focused on finding relevant suppliers of cryogenic technology, working in the biogas field. In this search the SGC reports were of great use. The work was then transferred to data collection from the suppliers found in the first step. The data presented in this report thus mainly originates from these suppliers. The data concerning the biogas introduction and more conventional technologies comes from different reports from acknowledged Swedish and International organisations, institutes and companies. To facilitate the reading of the report abbreviations for commonly used expression are used throughout the text. The explanations of these abbreviations can be found after the summary. 1.3 Delimitations The analyses are made in a Swedish perspective. In Sweden the interest in using biogas as a renewable vehicle fuel is growing and because of the limited gas network the production of LBG could be a good alternative to make biogas available for more end users. The results from analyses would differ if it were based on another country, with for example a wellextended gas grid or were biogas mainly is used for electricity generation. The costs for different technologies are not included in the report. This was meant to be included from the beginning but since only a few suppliers were willing to hand over this kind of information, it was excluded. The environmental aspects of using biogas as vehicle fuel, compared to fossil fuel, is not included in the report. 1.4 Method criticism The data presented in this report is mainly based on suppliers, which sometimes makes it less reliable. No study visits have been possible since the identified commercial and pilot LBG production plants are situated outside Sweden. Study visits probably would have raised the reliability in supplier’s data and the understanding in the technological issues. 1.5 Content The report begins with an introduction to biogas (chapter 2) followed by a description of the upgrading technologies in use today (chapter 3). After these two background chapters the report will focus on liquid biogas, LBG, in three chapters regarding production, distribution and fuelling (chapter 4, 5, and 6). Then follows a short chapter were commercial LBG production plants are presented (chapter 7) followed by a chapter that treats the use of liquid CO2, LCO2 (chapter 8). This leads up to chapter 9; Analysis and Energy Balances. In this chapter the different technical solutions are analysed and energy balances are evaluated. The report is then completed with discussions and conclusions in chapter 10. Three appendices are attached to the report and these concerns the cryogenic upgrading technologies (appendix 1), a technology using membranes for the production of LBG (appendix 2) and original data, data conversions and calculations (appendix 3). 5 2 Introduction to biogas Biogas is the name of the gas produced when organic material is decomposed under anaerobic conditions. These processes take place naturally when the amount of organic material is sufficient and where oxygen does not enter, for example in wetlands. (Energimyndigheten, 2008) In this report biogas is referred to as digester gas, gas produced under controlled conditions in digester chambers, and landfill gas, gas spontaneously produced in landfills. Digestion processes has been used since 1960 but then the main goal was to stabilize and thicken sewage sludge at sewage treatment plants and to treat polluted organic process wastewater. After the energy crisis in the 1970s, the interest in recovering energy from renewable sources grew and the biogas production was expanded to include industrial waste and manure. In the beginning of the 1990s the first co-digestion plants for the joint digestion of different substrates, like organic farm- and household waste, were built. Landfill gas has been collected since the 1980s. At first it was collected because of safety reasons, but today the reduction of greenhouse gas emissions is an important argument. (SBGF et al, 2008) The main constituents of biogas are methane, CH4, and carbon dioxide, CO2, with small amounts of hydrogen sulphide, H2S and water vapor. The gas can be used directly for production of heat and/or electricity or it can be further processed to natural gas quality for use as vehicle fuel or for injection into the gas grid. (Persson & Wellinger, 2006) 2.1 Biogas process As mentioned above biogas is produced when microorganisms, in an anaerobic environment, decompose organic material. The energy-carrying compound is CH4 and a higher CH4 concentration means higher energy content. There are two sources of biogas and these are landfills and digester chambers. In landfills, gas is produced spontaneously as long as there is decomposition of organic material. Since the process is not controlled or optimized, it results in a lower CH4 content, around 50 %, in comparison to digester gas. The landfill gas is collected with permeable tubes by applying a slight under-pressure. Since Jan 2005 it is prohibited to landfill organic material, which will result in a decreasing biogas production. However, the decomposition process in a landfill is slow, so they will probably give gas for another 30 – 50 years. (SBGF et al, 2008) Digester gas is produced under controlled situations in a digester chamber. Most of the gas is produced in sewage sludge treatment plants, but the production from co-digestion is steadily rising. In co-digestion plant different substrates like manure, slaughterhouse and industrial waste and sorted food waste from food industry, restaurants and households are digested together. (Energimyndigheten, 2008) The digester gas is produced in three main steps, by a number of different microorganisms: 1. Hydrolysis In the hydrolysis, microorganisms use enzymes to break down complex organic material to more simple compounds like sugars and amino acids. 2. Fermentation Through fermentation organisms form intermediate products like fatty acids, alcohols and hydrogen. 6 3. Methane Production In this step a unique group of microorganisms, called methanogens, produce methane from acetic acid. These organisms have very specific requirements on their environment. They are sensitive to temperature fluctuations and pH, they grow slowly and they die when in contact with oxygen. (SBGF et al, 2008) The duration in the digester chamber is between 15-30 days, depending on substrate and temperature (Energimyndigheten, 2008). The process is mesophilic (~37 °C) or thermophilic (50-55 °C), which is the temperature at which the CH4 producing bacteria have growth rate peaks. This means that heat must be added to the process. A stirring device helps to keep a steady temperature, and at the same time it gives better contact between microorganisms and substrate and prevents stratification. (SBGF et al, 2008) The gas is taken out from the top of the tank and the CH4 content varies between 60-70 %, depending on substrate. After digestion, there is a rest of organic material, called digestate, which is pumped out to a storage tank. Depending on the substrate origin and pretreatment, this digestate can function as an excellent fertilizer. Further, it could be certified and used as an organic fertilizer. (SBGF et al, 2008) A flow diagram over a digestion process can be seen in Figure 1. Figure 1 Flow diagram over the digestion process. (SGC, 2008a) 2.1.1 Pre-treatment If the substrate has an animalistic origin the material must be hygienized to eliminate pathogenic bacteria. The material is heated to 70°C for at least one hour before it is injected into the digester chamber. (SBGF et al, 2008) Some substrates, like food waste from households and restaurants, needs to be sorted and grinded into a fine homogenous material, called slurry, before it is injected into the gas chamber. Metals are removed from the waste with a magnet. (SBGF et al, 2008) 7 2.2 Composition Typical properties and compositions of digester and landfill gas can be seen in Table 1 (The gas properties on the first three lines will be discussed in chapter 2.4.1). As mentioned above the main constituents of biogas is CH4 and CO2. The gas also contains traces of other substances like hydrogen sulphide, H2S, ammonia, chlorinated compounds, siloxanes and dust particles and it is usually saturated with water vapour. Landfill gas can also contain traces of halogenated compounds, higher hydrocarbons and aromatic compounds (not presented in Table 1). (Persson & Wellinger, 2006) Table 1 Typical properties and composition of landfill gas and digester gas. (SGC, 2007) Character: Unit: Landfill gas: Digester Gas: Calorific value, lower kWh/Nm3 4.4 6.5 Density kg/Nm3 1.3 1.2 Wobbe index, upper MJ/Nm3 18 27 Methane vol-% 45 65 Methane, range vol-% 35-65 60-70 Long-chain hydrocarbons vol-% 0 0 Hydrogen vol-% 0-3 0 Carbon dioxide vol-% 40 35 Nitrogen vol-% 15 0.2 Nitrogen, range vol-% 5-40 - Oxygen vol-% 1 0 Oxygen, range vol-% 0-5 - Hydrogen sulphide ppm < 100 < 500 Hydrogen sulphide, range ppm 0-100 0-4000 Ammonia ppm 5 100 Total chlorine as Cl- mg/Nm3 20-200 0-5 Siloxane* µg/g DW 12.9 - * Average for samples on Swedish municipal sludge (Kaj et al., 2005) The range in which different compounds lies within depends on many factors, like substrate origin and process design. Usually digester gas has a higher CH4 content than landfill gas, due to the controlled and optimized process. A specific feature with landfill gas is that it usually has a high content of N2. When the gas is sucked out from the landfill it makes air entering the empty space. The oxygen is consumed in the decomposing processes but N2 follows with the gas. Landfill gas also contains higher amounts of chlorinated compounds and siloxanes (organic silica compounds), while digester gas has a higher content of H2S and ammonia. (SGC, 2007) 2.3 Biogas in Sweden In 2006 there were 223 biogas production plants in Sweden, 60 of them were landfills and the rest digester chambers. The different types of biogas facilities, together with their average methane content and biogas production, can be seen in Table 2. Most of the digester chambers are sewage sludge treatment plants, which count for 138 plants of 163 totals. Interesting to notice is the high part of thermophilic processes and the higher average methane content for co-digestion plants. (Energimyndigheten, 2008) 8 Table 2 Number of different biogas production plants and their average methane content and biogas production, in Sweden year 2006. (Energimyndigheten, 2008) Type: Number of plants: Number of mesophilic: Number of thermophilic: Methane content, Average (%): Biogas production, (GWh): Industrial waste 3 3 0 71.2 91.20 Farm-based 8 7 1 64.9 13.88 Co-digestion 14 6 6 67.4 183.90 Landfill 60 - - 50 342.37 Sewage sludge 138 130 4 64.5 581.83 Total 223 146 11 - 1,213.18 The total biogas production for year 2006 was 1.2 TWh. It is expected to be higher for 2007 and 2008 since the co-digestion capacity has increased during these years. However, the landfill gas production has probably declined during the same time period due to the prohibition of depositing organic material, but not at the same rate. (Energimyndigheten, 2008) In Figure 2 the percental contribution from each biogas production plant type can be seen. Almost 50 % originates from sewage sludge treatment plants while 28 % was produced in landfills and 15 % in co-digestion chambers. Figure 2 Percental distribution of biogas production from the different types of facilities, Sweden year 2006. (Energimyndigheten, 2008) 2.4 Biogas utilization The main utilisation of biogas has been internal heat and/or power production. This is especially the case for landfill gas since it contains traces of many different contaminants and N2 that is difficult to separate from CH4. When used for heat and/or electricity production the gas does not need to be further processed. (SBGF et al, 2008) Figure 3 shows that more than 50 % of the biogas produced in Sweden 2006 was used for heat production, and 8 % for electricity generation. (Energimyndigheten, 2006) 9 Heat production 57% Electricity production 8% Vehicle fuel 18% Distribution gas grid 4% Flare 13% Figure 3 Percental distributions for the biogas utilization in Sweden year 2006. (Energimyndigheten, 2008) A problem with heat production is that the need of heat varies with season, and during summer unused biogas is flared. In 2006 this amount was as much as 13 %. An alternative that becomes more common is to purify and upgrade biogas to natural gas quality for use in natural gas applications, such as vehicle fuel. In 2006 18 % of the produced biogas was used as vehicle fuel and 4 % was injected into the gas grid. Most of this gas was probably used as vehicle fuel in a later state. (Energimyndigheten, 2008) In this report it is assumed that the final use of the produced LBG is just as vehicle fuel. 2.4.1 Vehicle fuel Biogas used as vehicle fuel must follow the "Swedish standard for biogas as vehicle fuel, SS 15 54 38". This standard contains two types, A and B. There are only small variations between them and concerns vehicles without and with lambda regulation. (SGC, 2007) Since a fuel station must be able to supply gas to all kinds of vehicles, only the details for type A (the type with the most stringent requirements) is presented here, see Table 3. Table 3 The Swedish Standard for biogas as vehicle fuel, SS 15 54 38, type A. (SGC, 2007) Property: Unit: Value: Wobbe index MJ/Nm3 44.7 – 46.4 Methane content vol-%* 97 ± 1 Water dew point at the highest storage pressure (t = lowest average daily temperature on a monthly basis) °C t – 5 Water content, maximum mg/Nm3 32 Maximum carbon dioxide + oxygen + nitrogen gas content, of which oxygen, maximum vol-% vol-% 4.0 1.0 Total sulphur content, maximum mg/Nm3 10 Total content of nitrogen compounds (excluding N2) counted as NH3, max. mg/Nm3 20 Maximum size of particles µm 1 The different parameters in the standard define the energy content in the gas and the maximum concentration of different trace substances. The wobbe index is a parameter that is used to determine the interchangeability for different fuel gases. This is an important 10 parameter since both biogas and natural gas are used as vehicle fuel, in the same applications. The CH4 concentration determines the energy content in the gas since neither CO2 nor N2 (in landfill gas) contain any energy. (Näslund, 2003) The listed trace substances can cause corrosion, deposits and wear in compressors, storage equipment and engines if the concentrations are too high. (Persson & Wellinger, 2006) To be able to live up to the Swedish standard raw biogas needs to be purified and upgraded. This will be treated in the following chapter. One parameter that is not represented in the standard is the siloxane content, however, the purified gas should not contain any of these compounds either. (Persson & Wellinger, 2006) 11 3 Purification and upgrading Biogas used as vehicle fuel must first be purified and upgraded. Purification means that contaminants are removed from the gas stream while upgrading means that the energy content is raised through removal of CO2. In the following chapter conventional purification and upgrading technologies will be briefly described. 3.1 Purification technologies In the purification step damaging compounds like H2O, H2S and particles and, if present, siloxanes and halogenated compounds are removed. This could otherwise cause problems with corrosion, deposits and mechanical wear on the downstream equipment and engines. (Persson & Wellinger, 2006) Below follows a description of the most commonly used technologies for the removal of each component. 3.1.1 Hydrogen sulphide - H2S H2S is formed when organic material containing sulphur is decomposed under anaerobic conditions. It is very corrosive on most metals and the reactivity increase with concentration and pressure, elevated temperature and in presence of water. Also, H2S can cause problems with bad smell from the upgrading plant. (Persson, 2003) H2S can be removed in a catalytic oxidation reaction on activated carbon, forming elementary sulphur, S, and H2O. By impregnating the carbon with potassium iodide or sulphuric acid the reaction rate can be increased. When saturated the activated carbon can be regenerated or replaced with new carbon. The technology is commonly used when a PSA system is used for the upgrading. (Persson & Wellinger, 2006) Another alternative for H2S removal is chemical absorption on a solid material containing a metal oxide. Commonly used metal oxides are iron hydroxide and oxide. Some materials can be regenerated while others need to be replaced when saturated. (Persson, 2003) 3.1.2 Water vapor – H2O Digester gas and landfill gas are usually saturated with water vapour. The concentration is increased with elevated temperature and at a temperature of 35°C the water content is around 5 %. Water forms corrosive acids in reaction with CO2 and H2S that can damage equipment if it is not removed. (Persson, 2003) The most common technology for water removal is adsorption on the surface of a drying agent. This drying agent can be zeolites, silica gel, aluminum oxide or magnesium oxide. The drying agent is packed in two vessels and while one is in operating mode the other one is regenerated. (Persson, 2003) 3.1.3 Other components Siloxanes Siloxanes are organic silica compounds that occasionally occurs in landfill gas and digester gas produced from sewage sludge. During combustion it is converted to inorganic siliceous 12 compounds, forming a white powder. Deposits of this powder in the downstream equipment cause extensive damage by erosion and blockage. Siloxanes can be removed from the gas stream through absorption in a liquid mixture of hydrocarbons or with activated carbon. Spent activated carbon cannot be regenerated. (Persson & Wellinger, 2006) Halogenated compounds Halogenated compounds are often present in landfill gas. During combustion it forms a corrosive product and, under certain conditions, dioxins and furans are formed. Halogenated compounds can be removed through adsorption on impregnated activated carbon. (Persson, 2003) Dust and particles Dust and particles are removed with filters with different mesh size. These filters also remove droplets of water and oil. (Persson & Wellinger, 2006) 3.2 Conventional upgrading technologies There are a number of different technologies for the separation of CO2 from CH4 and the most common solutions are; absorption, adsorption and membrane separation. These three technologies will be briefly presented below. 3.2.1 Absorption The absorption technology uses the differences in binding forces for different molecules to separate CO2 and H2S from CH4. CO2 and H2S are more polar and therefore more soluble in a polar absorption fluid than the non-polar CH4. Examples of absorption fluids are water and organic solvents. (Persson & Wellinger, 2006) Water scrubbing The most common upgrading technology in Sweden is water scrubbing, were water is the absorption fluid. The gas is compressed and fed into a column were it meets a counter flow of water. The column is filled with a package material to create a large surface between the gas and the liquid. Both CO2 and H2S are more soluble than CH4, and can thus be separated from the gas stream. However, H2S accumulates in the water and can cause corrosion and plugging of pipework. Also, it can cause problems with bad smell if it is vented to the atmosphere. Therefore, it is recommended to remove it before the absorption column. Upgraded gas leaving the column has a methane content of around 97 % and is saturated with water. (Persson & Wellinger, 2006) Water leaving the column is enriched with CO2, but also small amounts of dissolved CH4. Leading the water through a flashing tank, were the pressure is reduced, makes this CH4 to leave. The vent from the flashing is then sent back to the gas injection, reducing the CH4 losses in the processes. (Persson & Wellinger, 2006) The process can recirculate the water or it can use fresh water continuously. The latter is common at places with large water supply, for example sewage water treatment plants. (Persson & Wellinger, 2006) If water is recirculated, it is treated in a stripper column to remove CO2 and other contaminants. An example over a process scheme of a water scrubber, with recirculating water, can be seen in Figure 4. 13 Figure 4 Process scheme over a water scrubber with recirculating water, developed by Flotech. (Flotech, 2006) Organic solvent Another type of absorption process is to use organic solvents as absorption fluids. These organic solvents can be polyethylene glycol or alkanol amines, were Selexol® and Genosorb® are examples of the first and LP Cooab® is an example of the latter. The reason to use an organic solvent is that CO2 is more soluble in it, which results in smaller plants for the same gas flow. The solvent is regenerated in a regenerating process. (Persson & Wellinger, 2006) In this report this technology is represented by the LP Cooab® process, developed by Purac/Läckeby Water Group, since it is represented in an upgrading plant in Gothenburg. LP Cooab is the name of the technology but also the name of the absorption liquid, a specifically composed amine. (Purac, 2008) A sketch over a LP Cooab process can be seen in Figure 5. Saturated Cooab is regenerated in a CO2 stripper, were heating of the absorption liquid makes CO2 to leave. The process is a fully reversible chemical absorption process. (Purac, 2008) Figure 5 Process flow diagram over LP Cooab. (Karlsson, 2008) 14 3.2.2 Adsorption In an adsorption process CO2 is adsorbed on a material, like activated carbon or molecular sieves. The molecules are trapped in pore spaces in the adsorbent and the separation takes place due to different mesh size of different molecules. The most common adsorption processes, and the second most common upgrading process in Sweden, is Pressure Swing Adsorption, PSA, were the adsorption takes place at elevated pressure. Another type is Temperature Swing Adsorption, TSA and in this process the adsorption takes place at elevated temperature. (Persson, 2003) Pressure Swing Adsorption - PSA As mentioned above the adsorption takes place at an elevated pressure and separation is possible due to different mesh sizes of CH4 and CO2. The system consists of a number of columns in series, for continuous operation. When the adsorption material is saturated in one column, the gas flow is led to the next, while reducing the pressure regenerates the saturated column. Reducing the pressure makes the adsorbed molecules to leave. The pressure is first reduced to atmospheric and then to a light vacuum. The vent from the first stage contains significant amounts of CH4 and therefore it is sent back to the gas inlet, in order to keep the CH4 losses low. In the second stage the vent mainly consists of CO2 and is vented to the atmosphere. (Persson & Wellinger, 2006) Before entering the adsorption column the gas needs to be dry and free from H2S. H2S is removed by adding an additional column with activated carbon. When the adsorption material is saturated it is exchanged. (Persson & Wellinger, 2006) 3.2.3 Membranes There are two types of membranes; dry membranes and gas-liquid membranes. Only the first will be treated below. In the latter CO2 diffuses through the membrane and is absorbed by an absorption liquid. Dry membranes Dry membranes are membranes with a gas phase on both sides and the driving force is the differences in partial pressure. Molecules with different sizes have different permeability and when a pressurized gas stream enters the membrane, CO2 permeates to the low-pressure side, while CH4 stays under pressure. (Persson & Wellinger, 2006) An example of a membrane can be seen in Figure 6. Figure 6 Principle sketch over a MEDAL membrane, a dry membrane from Air Liquide. (Rouaud, 2008) 15 Also, some CH4 passes through the membranes. This leads to a conflict between high CH4 levels in the gas and at the same time a high CH4 recovery. A larger size of the membrane gives higher CH4 levels in the outgoing gas stream but more CH4 permeates through the membrane. Using membranes in series can reduce this problem. The vent from the first membrane is CO2 rich and sent to a flare while the permeated gas from the second membrane consists of significant amounts of CH4 and is sent back to the fed gas. (Brown, 2008) The membranes separate some H2S but since H2S is corrosive it is recommended to remove it before the process. Also, the gas needs to be compressed and dried. (Persson & Wellinger, 2006) One supplier of membranes is MEDAL, a division of Air Liquide. Air Liquide Advanced Technology has recently presented a total system for the production of LBG from landfill gas using these membranes for the separation of CO2 and CH4 (more information about this processes can be find in appendix 2). The MEDAL membranes are also used in Acrion's process (see chapter 4.1.2 and appendix 1). 16 4 Liquid biogas As mentioned in the introduction to this report cryogenic technology refers to as the development and utilization of low temperatures (Barron, 2005). This technology can be used to purify and upgrade biogas. The theory is based on different condensation temperatures for included compounds in the biogas, which can be seen in Table 4. (Benjaminsson, 2006) Table 4 Condensation temperatures, at atmospheric pressure, for different compounds in the biogas. (Benjaminsson, 2006) Compound: Condensation temperature (°C): CO2 -78.5 CH4 -161 N2 -196 The technology can be used to upgrade biogas by chilling the gas to around -80°C (atmospheric pressure) but usually cryogenic technology is associated with the production of liquid biogas, LBG. Then the gas is further chilled to -162°C. Another product that often is mentioned when discussing cryogenic upgrading technology is liquid CO2, LCO2, which is used in many commercial applications (for more information, see chapter 8). (Pettersson et al, 2007) Another alternative to produce LBG is to use conventional upgrading technology, like the ones described in chapter 3, connected with a small-scale liquefaction plant. Both solutions will be presented and discussed in this text. Production of liquid biogas is a suitable upgrading technology for landfill gas. Landfill gas usually consists of significant amount of N2, which is hard to separate from CH4 with conventional technologies. However, when CH4 is liquefied in the liquefaction step, N2 can be separated due to its lower condensation temperature. (Benjaminsson, 2006) Chilling biogas to very low temperatures is energy intensive but in some occasions the product is more valuable. If the biogas production plant is situated on the countryside, far from the end users, it is more space efficient to transport biogas in its liquid state. Today pressurised (200 bar) gas is delivered in gas vessels stored on a mobile CBG storage, leading to transportation of a huge share of steel, compared to gas. (Pettersson et al, 2006) Producing LBG also leads to a renewable fuel available for heavier vehicles. The fuel can be stored as LBG on the vehicle, which increase the driving distance per tank. The requirement is that the vehicle is running frequently, otherwise LBG will vapourize and CH4 will be vented to the atmosphere. LBG is only how the gas is stored on the vehicle. When it gets to the engine it is in its gas phase. (Storrar, 2008) A variant of cryogenic technology is the production of LBG at pressure letdown stations in the natural gas grid. Here the pressure reduction is used to liquefy a part flow of the gas stream (around 20-30 %). (Pettersson et al, 2007) This alternative will be briefly discussed. 17 4.1 Cryogenic technology Cryogenic technology means that impurities, but mainly CO2, are separated from the gas flow through condensation. In this report three main suppliers of cryogenic technology have been identified. These three suppliers are: - Scandinavian GtS - Acrion Technologies/Terracastus Technologies - Prometheus-Energy Below follows a brief presentation of these companies, together with a description of their technology (for more technical information, see appendix 1). Two of the three technologies, the ones developed by Scandinavian GtS and Prometheus-Energy, are cryogenic technology. The third technology, developed by Acrion, is a combination of cryogenic technology and commercial technology connected with a liquefier, since it only separate a small part of the CO2 content through condensation (writers’ opinion). 4.1.1 Scandinavian GtS Scandinavian GtS (SGtS) was formed in May 2007 through a partnership between the Dutch company Gastreatment Services (GtS), a company that works with gas treatment and gas processing and has developed their own technologies for this purpose, and the Swedish company Scandinavian Biogas, working with biogas production optimizing with patented technology and end-to-end expertise of the biogas process. Scandinavian GtS is now working with the development of a technology to produce LBG from landfill gas and digester gas. (Scandinavian GtS, 2008) Scandinavian GtS uses a concept with four modules in series that can be seen in Figure 7. Figure 7 Scandinavian GtS uses a concept with four modules to produce LBG from raw biogas. (Scandinavian GtS, 2008) 18 In the 1st module the gas is cooled to +6°C. This makes the moisture condense, together with most contaminants. Many remaining contaminants dissolve in the condensed moisture and everything is drained. In module 2 H2S and siloxanes are removed from the clean gas. The gas is further chilled to approximately –25°C to freeze out the remaining water and to condensate siloxanes. H2S and the remaining traces of siloxanes are then removed with a SOXSIA® -filter. SOXSIA® is a catalyst that adsorb siloxanes at the same time as H2S is converted to elementary sulphur, S, in a regenerating chemical reaction with iron oxide, Fe2O3. In the 3rd module, CO2 is separated from the gas stream by chilling the gas to –78°C and then freeze the CO2 out. The liquid CO2, LCO2, leaving module 3 is sent to a storage tank and will be used as a refrigerant in the process or as a valuable by-product. Gas leaving module 3 is dry and clean and could, after compression, be used as CBG, or further processed in module 4 to produce LBG. By chilling the gas to around –190°C, CH4 will condense and be separated from N2, which has a lower condensation temperature. The product is LBG with a CH4 content over 99 %. (Kättström, 2008) Combinations of module 1 and 2 have been in commercial use for three years, in around ten existing plants. A pilot of module 1-3 has been running on a landfill in Helsinki during the summer of 2008. The company that used the pilot does not want to reveal the results but according to Mr. Kättström, CEO, Scandinavian GtS, the tryouts “achieved the purpose” (2008). This pilot is now in the Netherlands and module 4 has been added to the process. The pilot is ready for show-off and the first commercial plant will take off during second quarter of 2009. (Kättström, 2008) A commercial plant of module 1-3 will be built in Varberg for injection into the gas grid. Upgraded biogas will be produced from digester gas from an existing digester plant. This plant is at present producing 50 Nm3 /h but is built for a higher capacity. The present work is focusing on finding more substrate and the project is still in the planning phase. (Kättström, 2008) 4.1.2 Acrion Technologies/Terracastus Technologies Acrion Technologies is a small American company whose main area is separation and purification of CO2 rich gases (> 10%) and the use of CO2 as a working fluid to achieve separation and purification. In 1998 they received a small business innovation research grant from the U.S. Department of Energy. The purpose was to develop a technology for production of marketable LNG and liquid CO2 from landfill gas, which resulted in CO2 Wash® . (DOE, 2001) AB Volvo holds the license for the production of LNG with Acrion's technology. Mack Trucks Inc. and Volvo Technology Transfer (VTT), both a part of AB Volvo organisation, have the responsibility for the commercialisation of the technology. Mack Trucks Inc. and VTT have recently started Terracastus Technologies that will work with the specific production of LBG from biogas sources. (Brown, 2008) Acrion's technology is a combination of cryogenic and conventional technology. They use a distillation column (CO2 Wash®) to clean the raw gas followed by two membranes and a liquefaction step to produce LBG. Before entering the CO2 Wash® the gas is compressed, desulphured and dried. H2S is removed with a Sulfa Treat in which it reacts with iron oxide in a non-recoverable process. A sketch over the whole process can be seen in Figure 8. (Brown, 2008) 19 Figure 8 Process flow diagram over Acrion's process for the production of LBG from raw gas. The polishing step for CO2 is missing in the figure. (Acrion, 2008b) In the CO2 Wash® a part of the CO2 content in the gas stream is condensed and most of this is taken out in the top as LCO2. The rest is used as an absorption liquid in the process, which efficiently removes contaminants such as siloxanes, halogenated compounds and nonmethane organic compounds. The adsorbent and contaminants are taken out in the bottom and sent to a flare. At the top a clean gas stream containing CH4, CO2, O2 and N2, with a CO2 content of approximately 25 %, exits the column. CO2 and any existing O2 are then separated from the gas stream with two MEDAL membranes. (Acrion, 2008a) Permeate from the first membrane is CO2 rich and is used as fuel or sent to flare, while the second permeate has a high CH4 concentration and is sent back to the fed gas. Gas leaving the membranes has a CO2 content of around 1-2 % and before entering the refrigeration module the last CO2 is removed with a mol sieve (not included in Figure 8). Any existing N2 is separated and flashed in the refrigeration plant. (Brown, 2008) In 2005 Acrion produced LBG from landfill gas, processed with CO2 Wash® , in a demo project at Burlington County Landfill, New Jersey, USA. The plant produced over 37,850 litres (equal to ~22,300 Nm3) of LBG and, according to VTT, the tryout was “a huge success”. (Elmquist, 2008) They were able to produce a gas with a methane content over 99.2 % and the purity of the methane gas and liquid CO2 were continuously analysed by a third part (the results can be find in Appendix 1). (Acrion, 2008b) This pilot project was only a small-scale project producing around 650 –1,100 Nm 3 /day and the most important experience with it was that they have been able to show that the whole chain works. VTT has just finished the work with designing large-scale plants able to produce 230, 465 and 930 Nm3 /h (converted from gallons/day, see appendix 3). The technology has not yet been tested in full-scale commercial applications but discussions are held with a number of different companies, among others in Sweden and USA. (Elmquist, 2008) 4.1.3 Prometheus-Energy Prometheus-Energy is an American fuel company that produces, sell and distribute LNG. LNG is produced from small, overlooked sources of methane such as landfill sites, stranded gas wells, wastewater treatment facilities and coal mines. (Prometheus-Energy, 2008a) According to Mr. Barclay, Chief Technology Officer at Prometheus-Energy, it is important that it is not index sources, such as pipeline gas, because they do not want to focus on feed stock prices (2008). Their idea is to produce LNG from small-scale facilities close to the 20 consumers. The company was incorporated Prometheus-Energy Company in 2003. (Prometheus-Energy, 2008b) Prometheus-Energy's idea is to use commercial technologies in integrated gas purification and liquefaction systems, to produce LBG with a CH4 content over 97 %. By using basic equipment they minimize costs and manufacturing time and by integrating the different technologies it is possible to increase the overall efficiency. They do not want to reveal their technical characteristics but they build up their systems with a modular approach that can be seen in Figure 9. From this description the general technologies can be derived. (Barclay, 2008) Figure 9 An overlook over Prometheus-Energy's modular approach. (Prometheus-Energy, 2008c) In the pre-purification module (module 1 and 2) the gas is compressed and water, sulphur compounds and low concentrations of non-methane-organic compounds, including siloxanes, are removed. In the following bulk purification module (module 4) CO2 is removed from the gas stream by using a proprietary cryogenic freezing technique that freeze out the CO2 and at the same time pre-cools the methane and any N2. The separated CO2 is vented to the atmosphere. After the bulk purification module the dry and clean gas is led to the liquefaction and post-purification module (module 5 and 6). CH4 is liquefied and after liquefaction the CH4 concentration is enhanced through dynamic flash evaporation of N2. The refrigerant module (module 7) provides the cooling to the process through a closed Brayton N2 cycle. To increase the thermodynamic efficiency of the overall process the refrigerant cycle is designed to maximize the pre-cooling of the LFG gas stream. (Prometheus-Energy, 2008c) A first pilot plant was built on Hartland Landfill, Victoria BC, in November 2000 producing methane to 96 % purity and 99 % pure CO2. Since then they have increased the capabilities and performance of their biogas to LBG systems. The facility at Hartland landfill was designed to take care of the separated CO2. The reason why they excluded this in the present design, according to Mr. Barley, is that the risk for legal actions in the USA is too high and the insurances are very expensive. They could however produce a gas with 99 % CO2 "fairly 21 easy” and he adds that it could be a good and interesting alternative for projects in other countries, for example Sweden. (2008) Figure 10 A picture over the LBG production plant at Bowerman landfill. (Prometheus-Energy, 2008) In late 2006 a commercial facility for the production of LBG from LFG was installed at Frank R. Bowerman Landfill in California. There have been some technical issues, mainly to purify the landfill gas in an economical fashion. These problems are now solved and the facility has a commercial production of 6,700 Nm3 /day (converted from gallons/day) slowly moving forward to the designed capacity of 11,150 Nm3 /day. They sell all the produced LBG and a part is used for fuelling a fleet of over 200 buses in the Orange County, California. (Montague, 2008) Prometheus-Energy is planning to build one more facility, twice this size, but the site is not yet decided. (Montague, 2008) 4.2 Small-scale liquefaction The second main way to produce LBG is to upgrade the raw gas with traditional technologies, described in chapter 3, and then liquefy CH4 using small-scale liquefaction technology. To prevent dry ice formation and corrosion in the downstream liquefaction step, the components in the upgraded biogas needs to live up to the concentrations in Table 5. (Pettersson et al, 2007) Table 5 Maximum component concentrations to be able to liquefy biogas. (Pettersson et al, 2007) Component: Requirement: CO_2 < 25 ppmv H_2S < 4 ppmv H_2O < 1 ppmv If the upgrading process does not reach these requirements an extra polishing step is needed before liquefaction. There are several types of liquefaction techniques but here only the ones used for biogas liquefaction will be presented. These liquefier types are either closed-loop or opened-loop cycles. In closed-loop cycles an external refrigerant is used while in opened-loop cycles the refrigerant is a part of the gas stream. (Pettersson et al, 2007) The liquefaction techniques presented are well known and have been in use for several years in the technical gas industry, for example for the liquefaction of natural gas, but in a much larger scale. 22 4.2.1 Closed-loop cycle In a closed-loop cycle the refrigerant and the gas stream are separated. The refrigeration can be done with one or more cooling cycles and a sketch over a closed-loop system can be seen in Figure 11. Figure 11 Sketch over a closed-loop cycle. (Pettersson et al, 2007) The refrigerant is compressed in a compressor (CP) and cooled to room temperature in a heat exchanger (HE) before entering the cryogenic heat exchanger (MCHE) were it is further chilled. After the first pass through the cryogenic heat exchanger the refrigerant is cooled through expansion in an expansion valve (E-V) or in a turboexpander (TEX). In a turbo expander the refrigerant expands in a turbine producing work that can drive the compressor. Since energy is taken out it results in a drastic temperature drop. After expansion the refrigerant enters the cryogenic heat exchanger for the second time cooling the incoming biogas flow. The cycle is closed when the refrigerant returns to the compressor. (Pettersson et al, 2007) The incoming biogas (feed gas) is cooled and partly condensed in the cryogenic heat exchanger. The remaining gas is condensed through expansion. Any gas that is dissolved in the liquid is separated in the following flash tank. (Pettersson et al, 2007) Examples of closed-loop cycles are the Nitrogen/Brayton cycle and the Mixed-refrigerant cycle. Nitrogen refrigeration cycle/closed Brayton cycle In the Nitrogen cycle, also called closed Brayton cycle, N_2 is the working fluid. The system consists of a compressor, turboexpander and heat exchanger and the biogas is liquefied in the later. The system is simple and robust but has a low efficiency since the cooling curve for N_2 does not correspond to the one for CH_4. (GTI, 2008a) One supplier of this type of refrigerant process is Cryostar. They have developed a system they call EcoRel to re-liquefy boil off gas, BOG, on LNG ships. The EcoRel system is design to cope with big variations in gas flows, it is sturdy, easy-to-operate and allowing a quick start of the process. (Cryostar, 2007) This system is also applicable on small-scale projects on land. 23 It is built up with one compressor and one turboexpander in a closed Nitrogen cycle, with one electrical motor driving the compressor. The extracted energy in the turbo expander is used to drive the compression side of the machine. The technology is not in use in any projects on the mainland but they have 14 EcoRel-systems on order that will equip the largest ever built LNG carriers. (Rivollier, 2008) The requirements of the gas to be liquefied are a content of H_2O < 0.1 – 0.2 ppmv and CO_2 < 25-50 ppmv. Cryostar does not have their own purification technology but they are reviewing different technologies that could be used to remove the last CO_2. They want to be able to include it in a complete package. (Rivollier, 2008) Another supplier of a closed N_2 cycle process is Air Liquide and they use this technology in their recently presented process for the production of LBG from landfill gas (for more information, see appendix 2). Mixed-refrigerant cycle (MRC) The Mixed-refrigerant cycle consists of multiple stages of expansion valves, phase separators and heat exchangers. (GTI, 2008a) The system has one working fluid that is a mix of N2, CH4 and other hydrocarbons. The mix of refrigerants is designed to match the cooling curve for CH4 resulting in a continually cooled gas stream and thereby a lower energy demand. However, this process is much more complex than using a single refrigerant, and therefore more difficult to scale down. (Pettersson et al, 2007) A supplier of this technology is Hamworthy. They hold the licence rights to a patented MiniLNGTM technology for the production of 7,000 – 70,000 Nm3 LBG/day (converted from t LBG/day), developed by SINTEF. They use an energy efficient closed loop mixed refrigerant cycle built up only using standard equipment, which reduce investment costs. (Hamworthy, 2008) The unique with their technology, according to Mr. Jacobsen at Hamworthy, is that they are able to use plate fin heat exchangers in their system, which gives a low energy demand for a liquefaction plant in this scale (2008). Before liquefaction the gas needs to be cleaned and pre-cooled to –10°C. This takes place in separate containers with conventional technology (PSA or TSA). (Jacobsen, 2008) A fully instrumented pilot plant, five times smaller than a full-scale plant, have been operating since Oct 2003, producing 1,400 Nm3 LNG/day. The technology is not in use in any commercial projects and they have no written contracts, but there are many interesting projects underway. (Jacobsen, 2008) Another developer of small-scale mixed refrigerant cycle is GTI. The system is similar to the one developed by SINTEF. Linde BOC holds the license of the technology and a precommercial prototype has been producing 2,200 Nm3 LBG/day (converted from gallons/day) over longer time periods. (GTI, 2008c) 4.2.2 Open-loop cycle In the open-loop cycle the refrigerant is a part of the gas stream. A general sketch over a system can be seen in Figure 12. The biogas (feed gas) is compressed (CP) and then chilled to room temperature in heat exchangers (HE). LBG is then produced in a turbo expander at the same time as work is extracted. Finally any N2 is separated from the liquid methane in the flash tank. (Pettersson et al, 2007) 24 Figure 12 Sketch over an open-loop cycle. (Pettersson et al, 2007) Turboexpander at gas pressure drop A special application of the open-looped cycle is at pressure letdown stations in the gas grid where high-pressure gas is received and low-pressure gas is sent out. Here the expansion of the gas can take place through a turboexpander. A fraction of the gas stream can then be liquefied with little or no power investment since the work taken out in the turboexpander drives the compressor. This process is very high efficient. (GTI, 2008a)

9.2.3 Energy balances Chilling to very low temperatures is energy intensive. Therefore it is interesting to find out when inserted energy for the LBG production is paid back, due to more efficient distribution. It is assumed that both the LBG and CBG distribution vehicle is running on diesel and numbers on fuel consumption comes from each distributor (see Appendix 3, Table A3 20). LBG is produced with SGtS's and Acrion's technologies while CBG is produced with water scrubber, PSA and Cooab, and added to these processes are the energy demand for pumping or compression to 250 bar. In the numbers for the Cooab process is heat recovery included. For calculations, see Appendix 3. Figure 23 reveals that LBG must be distributed 500 – 2,100 km, depending on technology, before the inserted energy is paid back. The consumed diesel fuel per kilometer is shared per loaded Nm3 gas and added to the energy consumption for production of CBG (200 bar) and LBG respectively. 0 0,5 1 1,5 2 2,5 0 400 800 1200 1600 2000

Distance (km) Primary energy (kWh/Nm3 clean gas) SGtS + LBG semitrailer Acrion + LBG semitrailer Water scrubber/PSA + mobile CBG storage Cooab (incl. heat recovery) + mobile CBG storage Figure 23 The Y-axis shows the inserted primary energy per Nm3 clean biogas. The starting point of the lines represent the primary energy consumption for production of CBG+compression to 250 bar (water scrubber/PSA/Cooab) or for production of LBG+pump work on the fuel station (SGtS/Acrion). Added to this primary energy consumption is the inserted energy for delivery with a mobile CBG storage and semi-trailer respectively. If the inserted energy should be paid back, due to more efficient distribution, the LBG must be distributed over long distances. However, to deliver the same amounts it takes more than five CBG distribution vehicles per LBG semi-trailer. It is therefore more economically efficient to distribute biogas as LBG. 47 9.3 Liquid CO2 In this report two applications of LCO2 have been presented and these are cryogenic transport temperature control and cultivation in greenhouses. 9.3.1 Cryogenic transport temperature control There are many advantages using cryogenic transport temperature-control instead of temperature-controlling system that is diesel-generated. First, the use of fossil fuels and fluorinated refrigerants are avoided. Further it is very silent, which makes it suitable for urban areas with strong noise regulations and finally, the cooling effect is very good which enables rapid temperature pull-down and recovery (Thermo King, 2003). Because of the very good chilling effect it is suitable to use CO2 as a refrigerant when transporting small packages on routes with frequent stops and also when transporting frozen goods. For chilled goods the effect needed is lower resulting in a minimum consumption of CO2 that is bigger than necessary (Rydström, 2008). Using CO2 cooling systems is an option for companies that want to profile themselves as environmentally friendly. However, a problem could be the scarce access to public fuel stations. The driver of the vehicle fuel diesel (or gas) at one place and have to go to another place to fuel LCO2, which takes extra time. The best would be if the driver could fuel both diesel and LCO2 at the same place. (Larsson, 2008) Another negative experience is the large consumption of CO2, which makes it very expensive compared to diesel-driven cooling systems. The actual CO2 consumption differs substantially from the supplier data. The consumption is also very season depended. In the summer the drivers have to refuel every day while the frequency is every third day in the autumn. The consumption is partly dependent on the driver. It is very important to turn of the cooling system when loading otherwise the cooling system is working on full effect. The consumption could also be lowered with the development of better steering and control system (Rydström, 2008). Since the consumption of CO2 is a big cost it could be attractive to buy it from another source, maybe to half the market price. Since CO2 does not go into the cargo space, food grade quality is not required. However, the LBG production plant probably has to invest in an own LCO2 distribution vehicle to be able to deliver it to the buyer. 9.3.2 Cultivation of plants and vegetables in greenhouses The common way to get CO2, and at the same time heat, for greenhouses has been to burn natural gas. However, natural gas is a fossil fuel and, to get a more environmentally friendly profile, many gardeners have switched to LCO2 together with an external source of heat, often burning of forest fuel. This concept is at present much more expensive than burning natural gas. (Carlén, 2008) Therefore, it probably would be interesting to get CO2 from another source, for maybe half the price. An interesting solution could be to build a greenhouse in connection to a digester and upgrading plant. The greenhouse could get wasted heat, CO2 and an organic fertilizer from the 48 biogas plant. However, the downside of it is that the plants will be dependent on each other. A back up system is probably needed, which would raise the investment costs. 9.3.3 Energy balances When LCO2 is used in cooling systems, 20-25 kg of CO2/h can replace 1.5 litres of diesel/h. How much that can be replaced, per Nm3 clean biogas, depends on the CO2 concentration in the raw gas and the CO2 recovery applied by the suppliers. In this report two suppliers, SGtS and Acrion, produce LCO2 with a CO2 recovery from 30-100 % (see Appendix 3, Table A3 4). The primary energy that can be replaced for different CO2 concentrations and recovery can be seen in Figure 24. For calculations and assumptions, see Appendix 3. 0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 50 55 60 65 70 CH4 concentration in raw gas (%) primary energy (kWh/Nm3 clean gas) Acrion - 30 % CO2 recovery Acrion - 50 % CO2 recovey SGtS - 100 % CO2recovery Figure 24 The amount of diesel, expressed in primary energy, that can be replaced per Nm3 clean biogas. The amount varies with CH4 concentration in the raw gas and with the different CO2 recovery applied by the suppliers of upgrading technology. Logically, the amounts that can be replaced per Nm3 clean biogas decrease with decreasing CO2 concentration and recovery. In an arithmetic example it is assumed that a digester plant has a raw gas flow of 800 Nm3 /h with 65 % CH4. Based on this data, and the assumption that the CO2 cooling system and the digester plant is running 10 and 24 h/day respectively, it results in the net primary energy consumptions presented in Figure 25. With a 100 % CO2 recovery, as in SGtS process, the primary energy consumption is lowered with more than 50 %. 49 Figure 25 Net primary energy consumption for the production of LBG, for different processes with different CO2 recovery. The numbers are valid for a raw gas flow of

800 Nm3 /h and 35 % CO2 (for calculations, see Appendix 3). For each case in the arithmetic example above (30, 50 and 100 % CO2 recovery respectively), 16, 27 and 53 cooling systems can be supplied. CO2 cooling systems are most suitable for distribution of goods with frequent stops for loading and unloading, like in the city. In this environment it is also favourable because of its low noise and low emission of harmful compounds. According to Mr. Smedbro (2008) it exist around 100 CO2 cooling systems on the Swedish market. This amount will probably grow over the next few years but the market is not huge. The CO2 consumption in a greenhouse is around 25 kg/(m2 and year) and the size of a normal sized greenhouse is around 10,000 m2 (Christensen, 2008). The traditional way to get CO2 for a greenhouse is to burn natural gas. When instead using a pure CO2 source, the heat from the natural gas burning must be replaced. This is usually done with the burning of forest fuel in a boiler, and since one source of heat will replace a new one, it probably will have very little effect on the energy balance. Therefore, it will not be brought up any further, except for an arithmetic example. However, a fossil source is replaced with a renewable source, which is an important aspect. If it is assumed that a digester plant has a raw gas flow of 800 Nm3 /h with 65 % CH4, this plant could supply between 6-19 greenhouses, see Table 14 (For calculations and assumptions, see Appendix 3). Table 14 CO2 recovery and supplied numbers of greenhouses for the two companies that produce LCO2 in their process. The numbers are valid for a raw gas flow of 800 Nm3 /h and 35 % CO2 (for calculations, see Appendix 3). Company: SGtS Acrion CO2 recovery (%): 100 30 50 Numbers of supplied greenhouses (10,000 m2 /greenhouse): 19 6 10 According to the calculations above there is a surplus of LCO2 from the biogas upgrading production plants. The market for the presented CO2

applications is probably too small and to spread out to be a possible client. There are however many more fields of applications for CO2, and if they are situated close by to the LBG production plant, the chances to sell the product increase. 50 Discussion and conclusions There are different ways to produce liquid biogas, LBG, and the ways presented and analyzed in this report are cryogenic technology, conventional technology connected with a small-scale liquefaction plant and LBG production at pressure letdown stations. The analysis shows that the process developed by SGtS is twice as energy efficient compared to the other two cryogenic LBG processes. However, SGtS just recently finished a pilot over the whole process so the numbers from this supplier are not as reliable as the ones from Acrion and Prometheus-Energy, who already tested their technology in pilot scale. The numbers from Prometheus-Energy even origins from their commercial LBG production plant at Bowerman landfill. However, since the origin is landfill gas, with a N2 content of 10 %, and the numbers are vague, Prometheus-Energy is not included in the analysis. The analysis also shows that the most energy efficient ways to produce LBG are with one of the conventional technologies; water scrubber, PSA or Cooab (including heat recovery), connected with a mixed refrigerant process or with SGtS's process. One explanation to this might be that the conventional technologies have had more time to develop, which have lowered the energy consumption, while SGtS's process and the MRC have not yet been commercially tested, which makes these numbers on energy consumption more optimistically. Figure 26 show how many percent of the energy content in the product that is needed to produce LBG. 100 % represents the energy content in LBG, which is 9.97 kWh/Nm3 clean biogas, while the bars represent the inserted primary energy to produce the product. The conventional technologies are connected with a mixed refrigerant or a N2 cycle. Figure 26 The bars represent how many percent of the energy content in the product that is used to produce LBG. The inserted energy is specified in primary energy and 100 % represents the energy content in the LBG product, which is 9.97kWh/Nm3 clean biogas. 51 Probably the numbers for Acrion's and Linde's processes are the most realistic. Numbers from these processes are similar to the numbers for Prometheus-Energy's plant at Bowerman landfill, and also, Linde have experience from one commercial facility, at Albury landfill. The numbers presented in Figure 26 is only for the upgrading and/or liquefaction. To these numbers will the energy consumption for the raw gas production be added. Using cryogenic upgrading technology results in very low CH4 losses. However, none, as Prometheus-Energy and Acrion express it, is not realistic. Small amounts will absorb in the liquid CO2 and if the origin is landfill gas there is CH4 losses connected to the flashing of N2. Another source of CH4 losses are the membranes used in Acrion process. The vent from these contains significant amounts of CH4 so it is very important how it is treated. Loss of CH4 is loss of income but, above all, it result in emissions of a greenhouse gas, 20 times stronger than CO2. However, they have small influence on the energy balance. An aspect that has big influence on the energy balance is the use of rejected low value heat in external processes. There are three identified suppliers that have developed technology to take care of this energy. The Cooab process uses significant amounts of heat and this technology would probably not be as interesting as if there were an available user of this. A possible user could be the biogas production plant but this require that the plant is situated close by, which is not always the reality. The dispose of low value waste heat in external processes is therefore very site specific. An alternative to produce LBG is to inject upgraded biogas into the gas grid and then liquefy a small part at a pressure letdown station. Beyond the conventional upgrading technologies, both SGtS's module 1-3 and Acrion's CO2 Wash® followed by membranes could be used to produce a biogas with 97 % CH4. The energy balance shows that LBG production at pressure letdown stations is an energy efficient way to produce LBG. The only energy that needs to be added to produce LBG from upgraded biogas is the compression work from 4 to 80 bar. Cryogenic technology is suitable for upgrading of landfill gas since N2, which is difficult to separate with the conventional technologies, can be separated in the liquefaction step. However, significant amounts of N2 will dissolve in the liquid CH4. This N2 will be removed through flashing but the flashing also makes some CH4 to leave. Depending on the N2 concentration in the raw gas, varying amounts of flashing is needed. A high N2 concentration results in a lower CH4 recovery and a higher CH4 loss, but also in larger energy consumption since more compression work is needed. It is important how the vent from this flashing step is treated. On a landfill the access to cheap gas usually is good so the most likely use of the vent is as fuel in a gas engine. When LBG is distributed to fuel station by a semi-trailer it is more than 5 times space efficient, compared to CBG distributed on a mobile CBG storage. Also, it is 5-10 times more energy efficient to raise the pressure by pumping (on a multi-purpose station) compared to compression. However, the LBG must be distributed 500-2,100 km, depending on upgrading process, before the higher energy consumption to produce LBG is paid back. When using cryogenic technology to separate CO2 it results in a very clean LCO2 product that could be used in external processes. The disposal of this CO2 is however very site specific. The possibility to sell it to AGA or Air Liquide (or other suppliers of industrial gases) is probably small. The scale of the biogas production plant is probably too small and to faraway to be of economic interest for them and they cannot use the same distribution vehicle for both 52 food grade and non-food grade gas quality. To be able to sell the separated CO2 the LBG producers probably has to invest in an own distribution vehicle and a LCO2 user has to be situated close by. Since the possible user will be dependent on the biogas production plant the use of this more insecure source must be connected with advantages, such as lower costs and easy access. The biogas producer on the other hand must be able to supply LCO2 in situations of production stop and maintenance. They would probably need a back-up of LCO2, which they have to buy from one of the market leading suppliers, to a significant cost. In this report two possible applications for the use of LCO2 from cryogenic upgrading have been identified and these are cryogenic temperature control and cultivation of plants and vegetables in greenhouses. The analysis shows that, if LCO2 is included in the energy balance, the net primary energy consumption for cryogenic upgrading technology can be lowered with as much as 50 %, depending on the CO2 concentration in the raw gas and the CO2 recovery in the process. However, there is a surplus of LCO2 from the LBG production plants for the presented applications. There are however many more fields for LCO2 use that probably could constitute a possible buyer of LCO2 from a biogas upgrading plant. All analysis in this report is based on a number of assumptions, which affects the results in different ways. Most of the data also comes from the supplier of each process, which makes the analysis even more insecure. However, the analysis shows the magnitude of each interesting aspect and this is enough when comparing different technologies with each other. To be able to do the comparisons, all data used in the energy balances have been converted to primary energy. Behind these conversions lies an assumption on how the energy carrier is produced or what the energy carrier would replace in an external application. This assumption affects the result in different ways, which is examined with a sensitivity analysis. Using primary energy factors is useful when comparing different technologies within a study, but it is not that practicable when comparing different studies to each other, since different assumption on energy factors can lead to big differences in the results. For the interested, all original numbers and assumptions can be found in Appendix 3: Original data, data conversion and calculations. In this report no consideration of costs for different technologies has been taken. This becomes extra clear when analysing the distribution of LBG. LBG must be transported at least 500 km before the inserted energy is paid back. However, it is more economically efficient to distribute biogas as LBG, since it takes more than 5 CBG distribution vehicles per each LBG. In a country like Sweden, where the gas network is limited and the interest of using biogas as a vehicle fuel is growing, producing LBG is a good alternative to CBG. The production is more energy intensive, but it probably results in a more valuable product since it becomes available for a bigger market. The use of cryogenic technology also opens for more smart solutions were LCO2 and rejected heat could replace fossil fuel sources in external applications, significantly affecting the energy balance in a positive way. LBG also makes biogas available for heavier vehicle, since it can be stored in its liquid state and thereby significantly increasing the driving range. 53 In Table 15, positive and negative aspects with each process identified in the work with this report are summarized. Table 15 Identified positive and negative aspects with each process. Company/process: Positive: Negative: SGtS Low CH4 losses Energy intensive compared to upgrading of biogas with conventional technology Extraction of LCO2 Pilot plant only recently available Appropriate for landfill gas No commercial experience Take care of waste heat for use in external process Acrion Low CH4 losses Energy intensive process Extraction of LCO2 No commercial experience Experience from pilot plant Appropriate for landfill gas Prometheus-Energy Low CH4 losses Energy intensive Experience from commercial and pilot plants No extraction of LCO2 Appropriate for landfill gas Water scrubbing Experience from commercial applications High water consumption Relatively high CH4 losses Amine Low CH4 losses Use of chemicals Experience from commercial applications Large use of heat PSA Experience from commercial applications Relatively high CH4 losses Membrane Experience from commercial applications High CH4 losses in the membranes N2 Brayton cycle Simple and sturdy Low efficiency No commercial experience Mixed refrigerant cycle High efficiency Complex for small-scale applications CO2 polishing step included No commercial experience Experience from pilot plant 54 In the following points the main conclusions will be summarized: • It takes around 0.8-1.8 kWh electricity (and heat)/Nm3 clean biogas to produce LBG. • Inserted primary energy to produce LBG is between 12-23 % of the energy content in the product. If the energy consumption instead is expressed in electricity (and heat), it correspond to 8-18 % of the energy content in the product. • The most energy efficient ways to produce LBG are to use one of the conventional upgrading technologies; water scrubber, PSA or Cooab (including heat recovery), connected with a mixed refrigerant process or to use SGtS's process. • Loss of CH4 has little influence on the energy balance. • Disposal of low value waste heat has a big impact on the energy balance but the possibility is very site specific. • Producing LBG at a pressure letdown station is energy efficient in comparison to cryogenic technology and conventional technology connected with a small-scale liquefaction plant. However, as much as 7-9 % of propane must be added to the biogas, which is an extra cost and an input of a non-renewable energy source. • The results on primary energy consumption are very dependent on choice of primary energy factors. However, it is very useful to use primary energy factors when different energy carriers are compared to each other, as in this report. • Cryogenic technology is suitable for upgrading of landfill gas since N2 can be separated in the CH4 liquefaction step. To keep CH4 losses low, it is very important how the vent from the flashing system is treated. • It is more than 5 times space efficient to deliver LBG in a vacuum insulated vessel compared to CBG (200 bar) delivery on a mobile CBG storage. • LBG has to be transported 500-2,100 km before the extra inserted energy to produce LBG is paid back, due to more efficient delivery, compared to a CBG system. • The possibility to sell LCO2 to one of the industrial gas producers is probably small. An alternative is to sell directly to a buyer, but the markets for cryogenic transport temperature control and cultivation of plants and vegetables in greenhouses are probably too small.

UNIT V

INTRODUCTION

Cryogenics refers to all the phenomena, process, techniques, and apparatus, occurring or using temperatures below 120 K. Refrigeration technology covers the temperature range of 120 to 273.1 K. The choice of these temperature ranges is somewhat arbitrary but has been accepted as an international standard. Around or below the temperature of 120 K, permanent gases including methane, oxygen, argon, nitrogen, helium and hydrogen can be liquefied at ambient pressure.

The ability to condense a gas such that it can be stored and shipped as cryogenic liquid rather than a pressurized gas has found several applications. Natural gas is stored and transported in this manner in many countries. Liquid hydrogen is used for fuel for a space vehicle while the use of slush hydrogen, a solid-liquid mixture, is being considered for transonic and hypersonic aircraft's. Oxygen, nitrogen and argon are shipped as liquids by trucks and railcars to the point of end use.

The term cryogenic refrigeration refers to providing and maintaining low temperatures to refrigerate other materials or to alter their properties. Refrigeration for cryogenic applications is produced by absorbing or extracting heat at low temperatures and rejecting it to the atmosphere at relatively higher temperature.

Stirling engines need less heat energy to generate a given power of output. Versatile in performance, Stirling engines can be reversed to make refrigerators, cryocoolers, or heat pumps. So efficient is the engine, it can chill to cryogenic temperatures.

The salient features of the Stirling engine that make it suitable for use in cryogenic refrigeration systems or cryocoolers are:

- The Stirling cycle is the most economical and thermodynamically efficient cycle. Its theoretical coefficient of performance approaches that of a Carnot cycle

- This system is relatively silent in operation because of the absence of valves.

CRYOCOOLERS

Cryogenics is a science of low temperature physics and it deals mainly with the generation and maintenance of cryogenic temperatures (around 120 K). Cryogenic temperatures are achieved and maintained by one or more refrigerating units known as ‘cryocoolers’. Cryocoolers utilize liquid cryogen’s to achieve cryogenic temp.

The few basic methods employed by most cryocoolers to liquefy gases are:

a) **Liquid vaporization cycle**: In this process the refrigerant fluid with desired low temperature boiling point is compressed to a pressure at which it can be condensed with ambient air, cooling water or another refrigerant fluid with a high boiling temperature. The condensed low boiling refrigerant is enthalpically expanded to a lower pressure to achieve liquefaction. The desired liquefaction is obtained in cascaded refrigerating cycle.

b) **Joule-Kelvin expansion cycle**: In this process the refrigerant fluid is compressed and precooled below its inversion temperature. The cold refrigerant fluid is enthalpically expanded to a lower pressure. In this process the fluid partially liquefies and is separated from the remaining vapor that is circulated in the system.

c) **Engine expansion cycle**: In this process a refrigerant fluid is compressed, optionally precooled and expanded to a lower pressure through an expander while producing work to reduce both the enthalpy and the temperature of the fluid.

CLASSIFICATIONS OF CRYOCOOLERS

Cryocoolers can be classified by performance.

- Micro miniature (very low capacity for electronic applications)
- Miniature (low capacity for electronic and instrumentation applications)

- Small (general purpose laboratory and commercial systems)
- Intermediate (small-scale gas liquefaction and industrial super conducting systems)
- Large (large scale gas liquefaction systems, LNG production, tonnage oxygen, helium recovery, etc.)

STIRLING CYCLE CRYOCOOLERS

Stirling coolers are all based on an oscillating gas flow and a regenerative heat exchange. The heat extraction depends on the oscillating frequency of the gas flow and they provide cooling between 15k &150k. Stirling cryocoolers are usually operated at frequencies f ~ 20-60Hz and achieve minimal temperatures T min=30 - 55 K

Stirling cycle follows a path of isothermal compression, heat transfer at constant volume to the regenerator, isothermal expansion with heat transfer to the fluid at constant volume from the regenerator.

During Isothermal compression, an amount of heat equals to Q_c is being rejected from the compressor, which also equals to the work input (W_c).
$Q_c = mRT_c \ln (V_{max}/V_{min}) = W_c$

During Isothermal expansion, an amount of heat equals to Qe is being absorbed into the expander.
$Q_e = mRT_e \text{In} (V_{max}/V_{min}) = W_e$
The coefficient of performance
$COP = Q_e / W = Q_e / (W_c - W_e) = T_e / (T_c - T_e)$

The Stirling cryocooler consists of a compressor module, a displacer module and drive electronics. The heart of its unique technology's the "non-contact" dynamic piston seal coupled with linear electric drive. Its long life is provided by careful selection of low out gassing materials. It has got non-contacting clearance and no lubrication is required. The displacer module has one or more stages of cooling connected to the compressor - a small tube. Multistage designs provide for cooling at multiple temperatures at the same time. The main uses in the recent past were infrared cryocoolers for infrared detectors and other low temperature electrical or optical systems. The Stirling air cycle cryocoolers were found to be much less dependent upon the difference in temperature between the heat source and the heat rejection point.

COMPRESSOR UNIT

The compressor-linear resonant compressor eliminates the need for rotary-to-linear conversion, leading to a more compact and efficient compressor. The compressor piston-supported by thin metal flexures provides high radial and low axial stiffness. The high radial stiffness allows the piston to be accurately centered in the cylinder, maintaining a small gap-eliminates the need for piston rings. The resulting compressor has no rubbing or sliding parts-lubricated only by the helium working gas.

CONDENSOR UNIT

Condenser condenses the superheated vapor.

To minimize the system mass a compact condenser is required to condense the oxygen stream. A number of advantages such as reduced sensitivity to gravity, low-pressure drop and high heat transfer coefficient seemed.

HOW DOES IT WORK?

WORKING PRINCIPLE

A pressure wave is created by the PWG forces due to which helium in the system starts to oscillate back and forth. The pistons compress a gas parcel and its temperature rises to a temperature greater than that of the after cooler. The gas parcel also moves through the after cooler and it deposit heat. The gas parcel continues through the regenerator, which precools it before reaching the cold heat exchanger. At this point, the gas in the acoustic network moves away from the cold heat exchanger expanding the gas parcel. As it expands it gathers heat from its surroundings. The helium parcel then moves back through the regenerator and after cooler, and the cycle begins again. Major heat pumping cycle of the system, and the cold heat exchanger - we harness the cooling. Helium gas in the thermal buffer tube, hot heat exchanger, inert tube, and reservoir does only minor heat pumping. It behaves like a mechanical piston-expanding the precooled gas parcel-increases ability to absorb heat from cooled area. Major benefits of acoustic Stirling technology is that no mechanical parts is operating in the cold region of the system & only an acoustic network of compressed helium acts like a piston.

USES OF CRYOGENICS

- Liquefied gases, generation, storage and handling
- Hall Effect/Magnet Studies
- Materials and metallurgical research
- Thermal Gravimetric Analysis
- Radio Astronomy
- Ceramics research
- Fuels research
- cooling of special optical, x-ray and electron detectors
- Flash freezing of food products
- Vacuum degassing, processing, and testing
- Low temperature research
- Semiconductor laser development
- Tritium liquefaction
- Nuclear physics detectors

APPLICATIONS OF CRYOGENICS

An overview of a number of applications in which products of Stirling Cryogenics & Refrigeration are used is given below

The engine gained a 5% increase in power with a peak increase of 13 horsepower after cryogenic treatment. The most noticeable gain was at 7900 RPM with a net gain of 18.1 horsepower.

The Cryogenic treatment is a one-time stress relieving process that tightens grain structure, improving the path of energy and creating a denser microstructure while increasing surface area. This provides increased stress relief and dimensional stability resulting in components that last longer and perform better. For motor sports this means longer lasting parts with less fatigue and breakage while increasing horsepower, torque and time between rebuilds.

Treated engine components will have increases wear resistance, but the real gain is in relief of residual stresses. Every part and component undergoes extreme machining, forging, casting, and forming during manufacturing, all of which induce residual stress into the component. During operation, an engine undergoes immense heat and pressures every time the spark plug fires, the fuel ignites and combustion occurs.

The heat build-up and dimensional forces are the causes of friction, wear, and uneven power utilization, which are the primary factors in overall engine performance and life expectancy. Cryogenics can help overcome these manufacturing "flaws" and internal stresses imposed on the engine by tightening grain structure, reducing internal vibration, transferring energy more efficiently and dissipating heat faster. This allows the engine to run smoother, cooler, more efficiently and best of all helps reduce engine failure.

Automotive parts that benefit from cryogenics

Axles, bearings, blocks, brake rotors, brake drums, camshafts, cam followers, clutch packs, connecting rods, crank shafts, cylinder sleeves, drive shafts, gears, heads, intake manifolds, lifters, oil pumps, pistons, piston rings, push rods, rocker arms, spark plugs, spark plug wires, superchargers, transmissions, turbo chargers, u-joints, valves, valve springs, water pumps, wrist pins and MORE

Cryogenic distillation of gases

Cryogenic air separation uses pressure and temperature control in order to separate gasses. The cryogenic air separation process uses the boiling points of gasses as the main principle.

When a gas reaches its boiling point, it turns into a liquid state. The difference in boiling points causes gasses to separate because each gas will turn to a liquid at a different point. The temperatures at which gasses turn to a liquid are very low. Nitrogen liquefies at -320.4 F, argon at -302.6 F, and oxygen -297.3 F. Once each gas reaches its boiling point, it begins to condense and separate.

Machining & Tooling

Cryogenic tempering can reduce your annual perishable tooling costs by 25% to 30%, and in some cases more. In addition, productivity will increase and production costs will go down because machine downtime and maintenance costs will be dramatically reduced Companies with large tooling costs have a lot to gain from cryogenics.

Cryogenics is helping businesses cut tooling costs by 20-50%. Tools will last longer, resist breakage and perform better. Companies save on expenses associated with downtime, repair/replacement and the labor involved in replacing worn or broken tooling. Cryogenics is not a surface treatment. The tool is enhanced to its core, so tools requiring sharpening will hold a better edge and continue to perform even after numerous sharpening.

Liquefaction of gases:

Industrial gas is cooled down and liquefied at a temperature between 65K and 250K. The most common gases liquefied are nitrogen, oxygen, air, argon and methane. Liquid nitrogen is used for special effects in scenes and dark rides in theme parks. Efficient storage of industrial gases in liquid form is necessary for strategic reason. Typically this is used where supply is difficult but essential, e.g. hospitals; remote scientific basis; astronomy and defense requirements.

Super conductivity

Cryogenic developments supporting super conducting applications, and exploring new refrigeration cycles. Cryogenic refrigeration for High Temperature Superconductivity (HTS) devices: HTS devices for commercial applications need a refrigeration system designed for their specific requirements, which assures that the cryogenic cost factor does not eliminate the economical advantages of the device. Specially designed closed cycle refrigeration at temperatures down to 65 K needs to be considered in the planning of the commercial use of HTS products.

Infrared Detector Systems; Integration of Closed Cycle Cryocoolers:

High performance Infrared detectors are at the heart of a wide variety of military, industrial and medical systems. These detectors are typically composed of semiconductor material such as InSb or HgCdTe, and can directly detect infrared wavelengths from the Near IR (1µm) to the Far IR (25µm). Applications include thermal imaging, heat seeking missiles, molecular spectroscopy, laser monitoring, etc.

Engineering applications:

These include ***closed loop refrigeration systems*** (20K to 250K), projects where SCR takes responsibility for the design, solution, and implementation of a system to provide refrigeration applications, cryogenic engineering and vacuum technology, used for generating very high vacuums of the order of 10^{-10} Torr, cryogenic engineering support in feasibility studies, where SCR offers engineering support for feasibility studies to determine system requirements in low temperature projects involving cryostat design for super conductive magnet systems, HTS devices, cyclotrons, cryogenic vessels, heat exchangers, vacuum chambers, etc, and cold treatment to influence the characteristics of various metals. A cooling treatment at a certain adjustable temperature level must be provided. For example certain metals are cooled to approx. -80 to -120 °C to improve certain characteristics of the metal. The treatment process assures 100% quality control.

Other applications include conservation of foods with high cash value, storage of biological materials and Oxygen systems with liquid buffer for hospitals.

FUTURE DEVELOPMENTS:

Currently extensive research is being conducted in an effort to better the available cryocooler technology in fields like materials for the regenerator, cylinder heads, etc., refrigerants used, size of cryocooler, increasing the efficiency.

The basic focus has been to reduce the size of the cryocooler in an effort to keep the cold finger of infrared detection systems as close to the cold junction as possible. There have been significant advancements in miniaturized cryocooler technology.

CONCLUSION

The scope of cryogenics has expanded widely from basic military and space applications to various civil applications. Already Infrared sensors are being increasingly used for fire detection alarm systems, energy conservation thermo graphic analysis, astronomical observations, and medical thermo graphic analysis for early Cancer detection.

The future developments are expected to lead towards disposable miniature 80 K cryocoolers. Ever since the introduction of Stirling Cycle cryocoolers, it has found applicability in practically all fields because of its higher efficiency as compared to cryocoolers based on other refrigerating cycles

Cryogenics offer immense scope for the researchers and scientists for challenging ideas for new developments. Thus we conclude that the cryocoolers are playing a very important role in the researches and applications of its liquefaction, preservation and super cooling processes.

A **Cryogenic processor** is a unit designed to reach ultra-low temperatures (usually around -300 °F / -150 °C) at a slow rate in order to prevent thermal shock to the components being treated. The first commercial unit was developed by Ed Busch in the late 1960s.[1] The development of programmable microprocessor controls allowed the machines to follow temperature profiles that greatly increased the effectiveness of the process. Some manufacturers make cryoprocessors with home computers to define the temperature profile.

Before programmable controls were added to control cryogenic processors, the "treatment" process of an object was previously done manually by immersing the object in liquid nitrogen. This normally caused thermal shock to occur within an object, resulting in cracks to the structure. Modern cryogenic processors measure changes in temperature and adjust the input of liquid nitrogen accordingly to ensure that only small fractional changes in temperature occur over a long period of time. Their temperature measurements and adjustments are condensed into "profiles" that are used to repeat the process in a certain way when treating for similarly grouped objects.

The general processing cycle for modern cryogenic processors occurs within a three-day time window, with 24 hours to reach the optimal bottom temperature for a product, 24 hours to hold at the bottom temperature, and 24 hours to return to room temperature. Depending on the product, some items will be heated in an oven to even higher temperatures. Some processors are capable of providing both the negative and positive extreme temperatures, separate units (a cryogenic processor and a dedicated oven) can sometimes produce better results depending upon the application.

The optimal bottom temperatures for objects, as well as the hold times involved, are determined utilizing a number of different research methods and backed by experience and analysis to determine what works the best for a given product. As new metals are used in different combinations for newer products on the market, processing profiles change to accommodate the changes in structure. Also, profiles will sometimes undergo change from the results of a case study brought to attention by a large manufacturer or consumer of cryogenic services. Generally when a manufacturer sells a cryogenic processor they include the profiles for only that year of manufacture, or, more typically, profiles from when the processor model was first engineered, which sometimes will date back several years. Many businesses will include outdated profiles simply because they do not have adequate funding to perform the necessary ongoing research.

For people looking to find thermal profiles for cryogenics, a number of companies maintain thermal profiles of various products that are updated for accuracy at least a few times a year with their ongoing research, including data from independent trials and studies. However, obtaining these profiles is sometimes difficult if they are not used for educational purposes (mainly institutional research), as they typically only provide the updated profiles to their longtime "service center" partners around the world.

Overall, cryogenic processors are radically changing the way that cryogenics used to be done. Many years ago, cryogenics was simply theoretical, with spotty results when there were improvements. Now, cryogenic processors are ensuring the accurate and consistent results for all products that are treated these days. As the technology sector improves, cryogenic processors will only get better as they benefit from new computer systems. Ongoing research in the future will also improve their temperature treatment profiles.

Cryogenics in space research:

By simple observation we find that in space in space research high temperatures are produced during rocket launching and in many other processes. All of these high temperature phenomena seem a far cry from the world of low temperature.

However, space research is a major consumer of the cryogenics fluids, using oxygen as a chemical reactant, hydrogen both as a chemical fuel and also as a working medium for nuclear rockets, nitrogen for pre-cooling, flushing an cold flow testing of rockets on the stands and for cooling of space simulator chamber, and helium for cryopumping of space simulator chamber.

Cryogenics in missile launching:

Cryogenic fluids are the most important factors in a successful missile bunch, aside from the missile engine itself and the control mechanism. While solid propellants have been subject of much discussion and certainly will find application in tactical weapons for use in the field, liquid propellants still moves most of missiles.

Cryogenics liquids are used to test, precool and flush the piping in typical rocket test stand

For personal protection in fuel handling:

During earl days the first problem was the development of clothing to protect liquid fuel handler from harmful effects. A major development was the totally enclosed, impermeable suit, equipped with gloves but problem is of cooling the wears within the suit to relieve the stress, and supplying a source of pure air for breathing.

These problem were solved by a back-pack containing, liquid air as shown in figure. This device cools the suit furnishes, oxygen for breathing, maintains a positive pressure within the suit to keep toxic fumes from entering, and prevents fogging on the face of the mask.

As auxiliary power source:

Cryogenic liquids can be used to power two different kind of auxiliary power source. One type is a liquid nitrogen hydraulic system, in which nitrogen is heated and used to drive a motor. The motor in turn drives nitrogen pump and also furnishes power for other purpose.

A second type of auxiliary power source using cryogenic liquid is the fuel cell, in which both fuel and oxidizer are liquids, such as liquid hydrogen and liquid oxygen. A useful by product is the pint of drinking water produced for every kilowatt-hour of operation to augment the water supply carried in the spacecraft.

As propellants:

The concept of using a cryogenic liquid, as rocket propellant is attractive for several reasons:

Storage and handling as a compact liquid is the easiest and most efficient way of handling a material which is to generate many times its volume of propellant gas.

Liquid propellants motor offer higher specific impulse values than solid propellant motors.

The material with the most desirable characteristics are liquids only at cryogenic temperatures, hydrogen for instances.

The possibility of new exotic propellant based molecular species will certainly necessitate their handling and storage at cryogenic temperatures for reasons of stability.

Nuclear rockets:

Liquid hydrogen also finds its place as a propellant in nuclear rockets. A schematic diagram of a nuclear propulsion unit is show in figure. Energy is transferred from the reactor to the propellants. The propellant temperature and pressure are increased to high values, and the propellant is exhausted through the nozzle at a high velocity.

Space simulation:

In space research much testing must be done on components and even on complete spacecraft under condition duplicating the environments of a given mission.

One of the most important of this condition is that of temperature the near vacuum pressure of deep space where the temperature of a body depends on the heat losses by radiation from its surface and the heat it gains from radiation entering it.

The pressure of space is produced by cryopumps cooled by gaseous helium backed by diffusion pump to remove non condensable. The temperature of space is simulated by means liquid nitrogen. The irradiation is provided by mercury xenon lamp and quartz lens system.

Cryogenics in biology:

The use of cold in biology has given birth to a new sub science “Cryobiology”. There are wide applications of cryobiology that are discussed in the further topics.

In blood preservation:

Two techniques of cryogenic blood storage have been investigated:

Freezing red blood cells in mixture with protective agents.

Rapid freezing of whole blood to cryogenic temperatures.

In the first case the separation from blood of red cells, addition to them of glycerol freezing and storage -80°C. When blood is needed and the cells are suspended in plasma. The equipment is complex and costly, so that central hospitals and other large institutions should best adapt the method.

The second method of blood storage involves immersing the whole blood in a bath of liquid nitrogen to freeze the blood in less than 1 minute at -320°F. A protective additive, such as polyvinyl pyrrolidone (PVP), is often used to reduce red blood cells mortality. In contrast to glycerol, PVP need not to be removed from the blood before transfusion. When the blood is needed, it is thawed as rapidly as it was frozen.

Successful transfusion of bone marrow in human patients may soon become possible reality, due to application cryogenics. The same of quick-freezing methods, which proved successful with blood, are now being tested for application to bone marrow.

Tissue preservation:

Preservation of tissue and cells at cryogenic temperatures is also possible. Tissue that has been the subject of many preservation studies is the cornea of eye. Considerable success has been achieved in transplanting corneal tissues from cadavers to individual whose corneas have been damaged. Sophisticated freeze-drying techniques have been applied successfully to corneal tissue grafts in both man and animal.

In treatment of skin diseases:

Liquid nitrogen may be used in the treatment of warts and of scarring caused by acne. It is applied by an ordinary cotton swab, when the lesion is touched, freezing occurs almost instantly. Contact time may be 10 to 60 seconds, the aim being to initiate the formation of a blister just sufficient to separate the wart from the surroundings tissues. The blister appears 6 to8 hours after treatment, exfoliation of the undesired area occurs and the final cosmetic result is good.

Introduction: This paper aims at discussing some of the basic physics issues associated with long-term storage of cryogenic liquids in zero gravity or microgravity environments. By “long-term” we mean, for example, the durations of the currently envisioned extended storage periods in the low earth orbit (LEO), which range from months to years. For NASA’s present and future space exploration missions, understanding the behavior of cryogenic liquids over long periods of storage is of crucial importance, because of the fundamental role played by cryogenic propellants, primarily liquid hydrogen (LH2) and liquid oxygen (LOX), in rocket propulsion, specifically for long-range missions. The very feasibility of using liquid propellant engines based on LH2 and LOX in the future long-range missions depends on the success of storing these propellants under microgravity or zero gravity for extended periods of time. One of the currently considered exploration strategies calls for the development of propellant storage and transfer facilities in LEO .These “fuel depots” will need to be able to spend significant amounts of time (at least on the order of several months) in LEO without any substantial propellant losses due to boil-off With the current passive heat insulation technologies, it is theoretically possible to reduce the cryogen boil-off rate to below 3% per month [6]. Even so, this issue becomes a challenge when the required storage duration exceeds 6 months, and yet a greater one for manned missions to Mars. Cryogenic fluid management (CFM) in microgravity provides a number of fundamental physical challenges, many of which were previously discussed in the literature [6, 8–13]. This is especially relevant to storage of LH2 because of its low critical temperature. One of the main features of 2 microgravity environments is that due to much-reduced levels of g-forces and their generally timevarying character, the vapor bubbles that form as a result of boil-off at the tank walls mainly near MLI penetrations (hot-spots) will not rise quickly towards the ullage space, as they do under normal gravity. Instead, they may slowly grow to very large sizes (tens of centimeters), or they may detach from the wall, migrate toward the stagnation areas of the stirring flow and accumulate there, forming regions of saturated liquid and complicated foam-like vapor-liquid structures whose properties may be not easy to control. These processes are governed by the complex heat transfer mechanisms in the near-wall region; capillary and g-forces; complex dynamics of nucleate boiling; bubble growth, detachment and collapse; chemical traces that can accumulate in the liquid with time and affect its properties. In long-term storage missions foam or bubble colonies can grow at the expense of the single ullage space. They may not be easily removed by tank pressurization because the heat released from vapor condensation may raise the temperature of the liquid surrounding the bubbles to the saturation temperature at the higher pressure. Capillary forces may be sufficiently strong to prevent the detachment of the foam from the tank walls by any realistic stirring flow that keeps the ullage intact. Basic challenges, therefore, include control of the tank pressure, temperature, ullage space size and location, boil-off venting, and work of liquid acquisition devices (LAD) that can be clogged by the foam. Similarly, since the role of buoyancy-driven convection, which is the main mechanism of heat transfer on earth, is greatly reduced in microgravity, heat transfer mechanisms will be significantly altered. Vapor and fluid motion, in turn, will be dominated by the capillary forces, heat transfer-mediated bubble dynamics, bubble coalescence, Ostwald ripening and the induced thermocapillary convection. The resulting bubble patterns and near-wall dynamics, especially around the MLI penetrations can substantially depend on the type of the wall material, chemical traces, vibrations and other external factors. In view of these complications, the basic technical issues that need to be dealt with in today’s design of successful cryogenic storage and transfer devices for long-term operation in microgravity: heat transfer management, pressure control, design of tank stirring, mass gauging, liquid acquisition, and fluid transfer are much more challenging [11], compared to the Apollo era short duration missions, in which a low level of gravity was propulsively maintained [14–16]. A successful treatment of the pressing technical issues of cryogen management in microgravity is impossible without a thorough mechanistic understanding of the underlying physical processes of nucleate boiling. Surprisingly, detailed physical understanding of nucleate boiling phenomena is still lacking today This may be due to the fact that boiling is a strongly non-equilibrium phenomenon in which an interplay between stochastic nucleation events at the micro-scale and complicated deterministic nonlinear dynamics at macro-scale takes place (for reviews, see [18–21]). At the same time, in view of the fact that microgravity presents quite a different environment compared to the usual environment on earth, one should exercise caution in applying the engineering correlations developed under earth gravity conditions to the design of cryogenic systems to be operated in spaceTo address the above technology gaps, it is necessary to collect fundamental data on liquid-vapor structure and dynamics during long-term storage in microgravity from carefully designed in-space long-duration experiments. Experimental work should be done in combination with a detailed physics analysis, mechanistic modeling, first principles computational and multi-scale approaches. Here we perform some basic physical estimates in order to evaluate the relative importance of different physical processes during long-term cryogenic storage. We concentrate our efforts on LH2, since it is the cryogen of primary importance to rocket propulsion and is also the most difficult 3 I. Introduction HE Vision for Space Exploration (VSE) mission objectives will require the use of high performance cryogenic propellants (hydrogen, oxygen, and methane). The fundamental challenges associated with the in-space use of cryogens are their susceptibility to environmental heat, their complex thermodynamic and fluid dynamic behavior in low gravity and the uncertainty of the position of the liquid-vapor interface if the propellants are not settled. Cryogenic Fluid Management (CFM) technology development is addressing these issues through ground testing and analytical model development, while having crosscutting applications and benefits to virtually all missions requiring in-space operations with cryogens. Liquid hydrogen (LH2) is the most challenging of the three propellants but has the larger technology database since it has been used as the test fluid for many CFM experiments since the 1960’s.1 2 There is less CFM test experience and data with liquid methane (LCH4) and liquid oxygen (LO2) and these propellants are the primary focus of the current development activity.

Thermal Control - Insulation (launch environments and in-space) - Vapor cooled shields - Low conductivity/ cooled support structure Liquid Acquisition - Capillary retention devices for OMS/RCS Pressurization - Cold helium Pressure Control - Zero-g venting (thermodynamic vent and heat exchanger) Lightweight Cryogenic Tank - Metallic (Al-Li) - Composite overwrap (pressure fed system) Propellant Gauging - Settled propellant - Inventory (Bookkeeping) - Pressure-volume-temperature (PVT) - High accuracy zero-g techniques Vent or to vapor cooled shields E F STRUT Liquid Propellant To Main Engine/ RCS Manifold Compartment Divider & Fluid Communication Window (screen) Spherical or cylindrical tanks Pink - flight or extensive ground demonstration Blue - key components ground tested Orange - technology development required Color Code for Text

Thermal Control - Insulation (launch environments and in-space) - Vapor cooled shields - Low conductivity/ cooled support structure Liquid Acquisition - Capillary retention devices for OMS/RCS Pressurization - Cold helium Pressure Control - Zero-g venting (thermodynamic vent and heat exchanger) Lightweight Cryogenic Tank - Metallic (Al-Li) - Composite overwrap (pressure fed system) Propellant Gauging - Settled propellant - Inventory (Bookkeeping) - Pressure-volume-temperature (PVT) - High accuracy zero-g techniques Vent or to vapor cooled shields E F STRUT Liquid Propellant To Main Engine/ RCS Manifold Compartment Divider & Fluid Communication Window (screen) Spherical or cylindrical tanks Pink - flight or extensive ground demonstration Blue - key components ground tested Orange - technology development required Color Code for Text

Pink - flight or extensive ground demonstration Blue - key components ground tested Orange - technology development required Color Code for Text

Figure 1. Conceptual exploration vehicle cryogenic propellant tank elements.

The primary CFM technology elements are: passive and active thermal control, pressure control, liquid acquisition, mass gauging and propellant feed line conditioning. Other CFM technology areas affecting in-space propulsion systems include leak-free couplings and disconnects, light weight composite tanks and support structure, leak detectors and component and subsystem integration. The conceptual tank schematic in Figure 1 illustrates how these elements are combined into a cryogenic propellant storage and delivery system. The CFM development goal of allowing fluid management functions without settling propellants enables the exploration architecture and provides major propulsion system benefits by simplifying vehicle operations, reducing system mass, and expanding operational and architectural options. Performing these functions with settled propellants provides a potential backup mode, reducing the overall

CFM risk. T NASA/TM—2007-214810 2 Figure 1. The schematics of a cryogenic storage tank (from [6]). in terms of CFM due to its low boiling point. Let us emphasize that we aim at obtaining only relatively rough estimates that take into account the long-term nature of storage. Thus, our main tool will be dimensional analysis, with minimal reference to more advanced mathematical tools. Once the main physical processes acting on the considered long timescales are identified, relevant space experiments can be designed and more precise calculations may be made using advanced mathematical and high-fidelity computational tools. In short, our main goal is to identify these processes and the issues, such as safety hazards and design optimization parameters, which arise specifically during extended periods in microgravity.