KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	KLM Technology Group Engineering Solutiions www.klmtechgroup.com	Page : 1 of 60 Rev: 01 Rev 01 July 2013
KLM Technology Group P. O. Box 281 Bandar Johor Bahru, 80000 Johor Bahru, Johor, West Malaysia	Kolmetz Handbook Of Process Equipment Design LIQUIFIED NATURAL GAS (LNG) UNIT SELECTION, SIZING AND TROUBLESHOOTING (ENGINEERING DESIGN GUIDELINES)	Co Author Rev 01 - Aprilia Jaya Author / Editor Karl Kolmetz

TABLE OF CONTENT

INTRODUCTION

APPLICATION

CALCULATION SPREADSHEET

LIST OF TABLE

LIST OF FIGURE

INTRODUCTION

Scope

This design guideline covers the basic elements in the field of Liquified Natural Gas - LNG Units, in sufficient detail to allow an engineer to design a LNG unit with the suitable size of diameter, reflux rate, actual stages, exergy efficiency, liquefied temperature, minimum work and heat during liquefaction. This design guideline includes design of a fractionator LNG unit, and liquefaction process.

LNG will likely play an increasing role in the development of giant gas fields, as most countries, especially net oil importers, are keen on developing their gas reserves, however stranded, for greater energy independence and extending domestic oil reserves where applicable, as well as for environmental reasons.

The design of LNG unit may be influenced by factors, including process requirements, economics and safety. In the design section, there are figures that assist in making these factored calculations from the vary reference sources. Included in this guideline is a calculation spreadsheet for the engineering design.

All the important parameters used in the guideline are explained in the definition section, which helps the reader understand the meaning of the parameters or the terms used.

In the application section of this guideline, three case studies are shown and discussed in detail, highlighting the way to apply the theory for the calculation. The theory section explains fractionation sizing, feed gas processing, and liquefaction process.

Example Calculation Spreadsheets are part of this guideline. This Example Calculation Spreadsheets are based on case studies in the application section to make them easier to understand.

General Design Consideration

LNG is a mixture of hydrocarbons composed predominantly of methane and which can contain minor quantities of ethane, propane, butane, nitrogen or other components normally found in natural gas. LNG shall have a methane content of more than 75 % and a nitrogen content of less than 5 %. Although the major constituent of LNG is methane, it should not be assumed that LNG is pure methane

The density of LNG depends on the composition and usually ranges from 420 kg/m^3 to 470 kg/m^3, but in some cases can be as high as 520 kg/m^3. Density is also a function of the liquid temperature with a gradient of about 1,4 kg/m^3/K. Density can be measured directly but is generally calculated from composition determined by gas chromatographic analysis.

LNG has a boiling temperature depending on composition and usually ranging from –166 °C to –57 °C at atmospheric pressure. The variation of the boiling temperature with the vapour pressure is about 1,25 x 10-4 °C/Pa. The temperature of LNG is commonly measured using copper/copper nickel thermocouples or using platinum resistance thermometers. The viscosity of LNG depends of the composition and is usually from 1,0 × 10-4 Pa·s to 2,0 × 10-4 Pa·s at –160 °C, which is nearly 1/10 to 1/5 of the water. Viscosity is also a function of the liquid temperature.

Feed to LNG plants is composed primarily of methane, together with ethane, propane, butane and heavier components. Non-hydrocarbon components such as nitrogen, carbon dioxide, hydrogen sulphide and mercury are also usually present. A typical range of feed composition is shown in the table below.

Table 1: Typical LNG feed gas composition

Methane	CH_4	70 – 90%
Ethane	C_2H_6	0 – 20%
Propane	C_3H_8	
Butane+	C_4H_{10}+	
Carbon dioxide	CO_2	0 – 8%
Nitrogen	N_2	0 – 9%

The primary drivers for the capital cost of an LNG liquefaction facility are site specific in nature. Surprisingly, less than 50% of the LNG plant cost is capacity related. As a result, most of the cost of an LNG liquefaction project is beyond the influence of the design engineer and is a function of site related conditions, project development and project execution efforts.

Although there is no typical or standard LNG plant, the major elements that are found in most LNG plants include:

1. a feed gas handling and treating section
2. a liquefaction section
3. a refrigerant section
4. a fractionation section
5. an LNG storage section
6. a marine and LNG loading section
7. a utility and offsite section

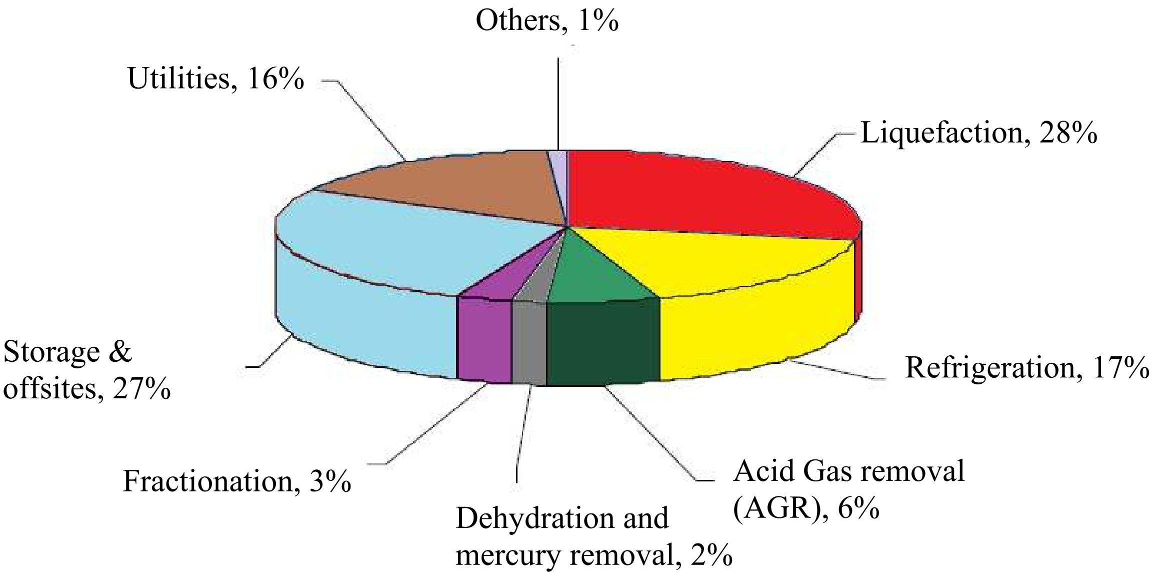

Figure 1: A typical cost distribution for an LNG plant

A typical LNG base load liquefaction plant flow scheme is shown in Figure 1. The process and utility requirement depends on site conditions, feed gas quality, and product specification. In a typical scheme, the feed gas is delivered at high pressure (up to 90 bar) from upstream gas fields via pipelines, and any associated condensate is stabilized and removed. The gas is metered and its pressure controlled to the design operating pressure of the plant.

The gas is pretreated to remove any impurities that interfere with processing or are undesirable in the final products. These treatments include sweetening and dehydration, and consist of the removal of acid gases and sulfur compounds—for example, carbon dioxide (CO_2), hydrogen sulfide (H_2S), and mercaptans, removal of mercury and other trace contaminants, as needed, and removal of water.

The dry sweet gas is then cooled by refrigerant streams to separate heavier hydrocarbons. The treated gas is subjected to multiple cooling stages by indirect heat exchange with one or more refrigerants, whereby the gas is progressively reduced in temperature until complete liquefaction. The pressurized LNG is further expanded and subcooled in one or more stages to facilitate storage at slightly above atmospheric pressure. Flashed vapors and boil-off gas (BOG) are recycled within the process. The resulting LNG is stored in atmospheric tanks ready for export by ship.

Heavier hydrocarbons that may be separated during cooling are fractionated and recovered. Ethane is normally reinjected into the gas stream to be liquefied. Propane and butane can either be reinjected or exported as LPG products and pentane (or heavier components) can be exported as a gasoline product.

Liquefaction processes mainly use mechanical refrigeration, in which heat is transferred from the natural gas, through exchanger surfaces, to a separate closed-loop refrigerant fluid. The refrigerant loop uses the cooling effect of fluid expansion, requiring work input via a compressor.

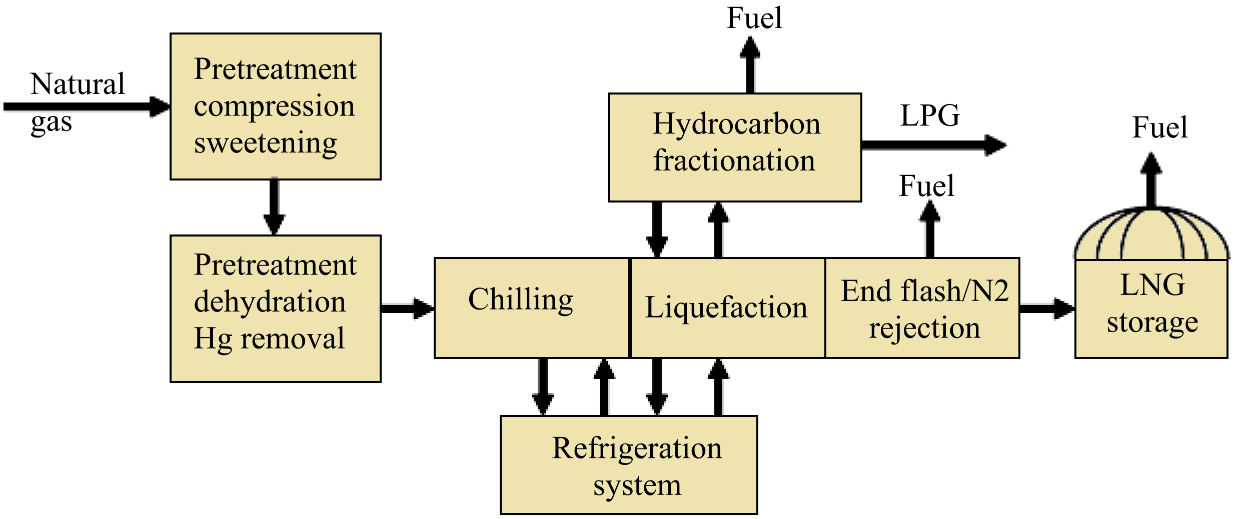

Figure 2: Typical LNG plant block flow diagram

Liquefaction

The liquefaction process is the key element of the LNG plant. Liquefaction is based on a refrigeration cycle, where a refrigerant by means of successive expansion and compression, transports heat from the process side to where the natural gas is. LNG plants often consist of a number of parallel units, called trains, which treat and liquefy natural gas and then send the LNG to several storage tanks. The capacity of a liquefaction train is primarily determined by the liquefaction process, the refrigerant used the largest available size of the compressor/driver combination that drives the cycle, and the heat exchangers that cool the natural gas.

The principal reason for liquefying natural gas is the 600-fold reduction in the volume which occurs with the vapor-liquid phase change. This volume reduction is important in the transportation and storage of the gas. In the liquid state, the gas can be transported in discrete quantities, can be economically stored in tanks for use as required, and can be transported long distances not feasible with gas pipelines.

Liquefaction uses the same principle as a household refrigerator to cool the feed gas to below the methane boiling point of around -161°C. At this temperature, the gas liquefies to 1/600th of its original volume. The liquefaction system in an LNG train comprises propane coolers, a heavy-hydrocarbon removal column, and cryogenic heat exchangers.

The feed gas from the mercury removal system will be cooled by propane coolers. The coolers liquefy the heavier hydrocarbons, which then flow to a heavy-hydrocarbon removal column. Heat and pressure will be used to separate the heavier hydrocarbons from the feed gas stream in the column. These heavier hydrocarbons (ethane, propane, butane and heavier components) will exit the bottom of the column and be sent to the common fractionation system

The main cryogenic heat exchanger is similar to the evaporator plate inside a refrigerator. It provides a sufficiently large surface area to efficiently transfer heat from the feed gas to the refrigerant. In the cryogenic heat exchanger, the feed gas will be further cooled and condensed by the refrigerant stream from the refrigeration system.

The refrigeration system cools and pressurises the refrigerants used in the liquefaction system. The refrigeration system will use closed-loop, refrigerant circuits to provide the low-temperature refrigerants. The refrigerants will be used to liquefy and subcool the feed gas in the cryogenic heat exchangers.

In order to produce the low temperature necessary for liquefaction, mechanical refrigeration systems are utilized. Three types of liquefaction processes can be used to accomplish this refrigeration:

1. Cascade Refrigeration Process, in which a number of separate refrigerant loops are used, with different single-component fluids, such as propane, ethylene, and methane
2. Mixed Refrigerant Process, which uses a mixture of nitrogen and light hydrocarbons.
3. Precooled Mixed Refrigerant Process

Cascade Refrigeration

The first LNG liquefaction units utilized the cascade refrigeration process. These facilities use the classical cascade cycle where three refrigeration systems are employed: propane, ethylene and methane. Two or three levels of evaporating pressures are used for each of the refrigerants with multistage compressors. Thus the refrigerants are supplied at eight or nine discrete temperature levels. Using these refrigeration levels, heat is removed from the gas at successively lower temperatures. The low level heat removed by the methane cycle is transferred to the ethylene cycle, and the heat removed in the ethylene cycle is transferred to the propane cycle. Final rejection of the heat from the propane system is accomplished with either water or air cooling.

The refrigeration heat exchange units traditionally were based on shell and tube exchangers or aluminum plate fin exchangers. Newer designs incorporate plate fin exchangers in a vessel known as “core-in-kettle” designs. A critical design element in these systems is the temperature approach which can be reached in the heat exchangers.

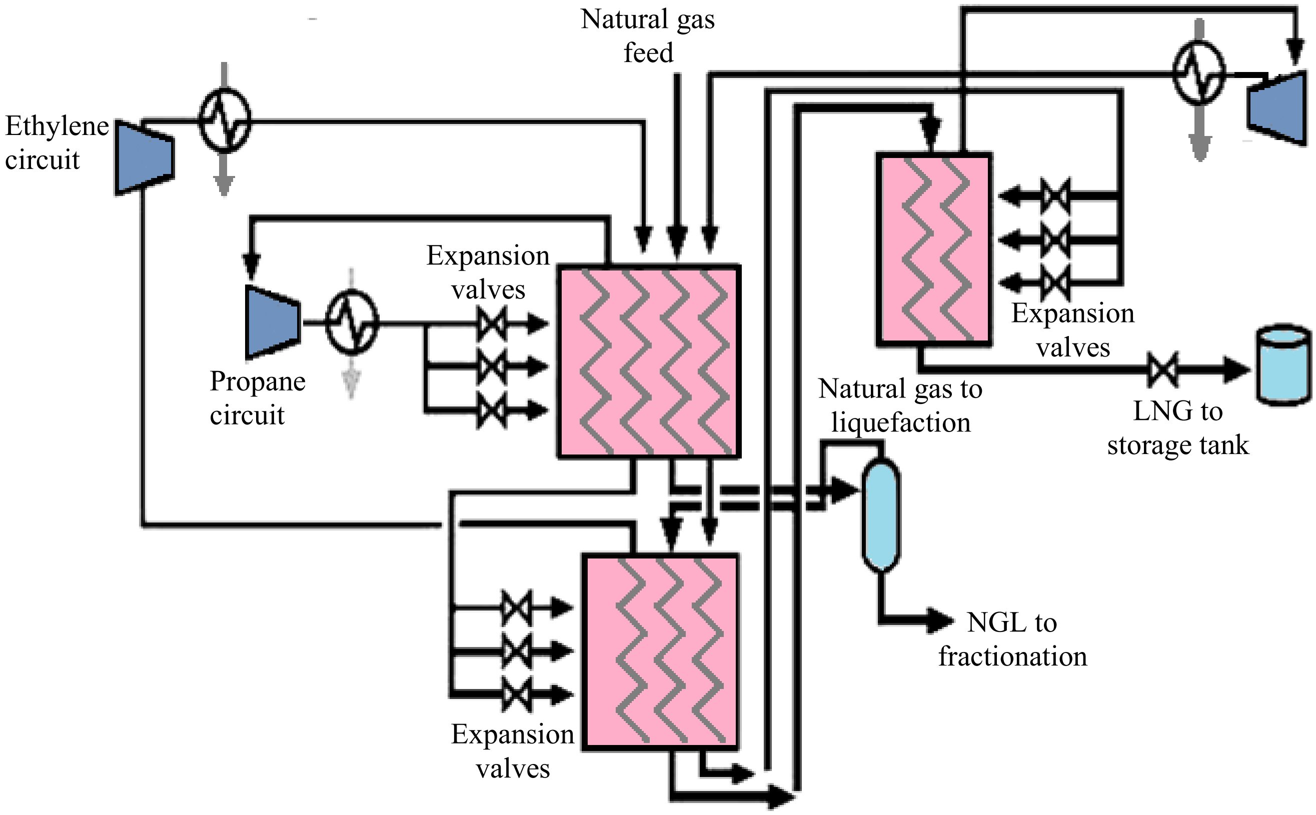

Figure 3: Cascade refrigeration process

Mixed Fluid Cascade Process

The Mixed Fluid Cascade Process (MFCP) is shown in Figure 4. The purified natural gas is precooled, liquefied, and subcooled by means of three separate mixed refrigerant cycles. The cold of the precooling cycle is transferred to the natural gas via two plate fin heat exchangers, whereas the cold of the liquefaction and subcooling cycle is transferred via two spiral wound heat exchangers by the other two refrigerants. The refrigerants are made up of components selected from methane, ethane, propane, and nitrogen. The three refrigerant compression systems can have separate drivers or integrated to have two strings of compression.

The process has been designed for large LNG trains (>4 MTPA). The MFCP is a classic cascade process, with the important difference that mixed component refrigerant cycles replace single component refrigerant cycles, thereby improving the thermodynamic efficiency and operational flexibility.

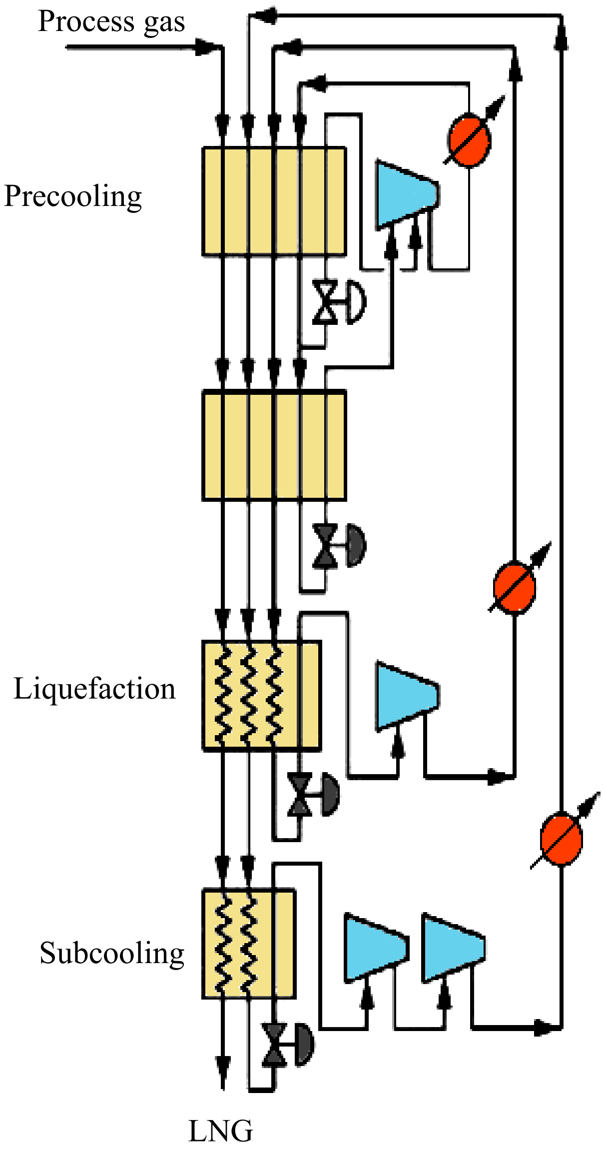

Figure 4: Mixed fluid cascade process

Mixed Refrigerant Processes

This system uses a single mixed refrigerant composed of nitrogen, methane, ethane, propane, butane and pentane. The refrigerant is designed so that the refrigerant boiling curve nearly matches the cooling curve of the gas being liquefied. The closeness of the match of these two curves is a direct measure of the efficiency of the process.

The process has two major components: the refrigeration system and the main exchanger cold box. The cold box is a series of aluminum plate fin exchangers which provide very close temperature approaches between the respective process streams. The low pressure refrigerant is compressed and condensed against air or water in a closed system. The refrigerant is not totally condensed before being sent to the cold box. The high pressure vapor and liquid refrigerant streams are combined and condensed in the main exchanger.

The condensed stream is flashed across a J-T valve and this low pressure refrigerant provides the refrigeration for both the feed gas and the high pressure refrigerant. Removal of pentane and heavier hydrocarbons from the feed gas is accomplished by bringing the partially condensed gas out of the cold box and separating the liquid at an intermediate temperature. The liquid removed is then further processed to produce a specification C5+ product. Light products from this separation are returned to the liquefaction system.

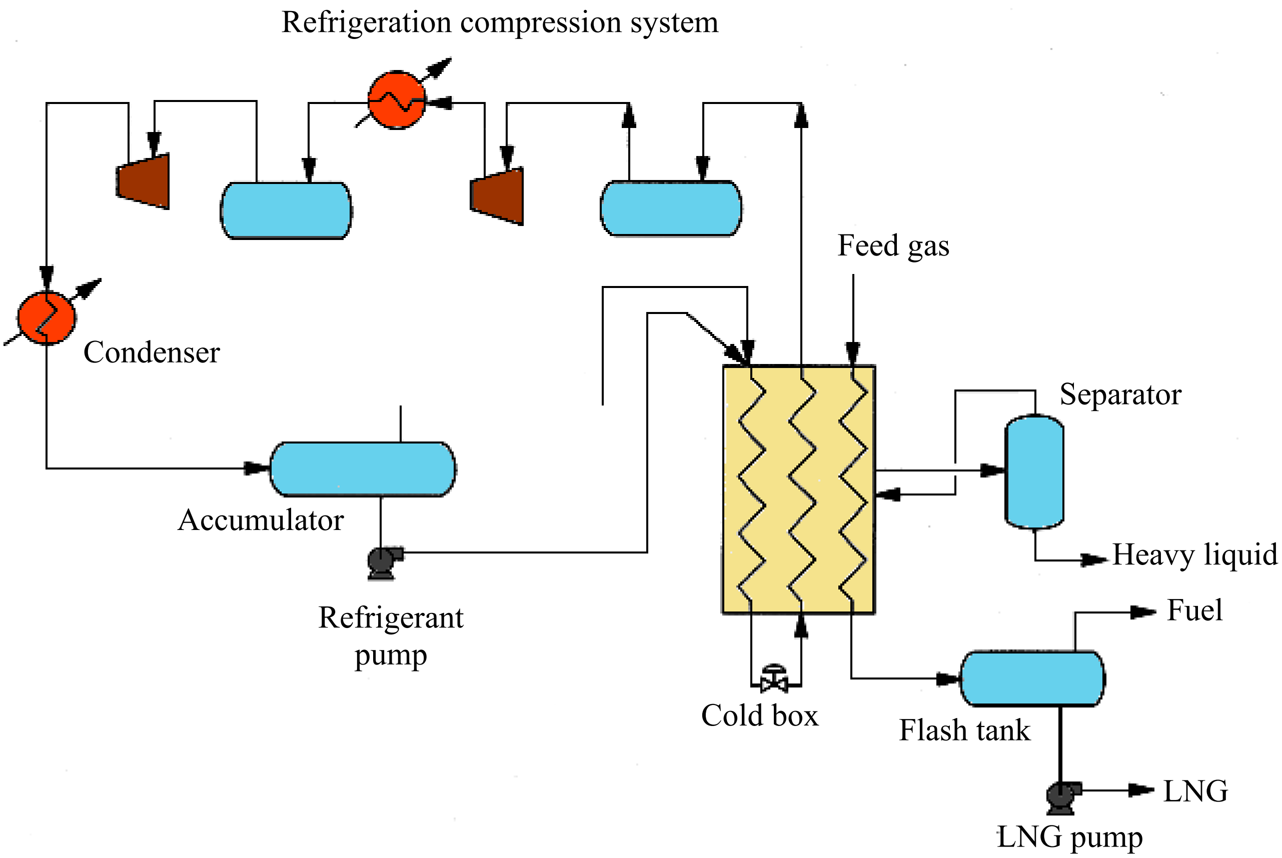

Figure 5: Mixed Refrigerant Liquefaction Process

Dual Mixed Refrigerant (DMR) Process

Dual Mixed Refrigerant (DMR) process for liquefaction, as shown in Figure 6, has two separate mixed refrigerant cooling cycles, one for precooling of the gas to approximately –50°C (PMR cycle) and one for final cooling and liquefaction of the gas (MR cycle).

Process configuration is similar to the Propane Precooled Mixed Refrigerant (PPMR) process, but with the precooling conducted by a mixed refrigerant (made up mainly of ethane and propane) rather than pure propane.

The cooling duty for liquefaction of the natural gas is provided by a second mixed refrigerant cooling cycle (MR cycle). The refrigerant of this cycle consists of a mixture of nitrogen, methane, ethane, and propane. Mixed refrigerant vapor from the shell side of the main cryogenic heat exchanger is compressed in an axial compressor followed by a two stage centrifugal compressor. Intercooling and initial desuperheating is achieved by air cooling. Further desuperheating and partial condensation is achieved by the PMR precooling cycle. The mixed refrigerant vapor and liquid are separated and further cooled in the main cryogenic heat exchanger, except for a small slipstream of vapor MR, which is routed to the end flash exchanger.

The DMR process has also employed double casing instead of single casing equipment. With a single precooling cycle and two parallel mixed refrigerant cycles, the capacity can also be boosted up to 8 MTPA. The process can either use propane or an MR in precooling. Proven refrigerant cycles can be used without step changes in technology. The capacity can be increased further with different (larger) drivers. Another possibility for the propane-MR process is to transfer power from the propane cycle to the mixed refrigerant cycle.

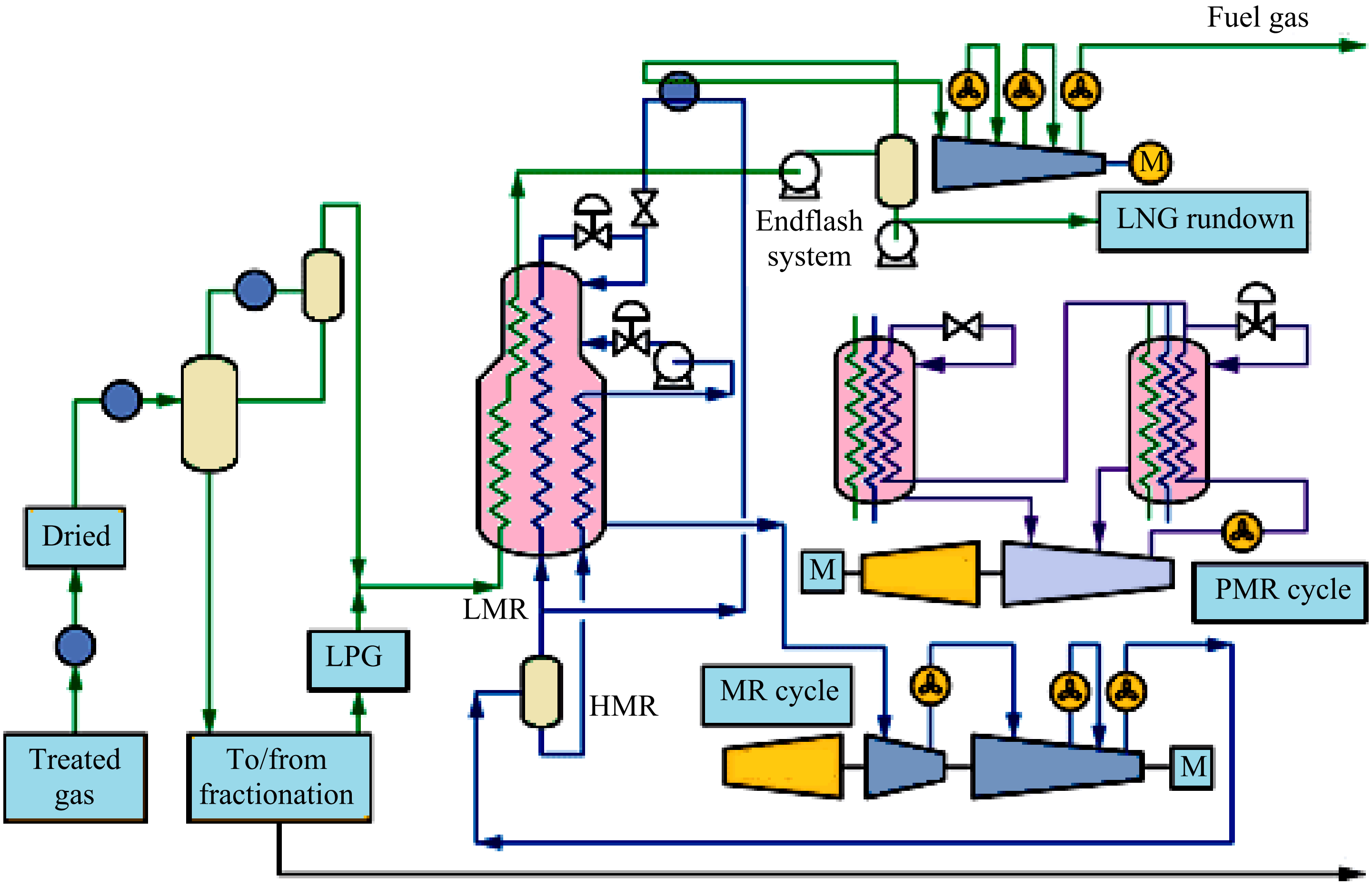

Figure 6: Schematic overview of the DMR refrigeration cycles

APCI propane pre-cooled mixed refrigerant process

The propane precooled mixed refrigerant process was developed from a combination of the cascade and mixed refrigerant processes. This technology is simple for train capacities up to 5 Mtpa. It accounts for the majority of the LNG facilities used worldwide. There are two main refrigerant cycles. The precooling cycle uses propane, the liquefaction and sub-cooling cycle uses a mixed refrigerant consisting of nitrogen, methane, ethane and propane.

In this process, the initial cooling of the feed gas is accomplished by using a multistage propane refrigeration system. The pre-cooling cycle uses propane to cool the process gas to -40ºC at which point the gas is processed in a scrub column to remove the heavy hydrocarbons and partially liquefy the mixed refrigerant. The cooling is achieved in an exchanger with propane refrigerant boiling and evaporating with process gas streaming through immersion tubes.

A centrifugal compressor recovers the evaporated propane stream and compresses the vapor to be condensed against water or air and recycled. The chilling of the gas is accomplished in a single, large, spiral-wound heat exchanger. This exchanger allows extremely close temperature approaches between the refrigerant and the gas to be achieved. Pre-cooling compression will typically require a 40 MW gas turbine plus helper motor or steam turbine.

The mixed refrigerant in this process is a lighter mixture composed of nitrogen, methane, ethane and propane with a molecular weight around 25. The mixed refrigerant after recompression is partially cooled with air or water and then further cooled in the propane refrigeration system. The partially condensed refrigerant from the propane chilling is separated and the high pressure vapor and liquid streams sent separately to the main exchanger. The liquid is flashed and provides the initial chilling of the gas. The high pressure vapor is condensed in the main exchanger and provides the low level, final liquefaction of the gas. As in the other processes, the LNG leaves the exchanger subcooled and is flashed for fuel recovery and pumped to storage.

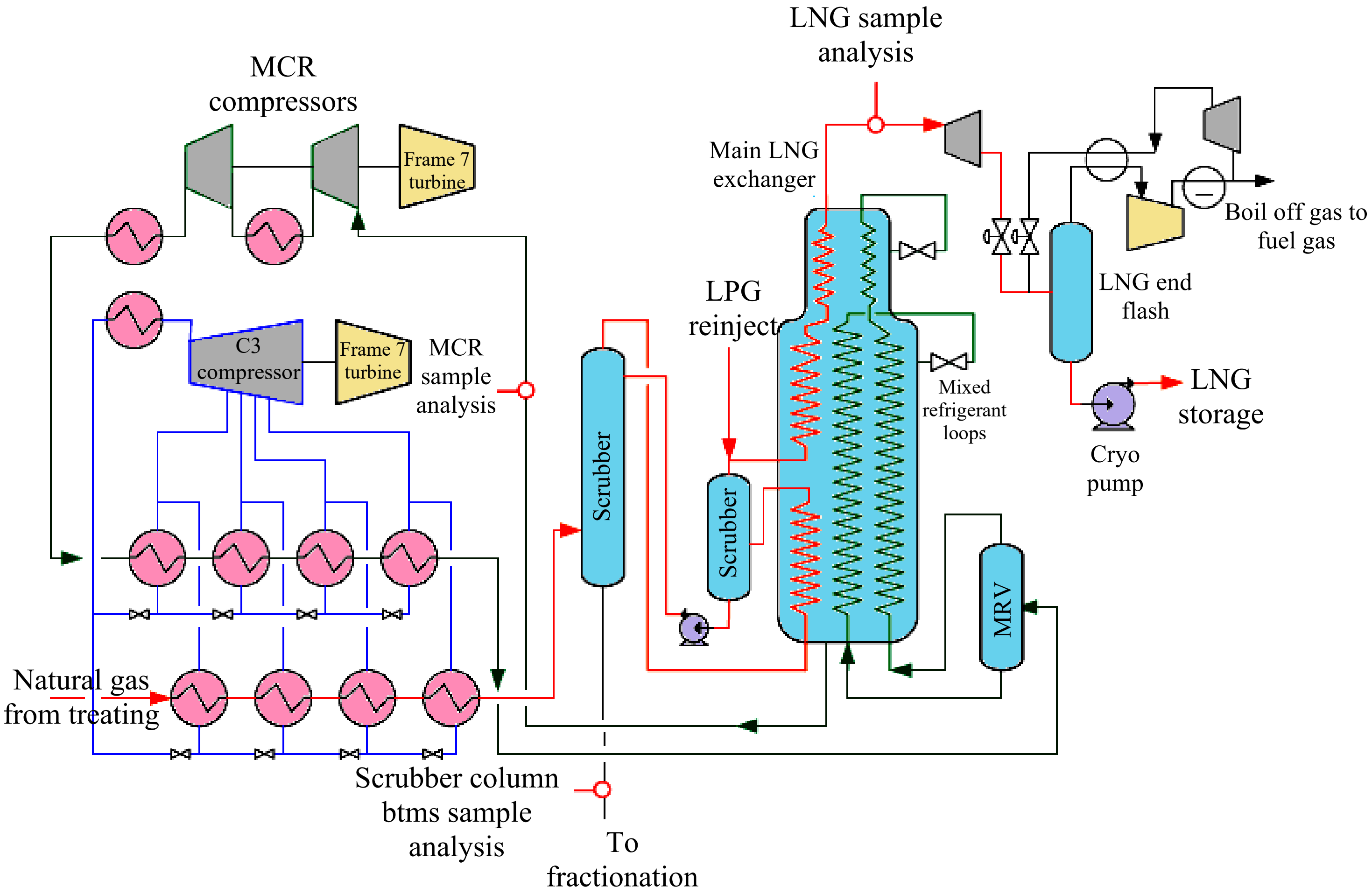

Figure 7: Typical (simplified) APCI C3/MCR LNG Liquefaction Process

DEFINITIONS

Acid Gas - Natural Gas containing Carbon Dioxide or Hydrogen Sulphide which forms an acid compound when combined with water.

Bottoms - The liquid or residual matter which is withdrawn from the bottom of a fractionator or other vessel during processing or while in storage

Boil-off gas - gas generated during the storage or handling of volatile liquefied gases

British Thermal Units (BTU) - A unit of heat widely used in the gas industry. Defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. Also described as a fixed 1055.056 Joules. Commonly used in multiples of one million Btu, abbreviated as MMBtu.

Condensate - A natural gas liquid with low vapour pressure produced from reservoir with high pressure and temperature. These very light hydrocarbons remain a liquid at normal pressure and temperature.

Cryogenics - The process of producing, maintaining and utilising very low temperatures (below -46ºC).

Condensate - a hydrocarbon liquid that forms by condensation from natural gas. It consists primarily of pentanes (C_5H_{12}) and heavier components. There will be some propane and butane dissolved within the mixture

The coefficient of performance or COP - The efficiency of a refrigerator or the ratio of the heating or cooling provided over the electrical energy consumed

Demethanizer - A fractionator designed to separate methane (and more volatile components if present) from a hydrocarbon mixture.

Downstream - A term used to describe activities along the gas value chain. Downstream typically refers to liquefaction, shipping and regasification.

Dry Gas - An alternative name for lean gas. It does not always mean free of water.

Exergy - The maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is the energy that is available to be used.

Fractionation - Generally used to describe separation of a mixture of hydrocarbons into individual products based on difference in boiling point and/or relative volatility.

Gas processing - The separation of constituents from natural gas for the purpose of making salable products and also for treating the residue gas to meet required specifications.

Hydrocarbon - An organic compound containing only elements hydrogen and carbon. Hydrocarbons exist as gases, liquids and solids. For example Methane, Ethane, Propane, Butane, Pentane, Hexane & Heptanes.

Liquefied natural gas LNG - a colourless and odourless cryogenic fluid in the liquid state at normal pressure composed predominantly of methane and which may contain minor quantities of ethane, propane, butane, nitrogen or other components normally found in natural gas

Liquefied natural gas plant or LNG plant - a plant the components of which are used to store liquefied natural gas and may also include a plant that conditions, liquefies, transfers or vaporizes liquefied natural gas.

LNG Train - An independent gas liquefaction unit within a processing facility. A liquefaction facility may contain one or more trains each producing a designed output measured in million tons per annum (Mtpa) .

Liquefied petroleum gas LPG - gaseous hydrocarbons at normal temperatures and pressures but that readily turns into liquids under moderate pressure at normal temperatures; e.g. propane and butane

LNG value chain - The commercial development of LNG which means LNG suppliers first confirm sales to the downstream buyers and then sign 20–25 year contracts with strict terms and structures for gas pricing.

Natural gas - gaseous forms of hydrocarbons, principally methane, with minor amounts of ethane, butanes, pentanes, and hexanes along with nonhydrocarbon impurities such as nitrogen, carbon dioxide and hydrogen sulfide.

Natural gas liquids NGL - liquid hydrocarbons, such as ethane, propane, butane, pentane, and natural gasoline, extracted from field natural gas

Raw gas - a mixture containing methane, other paraffinic hydrocarbons, nitrogen, carbon dioxide, hydrogen sulfide, helium and minor impurities, or some of them, that is recovered or is recoverable at a well from an underground reservoir and that is gaseous at the conditions under which its volume is measured or estimated.

Re-gasification - The reconversion (warming) of LNG to a gas for pipeline distribution.

Reflux ratio - A way of giving a relative measurement to the volume of reflux. Usually referred either to the feed or overhead product.

Sweet gas - Gas which has no more than the maximum sulfur and/or CO2 content defined by (1) the specifications for the sales gas from a plant; (2) the definition by a legal body. Also, the treated gas leaving a sweetening unit.

NOMENCLATURE

B	Bottom flow rate, kg/hr
C_{AG}	Acid gas concentration in sour gas, mole%
COP_{act}	Actual COP
COP_{rev}	Reversible COP
D	Distilate flow rate, kg/hr
Da	The diameter of an amine plant absorber, in
D_{RA}	the diameter of the regenerator above the feed point, in
D_{RB}	The diameter of the regenerator below the feed point, in
dT	Tower diameter design, m
E_{oc}	plate efficiency
F	Feed flow rate, kg/hr
GPM	Amine circulation rate, gpm
H	Tower height, m
h	Enthalpy, kj/kg
Lw	Weir length, cm
N	theoretical stages
N_{act}	actual stages
N_m	Minimum stages
P	Contactor pressure, psia
Q	Sour gas to contactor, MMscfd
QL	The rate of heat rejection during liquefaction, kj/h
q_{LL}	The refrigeration effect per unit mass liquefied gas, kj/kg liquid
q_{LG}	The refrigeration effect per unit mass of the gas, kj/kg gas
R_m	Minimum reflux ratio
s	Entropy, kj/kg.K
T_L	Low temperature, R
T_H	High temperature, R
uV	Max. allowable vapor velocity, m/s
V_m	Maximum vapor rate, kg/s
w_{act}	Work consumed in the cycle for the liquefaction, kj/kg liquid
w_{act}	Work of compression per unit mass of the gas, kj/kg gas
W_{min}	Minimum work input, kj/h

w_{rev}	Reversible work, kj/kg liquid
$\%W_{Amine}$	Amine concentration in liquid solution, wt%
x	The quality of the mixture
xB	mole fraction bottom light key
xD	mole fraction overhead light key
xF	mole fraction feed light key
y	The fraction of the gas

Greek letters

α	relative volatility
η_{ex}	Exergy efficiency,%
μ_L	liquid viscosity, Cp
ρ_L	Liquid density, kg/m³
ρ_V	Vapor density, kg/m³

Superscript

B	Bottom flow rate, kg/hr
D	Distilate flow rate, kg/hr
F	Feed flow rate, kg/hr
H	Tower height, m
N	theoretical stages
P	Contactor pressure, psia
Q	Sour gas to contactor, MMscfd