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ENERGY SAVING OPPERTUNITIES IN NATURAL GAS LIQUEFACTION PROCESS

فرص حفظ الطاقة في عملية إسالة الغاز الطبيعي

Dissertation submitted in partial fulfillment of the requirement for the Bachelor of Engineering (Horns) Degree in Transportation and Refining Engineering

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الاستهلال

قال تعالى:

(قَالُواْ سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ ﴿32﴾)

سورة البقرة

DEDICATION

To our prophet Mohammed the first student and the first teacher in our Islamic nation, to our beloved parents who were the first guiders that pushed us forward and the most prideful by this achievement, to our beloved brothers and sisters, to our immortal friendship owners, our dear friends, last and not least to those who were a part of this college and still a part of our motivation

muaaz taj-aldeen Ibrahim ***and*** Mohmmed mostafa Abo-algasem.

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Abstract

Natural Gas (NG) is a viable energy source that is dependent on pipelines and other infrastructures to reach consumers. To overcome this problem, the gas volume needs to be reduced so that it can be transported through Liquefied Natural Gas carriers and pipelines. Currently, the liquefaction process employed is energy intensive as NG needs to be cooled until it liquefies at -162˚C and atmospheric pressure. Chemical and gas plants are energy-intensive facilities so that any enhancement of their efficiency will result in abundant reduction of energy consumption. Liquefied natural gas plants consume a great amount of energy. In order to enhance LNG plant efficiency, the potential various options for improving liquefaction cycle efficiency is investigated in this study. After developing models for the LNG process using HYSYS software focusing on APCI C3MR cycle because it represent about 70% of the total LNG worldly produced . The simulation results show that the consumed energy decreased by replacing expansion valves with expanders from 1831KJ/Kg to 1478.33KJ/Kg.

Key Words:

NG, LNG, Energy consumption, Energy saving, APCI, C3MR, Cycle, Valve and Expander

المستخلص

الغاز الطبيعي هو مصدر طاقة طبيعي قابل للنمو كمصدر طاقة اعتمادا علي الانابيب والبنى التحتية لكي يصل للمستهلكين ولكي نتخطي مشكلة وصوله يجب ان يقلل حجمه وبذلك ينقل عبر حاملات الغاز الطبيعي المسال والانابيب . حاليا عمليات الاسالة المطبقة تستهلك طاقة مركزة حيث ان الغاز الطبيعي يجب أن يبرد الى درجة حرارة - 162 درجة مئوية عند الضغط الجوي العادي . منشاءات الكيمياء والغاز هي منشاءات كثيفة الاستخدام للطاقة لذلك أي تحسين في الكفاءة سينتج عنه تقليل كبير في استهلاك الطاقة . من أجل تحسين كفاءة منشاءات الغاز الطبيعي المسال تم دراسة والتحقيق في كل الخيارات المتعددة والممكنة في تحسين كفاءة دورات الإسالة.

وبذلك تم تطوير نمازج من الدورات باستخدام hysys software وتم التركيز علي APCI C3MR لانها تنتج 70% من الغاز الطبيعي المسال المنتج عالميا ,فاظهرت نتائج المحاكاة ان الطاقة المستهلكة تقل بإستبدال صمامات التمدد بالتوربينات من 1831الى 1478.33 كيلوجول لكل كيلوجرام .

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Chapter One

1 INTRODUCTION

1.1 Overview:

Natural gas is generally considered a nonrenewable fossil fuel. Natural gas is called a fossil fuel because most scientists believe that natural gas was formed from the remains of tiny sea animals and plants that died 200-400 million years ago.

It exists in nature under pressure in rock reservoirs in the Earth's crust, either in conjunction with and dissolved in heavier hydrocarbons and water or by itself. It is produced from the reservoir similarly to or in conjunction with crude oil. Natural gas has been formed by the degradation of organic matter accumulated in the past millions of years. Two main mechanisms (biogenic and thermo-genic**)** are responsible for this degradation Raw natural gas comes primarily from any one of three types of gas Wells, crude oil wells, gas wells and condensate wells. Natural gas wells average 6000 feet deep.

The global energy demand is increasing and the natural gas (NG) has obtained relevance as a clean fuel. At distances greater than 4000 km from the source of production, the most profitable way of transportation for the NG is as liquefied natural gas (LNG). Between years 2000-2010 the natural gas consumption increased 31.4% and LNG represents 30.5% of the global NG trade in 2010.

With a world market in full development and a global perspective with a strong trend towards globalization and free trade, it is evident the importance of gas liquefaction processes. (British Petroleum. (2011))

1.2 NATURAL GAS (NG)

Natural gas is what is used to describe a gas composed of a mixture of different hydrocarbons, compounds made of carbon and hydrogen, being pulled from the ground. It contains different proportions of methane (CH_4), ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). When the gas is initially extracted from the ground at the well sites, it also contains impurities in the form of hydrogen sulfide, carbon dioxide, and water, along with trace elements such as halogen gases. The normal compositions of these compounds in natural gas are listed below:

Table 1-1 **Natural gas composition** (Natural gas.org, 2004)

component	Composition %
Methane	70-90
Ethane, propane, butane	0-20
Carbon dioxide	0-8
Oxygen	0-0.2
Nitrogen	0-5
Hydrogen sulfide	0-5
Rare gases	Trace

There are two forms of natural gas: wet and dry. Wet natural gas is where the methane composition is on the low side of the estimation in the table 1-1, between 70% and 80%. The other compounds are present in their higher amounts. When methane is present in very high percentages, above 80%, with less percentages of the higher hydrocarbons present, it is considered dry.

After the gas has been removed from the ground it is transported to a processing facility. In the processing plant, there are four treatments that the gas goes through before it is ready to be transported for use: oil and solids removal, dehydration, separation of natural gas liquids (NGL), and scrubbing to remove hydrogen sulfide and carbon dioxide. When underground, the pressure causes the natural gas to dissolve in oil.

When it is released from the ground, the natural gas can separate from the oil as the pressure is decreased depending on the composition and pressure of the formation from which the gas is removed. Under the most basic removal conditions a simple tank with streams exiting from both the top and bottom is required, to allow gravity to naturally separate the liquid from the gas. Under other conditions a separator may be needed.

1.3 Chemical and Physical Properties:

Natural gas is colorless, odorless, tasteless, shapeless, and lighter than air (Table 1-2). The natural gas after appropriate treatment for acid gas reduction, odorization, and hydrocarbon and moisture dew point adjustment would then be sold within prescribed limits of pressure and calorific value. . (Natural Gas.org. 2004)

Table 1-2 Properties of NG

property	Value
relative molar mass	17-20
carbon content , weight %	73.3
hydrogen content , weight %	23.9
hydrogen/carbon atomic ratio	3-4
relative density , 15°C	0.72-0.81
boiling point , °C	-162
auto ignition temperature	540-560
octane number	120-130
methane number	69-99
stoichiometric air/fuel ratio , weight	17.2
vapor flammability limits , volume %	5-15
flammability limits	0.7-2.1

lower heating / calorific value , MJ/kg	38-50
stoichiometric lower heating value , MJ/Kg	2.75
methane concentration , volume %	80-99
nitrogen concentration , volume %	0.1-15
ethane concentration , volume %	2.7-4.6

1.4 Liquefied Natural Gas (LNG)

It is natural gas that has been cooled to the point that it condenses to a liquid, which occurs at a temperature of an approximately (-256℉-161℃) at atmospheric pressure. Liquefaction reduces the volume of gas by approximately 600 times thus making it more economical to store natural gas where other forms of storage do not exist, and transport gas over long distances for which pipelines are too expensive or for which other constraints exist.

Liquefaction makes it possible to move natural gas between continents in specially designed ships. Thus, LNG technology makes natural gas available throughout the world. (Michelle Foss) [4]

LNG is an energy source that has much lower air emissions than other fossil fuels, such as oil or coal; it is odorless, colorless, non-corrosive and non-toxic. Its weight is less than one-half that of water. The use of LNG is a proven, reliable and safe process, and it has been used in the United States since 1944.

Natural gas is the world's cleanest burning fossil fuel and it has emerged as the environmentally preferred fuel of choice. [5]

1.5 Global LNG Demand

With the startup of the world's first commercial scale liquefied natural gas (LNG) plant at Arzew in Algeria in 1964.

Total global natural gas demand is estimated to have grown by about 2.7% per year since 2000 however; global LNG demand has risen by an estimated 7.6% per year over the same period, almost three times faster. LNG demand growth is, however, expected to be even stronger, particularly through 2020. While a wide range of forecasts exists, a broad consensus of industry analysts/observers sees average annual growth of around 5% to 6% per year. After 2020, demand growth is expected to continue, albeit at a slightly slower pace (i.e., around 2% to 3% per year) as markets mature.

1.6 Measures and conversion factors:

Natural gas is most typically measured in volumetric terms, either in cubic feet (cuft) or cubic meters (cm). For international consistency here, cubic meters are used with the following equivalence:

1 cubic meter = 35.3 cubic feet LNG, however, is typically measured in millions (metric) tons per year (mtpa — sometimes abbreviated as mmtpa). For purposes of this report, the following conversions are used:

1 million tons of LNG = 1.36 billion cubic meters (bcm) of natural gas, or about 48 billion cubic feet (bcf) of natural gas.

1.7 The energy intensive processes and it is necessary to an efficient use of energy and particularly the liquefaction of (NG)

Chemical and gas plants are energy-intensive facilities so that any enhancement of their efficiency will result in abundant reduction of energy consumption and greenhouse gas emissions.

Liquefied natural gas (LNG) plants consume a great amount of energy. In order of enhance LNG plant energy efficiency.

The major challenge of implementing this issue with associated power requirement, increasing power consumption by about 15-25%. Therefore, the main scope is minimizing power consumption as well as that of the entire LNG plant though system integration and rigorous optimization. The power consumption of the LNG plant was reduced through improving the process of liquefaction itself.

Several papers in the open literature reported optimization studies on LNG plants conducted an optimization study on the simplest LNG mixed-refrigerant liquefaction cycle, using non-linear programming (NLP). Their approach was to optimize the refrigerant mixture composition of C1-C4 and N2 at given pressures and mass flow rates. If there is no temperature cross across the heat exchanger, they propose new refrigerant mass flow rate and pressure levels based on heuristics, judgment, or optimization.

Also compared three different forms of objective function:

minimization of the crossover, minimization of the sum of the crossovers, and minimization of the compressor power. (Deutsche, 2012) [6]

1.8 Enhancing the natural gas liquefaction process :

- **Reduce the power demand of natural gas liquefaction process**: (Optimize refrigerant mixture compositions and their operating variables against different type of heat exchangers, Optimize the propane cycle operating variables and develop a platform capable of handling complex process optimization).
- **Develop a robust refrigerant for natural gas liquefaction**: (Identify the challenge in natural gas liquefaction with uncertainty in natural gas field and Optimize refrigerant mixture compositions with uncertainty in natural gas field).(Shukri T., 2004) [7]

1.9 Project Objectives

The overall objective of the thesis is to develop LNG plants by enhancing the natural gas liquefaction process and reducing the energy consumption by: Optimizing the APCI process and Designing of the optimized process.

Chapter Two

2 Literature review

2.1 Liquefaction

Liquefaction is the most capital and energy intensive component of the LNG value chain. It consists of processes that chill natural gas to the point where it becomes converted to a liquid, i.e., at an average temperature of minus 161 ºC (minus 258 ºF). In order to achieve this low temperature, the gas transfers heat to a refrigerant fluid that has been previously chilled in a cooling cycle so that, in effect, this fluid steals the heat from natural gas until it is liquid. This is a process with an intensive consumption of energy (275-400 kWh/ton GNL).

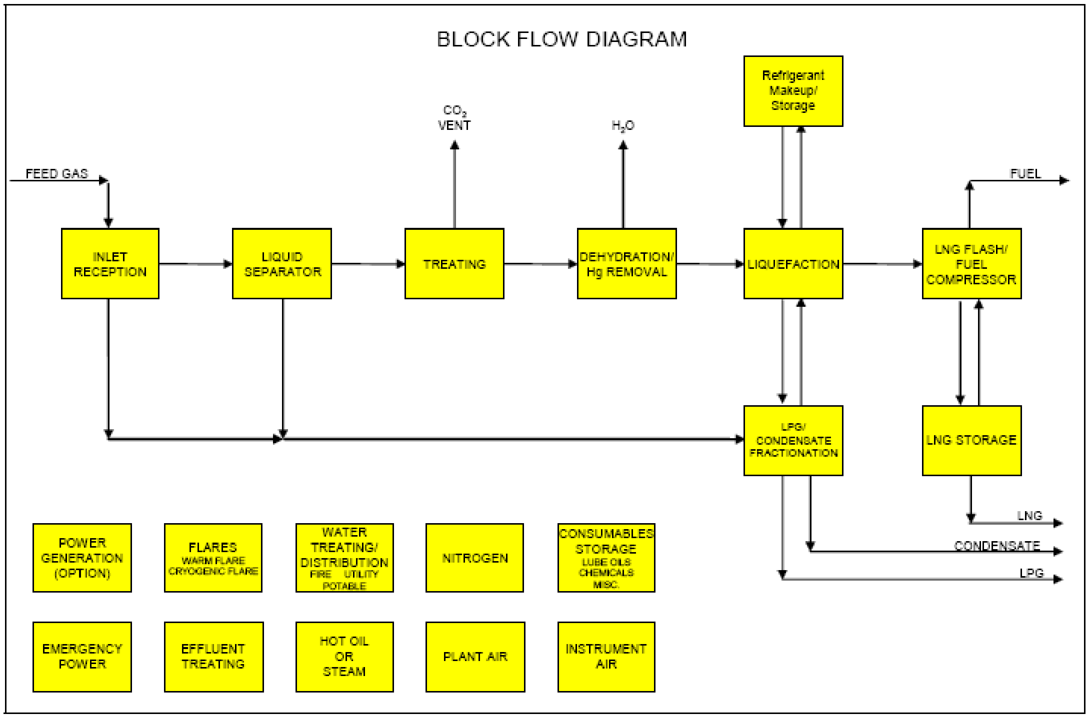


Figure 2-1 Block Flow Diagram of an LNG Liquefaction Plant

Prior to the liquefaction process, the feed gas, which flows directly from the reservoir to the liquefaction facility by pipeline, receive such treatments as:

- Filtration and solid removal

- Liquids separation
- Removal of acid gases dissolved in the water and carried in the natural gas stream as CO2 or H2S
- Dehydration
- Mercury removal

It is important to note in the liquefaction process that, as Figure 2-2 illustrates, natural gas must be fully chilled to minus 161o C so that it is completely liquefied. Otherwise the gas will exist partly in each phase, liquid and gas, and thus cannot be transported either as LNG or in pipelines using today's technologies.

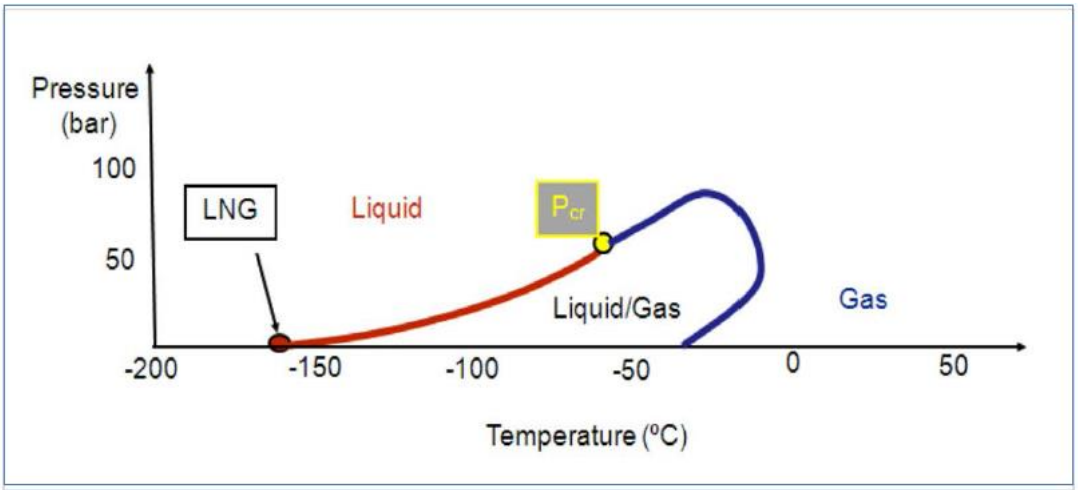


Figure 2-2 Natural gas phase diagram

High efficiency cooling is necessary to liquefy the natural gas by condensation. This is typically achieved by either of two different methods:

- Forcing the gas to develop a reverse thermodynamic cycle, i.e. expanding it after being compressed and cooled (in one or several steps)

- Allowing a heat exchange between the gas and a cooler fluid known as refrigerant or coolant, which has previously been chilled by a reverse thermodynamic cycle.

These two liquefaction methods are applied in different technologies that can be classified according to the refrigerant nature or thermodynamic cycle. (UNECE WPG LNG). (Shukri T., 2004, “LNG Technology Selection)

2.2 APCI

The APCI (Air Products and Chemicals Inc.) process, also called Propane Pre-cooled Mixed Refrigerant Process (PPMR) currently holds 80% of the liquefaction plants on the market.

They currently produce 107.5 mtpa of LNG with 53 trains in operation. Their technology uses a three stage refrigerant cooling powered by two 85 MW Frame 7 compressors. The first stage is a pre- propane cooling stage that cools the mixed refrigerant and inlet treated gas to around –35 F. The next two cooling stages, held in a heat exchanger tower, use mixed refrigerants (MR) of about 27% methane, 50% ethane, 20% propane, 2% Butane ,and 1% nitrogen to cool and condense the natural gas. The flow sheet is shown in the figure2-3:

Propane chills the gas during pre-treatment. A flash tank is used to separate the mixed refrigerant to a heavy coolant (bottom/red stream) and a lighter coolant (top/green stream).

The heavy coolant (propane, butane, and some ethane) takes care of the cooling in the warm bundle (bottom part) of the heat exchanger tower which cools down the natural gas stream (blue stream) to about -50 °C and then the light coolant is sprayed back on the streams of the warm bundle via valves to insure that the refrigerant cooled the natural gas stream to the maximum point possible for this mix. The light coolant (methane, ethane and nitrogen) cools down the natural gas stream to -160 °C in the cold bundle and this temperature is the point where natural gas is converted to LNG. Similarly to the warm bundle, the light coolant is then sprayed on the streams in the cold bundle of the heat exchanger tower and then mixed with the sprayed heavy Coolant in the warm bundle and then compressed; that is the end of the cooling cycle. The liquid coming out of the top of the heat exchanger tower is then separated via flash tank to LNG (bottom stream) and light fuel (top stream) which is later sent for fractionation in another sector.

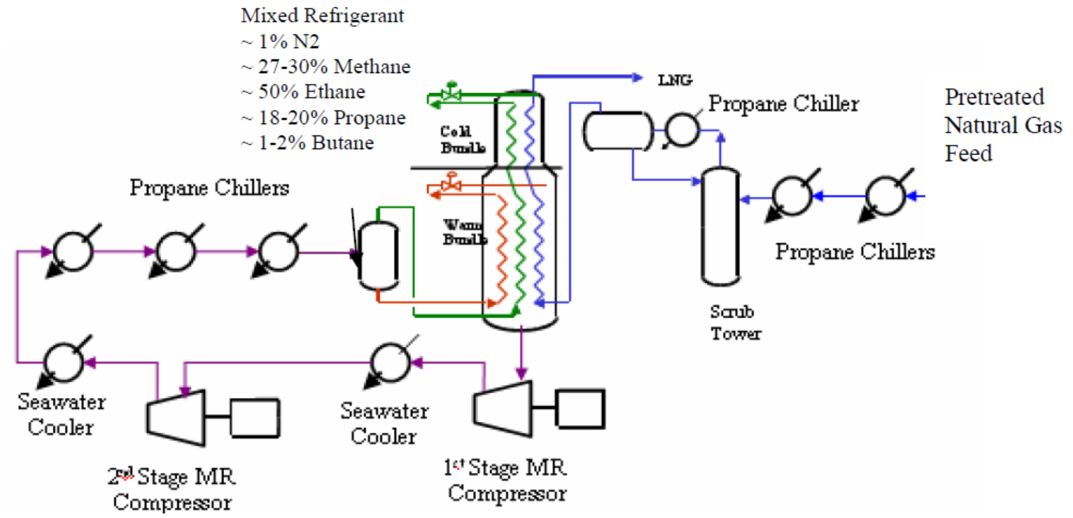


Figure 2-3 APCI process schematics

The overall process requires around 200,000 hp out of the three Frame 7 compressors and the heat exchangers in the tower are Spiral Wound Heat Exchangers (SWHE). A SWH heat exchanger is more flexible and easier to control and it could handle heavy and efficient heat exchanging process, like the liquefaction process, via one big heat exchanger. The MCHE consists of two or three tube bundles arranged in a vertical shell with the process gas and refrigerants entering the tubes at the bottom which then flow upward under pressure. The overall maximum is 5.0 MMmtpa but it cannot go less than 4 MMmtpa.

APCI has also invented their X technology. APCI-X uses nitrogen for the third refrigerant loop instead of MR to cool down the natural gas. The addition of nitrogen to the loop takes some of the compression work off of the propane pre-cooling compressor allowing for increased production. However, while APCI plans on implementing the new technology, production of LNG by APCI-X is not expected for a few years.

While APCI controls the majority of liquefaction plants in operation today, their older designs have limitations. As stated earlier, APCI uses Frame 7 compressors with a rating of about 85 MW. Being so large, Frame 7 compressors only have one vendor that makes them (GE). Additionally, the use of large compressors raises reliability concerns.

If one compressor goes down, production halts until the problem is fixed. Another disadvantage of having a large compressor is that it is only sufficient for large flow and it cannot handle low flow rates (less than 1000 BCFD). The heat exchanger tower and SWHE are manufactured only by Linde. If any clog or freezing occurs in one of the heat exchanging streams then the whole process is stopped until the problem is fixed.

2.3 DMR

The DMR (Dual Mixed Refrigerant) is very similar to the APCI liquefaction process. The process capacity is about 4.5 MMmtpa and there is only one DMR train in operation. The location of this train is in Sakhalin Island in Russia.

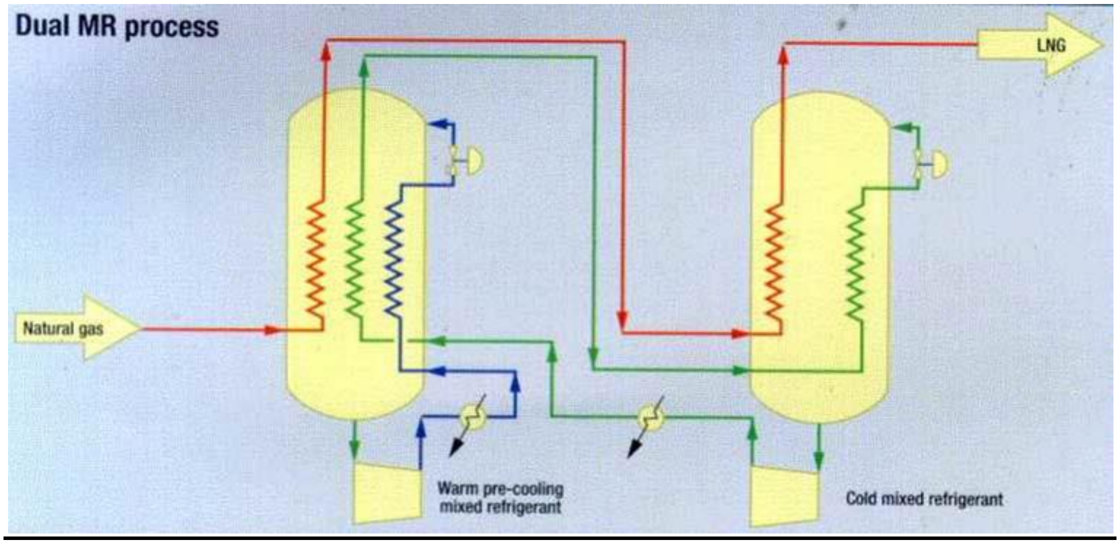


Figure 2-4 Duel mixed refrigerant flow diagram

The process is similar to the APCI, but in this process the heat exchanger tower is divided into two sections rather than one tower and this concept allows the designer to choose the load on each refrigeration cycle through controlling the two compressors work before each column.

The first stage, which is the left column, cools the natural gas (red stream) to -50°C while the second column cools the natural gas to -160°C. The composition of the pre-coolant cycle is 50/50 of Ethane/Propane on molar basis and the coolant composition of the cooling cycle is similar to the composition of APCI and that is why it is called the Dual Mixed Refrigerant process (due to having two different refrigerants). The two compressors are frame 7 compressors. The heat exchangers used in this process are also SWHE as used in the APCI. Shell also developed double casing equipment rather than a single casing to optimize the production to 5 mtpa. The advantages and disadvantages of this process is similar to the APCI, but since it has two separate compressors and heat exchangers it becomes more reliable than the APCI: Indeed, if one compressor or heat exchanger goes offline then the rest would do the liquefaction but with a smaller production rate.

2.4 LINDE

This process is also called the Mixed Fluid Cascade process (MFC). It was developed by Linde/Statoil LNG Technology Alliance and it has a capacity of 4 mtpa. Only one Linde train has been constructed with a maximum capacity of 4 mtpa for the Snohvit LNG project in Ekofish (Norway).

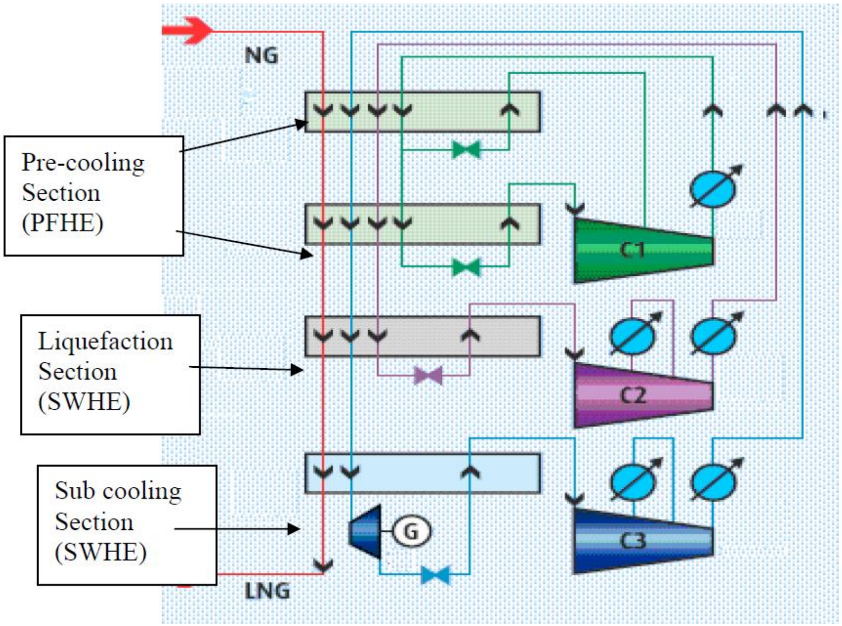


Figure 2-5 Linde process flow diagram

The natural gas (red stream) comes in from the top and goes through three mixed refrigerant cycles. The pre-cooling cycle (green cycle) cools natural gas through two Plate-Fin Heat Exchangers (PFHE) while the liquefaction (purple cycle) and sub-cooling (blue cycle) cycle cool via SWHEs. SWHE is made and patented by Linde and may also be used for the precooling stage. The only possible reason PFHE is used is because it is less expensive than SWHE. The refrigerants are made mainly of methane, ethane, propane, and nitrogen but the composition ratio of the refrigerants would differ among the three stages.

Table 2-1 Composition of Linde MRs

	Propane (%)	Ethane (%)	Methane (%)	Nitrogen (%)
Pre-cooling (Green Cycle)	60	28	10	2
Liquefaction (Purple Cycle)	3	12	80	5
Sub-cooling (Blue Cycle)	7	10	80	3

Frame 7 and 6 compressors have been proposed for this process to optimize it. The MFC has the same advantages and disadvantages of the other MR processes but it has an extra advantage which is the size and complexity of the separate SWHE applied in the MFC are less when compared to the single unit heat exchangers like in the APCI or DMR. That allows larger single compressors to handle refrigerant over a larger temperature range.

2.5 ConocoPhillips

ConocoPhillips currently has at least two trains in operation: Atlantic LNG, and Egyptian LNG. More trains are being constructed since this process is expanding to compete with the APCI. It shares about 5% of the world's LNG production and it has been in operation for more than 30 years.

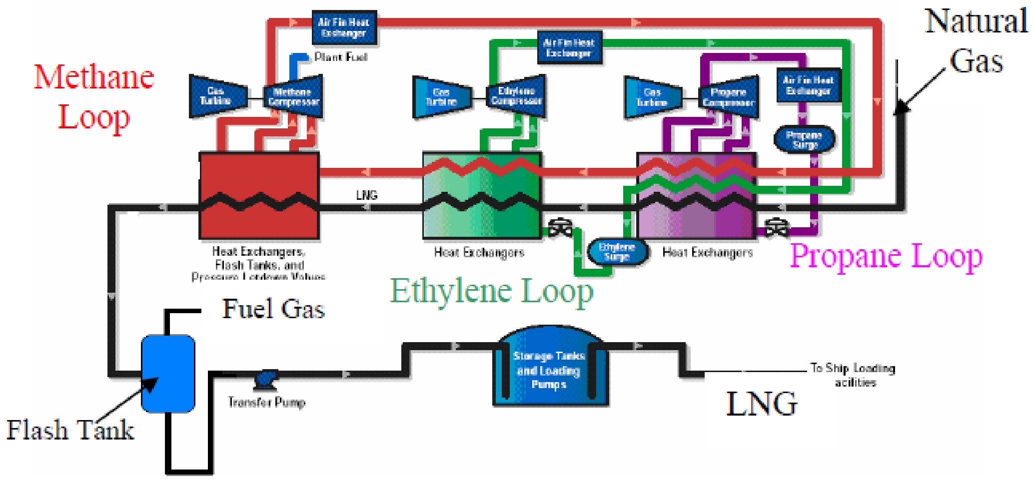


Figure 2-6 ConocoPhillips simple cascade schematic

The process uses a three stage pure component refrigerant cascade of propane (purple), ethylene (green), and methane (red).

The pretreated natural gas (black stream) enters the first cycle or cooling stage which uses propane as a refrigerant. This stage cools the natural gas to about -35 °C and it also cools the other two refrigerants to the same temperature.

Propane is chosen as the first stage refrigerant because it is available in large quantities worldwide and it is one of the cheapest refrigerants. The natural gas then enters the second cooling stage which uses ethylene as the refrigerant and this stage cools the natural gas to about -95 °C.

At this stage the natural gas is converted to a liquid phase (LNG) but the natural gas needs to be further sub cooled so the fuel gas produced would not exceed 5% when the LNG stream is flashed.

Ethylene is used as the second stage refrigerant because it condenses methane at a pressure above atmospheric and it could be also condensed by propane. After methane has been condensed by ethylene, it is sent to the third stage where it sub cools the natural gas to about -155 ° C then it is expanded through a valve which drops down the LNG temperature to about -160 °c. Methane is sent back to the first cooling stage and the LNG stream is flashed into about 95% LNG (which is sent to storage tanks) and 5% fuel gas used as the liquefaction process fuel. Methane is used as the sub cooling stage refrigerant because it could sub cools up to -155 °C and it is available in the natural gas stream so it is available at all times and at lower costs.(Al-hashimi et. al, 2008). (" UNECE WPG LNG Chapter 2).

2.6 Technology selection

Technology selection of liquefaction process and equipment will be based on technical and economic considerations. About 77% of LNG plants are using the APCI cycle for natural gas liquefaction.

2.7 Alternative pre-cooling fluids

Alternative pre-cooling fluids can be used to better balance the power split and increase train capacity in colder climates.

One option is to use the same cycle and equipment configuration as for the C3MR process with propane replaced by propylene or ethane.

Two important properties to be considered when choosing a pre-cooling fluid are boiling point and critical temperature.

Boiling point indicates how cold the pre-cooling fluid can get.

The critical temperature indicates the temperature at which the liquid and vapor phases can no longer be distinguished.

At this point the pre-cooling fluid can no longer provide refrigeration by boiling.

The boiling points and critical temperature for propane, propylene, and ethane are shown in Table (2-2).

Since propylene has a lower boiling point than propane it can pre-cool to a lower temperature at the same pressure.

This makes the power split between the pre-cooling and MR more balanced.

Since the critical temperature is substantially above ambient, propylene is far from its critical point.

By using propylene, capacity can be increased 5-10% using the same MR compressors and MCHE. Ethane has a much lower boiling point than both propane and propylene and can therefore pre-cool to an even lower temperature. However, its critical temperature is closer to ambient, and ethane is better suited for water-cooled plants where daily and seasonal changes in ambient temperature are less.

Table 2-2 Key properties for Pre-cooling Fluids

	Propane	Propylene	Ethane
Critical Temperature	97°C	92°C	32°C
Normal Boiling Point	-42°C	-48°C	-89°C

2.8 Main Exchanger Enhancement

Several enhancements have been made to the Air Products' wound coil main cryogenic heat exchanger. These consist of the capabilities to design, manufacture, and ship MCHEs which are larger, operate at higher tube-side pressure, and are more fully optimized for the specific process requirements. These improvements lead to larger throughput while improving efficiency.

Larger Main Exchangers Air Products has continually increased MCHE sizes to keep up with market demand. Previously, the maximum exchanger diameter was 4.6 meters and the maximum exchanger weight was approximately 310 metric tons. This was the maximum exchanger size necessary in order to achieve the required LNG train production with the power available from the compressor drivers. As the market demand for larger train capacity has developed, improvements have been made to the Air Products' manufacturing facility and shipping equipment as well as the rail transportation route from the manufacturing facility to the shipping port.

With these enhancements, the maximum exchanger diameter increases to 5.0 meters, and the exchanger weight increases to 430 metric tons. These larger exchangers play a key role in increasing capacity of the C3MR train beyond 5 MTA and the capacity of the APXTM train beyond 8 MTA. In addition, further increases in MCHE size are possible if demanded by market needs.

Design Optimization. Design of the wound coil heat exchanger is a sophisticated, highly technical process. The internal geometry of the main exchanger impacts performance. Number of tubes, length of tubes, winding angle, number of tube layers, spacing between tube layers, etc. affect the heat transfer and pressure drop in the exchanger and ultimately production. Over the years, Air Products has developed sophisticated modeling and simulation tools to optimize the internal geometry of the MCHE in order to maximize performance.

The process conditions towards the top of a bundle in the main exchanger are very different from those towards the bottom. Thus, the optimal internal geometry in the upper section of the bundle is different from that in the lower section. The design tools have been used to assess the performance benefit of splitting the refrigeration duty provided by one bundle into two bundles. This allows for increased optimization of the internal geometry for the local process conditions, leading to improved heat transfer and enhanced performance.

Chapter Three

3 Process Modeling and Simulation

3.1 Process Modeling Tool

Aspen Hysys v [7.3] was used for modeling the APCI Natural gas liquefaction. It is a Process modeling tool for steady-state simulation, design, performance monitoring, optimization and business planning for chemicals, specialty chemicals, petrochemicals and metallurgy industries.

Aspen Hysys solves the critical engineering and operating problems that arise throughout the lifecycle of a chemical process, such as designing a new process, troubleshooting a process unit and it's has many features like :

- **Windows Interoperability:** Interface contains a process flow sheet view for graphical layout, data browser view for entering data.
- **Simulation Basic Manager**: This feature available in Aspen Hysys for using different fluids like nitrogen, air, acetylene as per requirement. Also several fluid packages like Bing Robinson and ASME are provided to calculate properties at different states.
- **Design Specification** capabilities to automatically calculate operating conditions or equipment parameters to meet specified performance targets.
- **Plot Wizard.** Enables the user to easily create plots of simulation results.

3.2 APCI Liquefaction Cycle Modeling

Currently, about 77% of base-load natural gas liquefaction plants employ propane pre-cooled mixed refrigerant (APCI) cycle. In this process, as shown in Figure 3.1, the feed gas is sent to a gas sweetening unit for removal of H_2S, CO_2, H_2O and Hg. Subsequently, the feed gas temperature is reduced to approximately -30°C by passing through the pre-cooler and cold box. This process results in condensation of certain gas components which are be separated from the remaining gas in the separator.

The condensate is sent to the fractionation unit, where it is separated into propane, butane, pentane, and heavier hydrocarbons.

The remaining gas is sent to the cryogenic column where it is liquefied and cooled to below -160°C which is the natural gas boiling temperature at atmospheric pressure. After the cryogenic column, the LNG pressure is reduced to atmospheric pressure by passing it through the LNG expansion valve or expander. As shown in Figure 3.1, two refrigeration cycles are involved in the cooling and liquefaction of natural gas. These cycles are the propane cycle and the multi-component refrigerant (MCR) cycle. The propane cycle supplies the cooling demands of the pre-cooler, cold box and fractionation unit. The MCR cycle provides the cooling demand of the cryogenic column. Both the propane cycle and the MCR cycle condensers are typically cooled by sea water. Throughout this dissertation it is assumed that the sea water temperature and the ambient air temperature are 35ºC and 45ºC respectively.

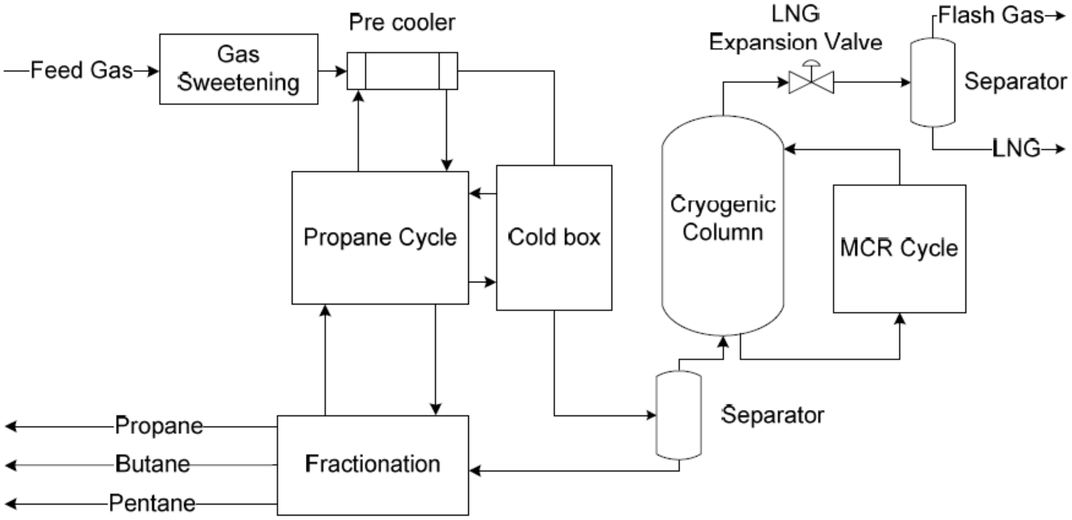


Figure 3-1 Schematic diagram of propane pre-cooled mixed refrigerant (APCI) Cycle (Mortazavi et al., 2010).

To perform an Aspen Hysys v [7.3] simulation the following parameters should be specified:

- Flow rates, compositions and operating conditions of the inlet streams.
- Operating conditions of the blocks used in the process, e.g., temperature and pressure.
- Operating heat and/or work inputs into the process. Flow rates, compositions.

The Hysys model convergence tolerances for the relative residuals were set to be 1×10-4. Due to the fact that heavier hydrocarbons do not affect the liquefaction cycle performance significantly, hexane plus hydrocarbons are approximated by n-hexane and iso-hexane with 0.16 and 0.24 for their mole fractions, respectively. The compressors of propane and MCR cycles are assumed to be centrifugal and axial types, respectively. All the condensers and inter-coolers are assumed to be cooled by sea water. The propane cycle is assumed to have five stages of cooling.

All the expansion processes of the APCI liquefaction cycle were done by expansion valves "The expansion process inside an expansion valve is assumed to be isenthalpic"

, which is true for some of the APCI's LNG plants. In this dissertation this cycle option is referred as "*APCI base cycle"*. The flash gas recovery process after the expansion of LNG is not considered.

Some of the other modeling assumptions used are listed in Tables: 3.1, 3.2 the schematic of the *APCI base cycle* modeled is shown in Figure 3.2. In Figure 3.2, the propane and MCR cycle refrigerant streams are shown by the red and blue streams respectively.

The natural gas streams undergoing liquefaction process are shown also by the blue streams. The streams from the separators are in liquid phase and are sent to the fractionation plant where they are separated into ethane, propane, and butane and pentane-plus. The ethane is sent to the cryogenic column for liquefaction. Ethane is then mixed with the liquefied natural gas before the expansion process.

Table 3-1 Gas composition after sweetening

Component	Mole fraction (%)
Methane	85.995
Ethane	7.5
Propane	3.5
i-butane	1
n-butane	1
i-pentane	0.3
n-pentane	0.2
Hexane plus	0.4
Netrogen	0.1
Carbon dioxide	0.005
Total	100

\

Table 3-2 MCR composition

Component	Mole fraction (%)
Netrogen	**8**
Methane	**36**
Ethane	**47**
Propane	**8**
Total	**100**

Table 3-3 Modeling assumptions

Axial compressor isentropic efficiency	**0.86**
Centrifugal compressor isentropic efficiency	0.83
Sea water temperature	35°C
Refrigerant temperature at condenser or super-heater exit	40°C
LNG temperature at the exit of cryogenic column	-160
Degree of superheating in propane cycle	10k
LNG expander exit pressure	101.3 kPa

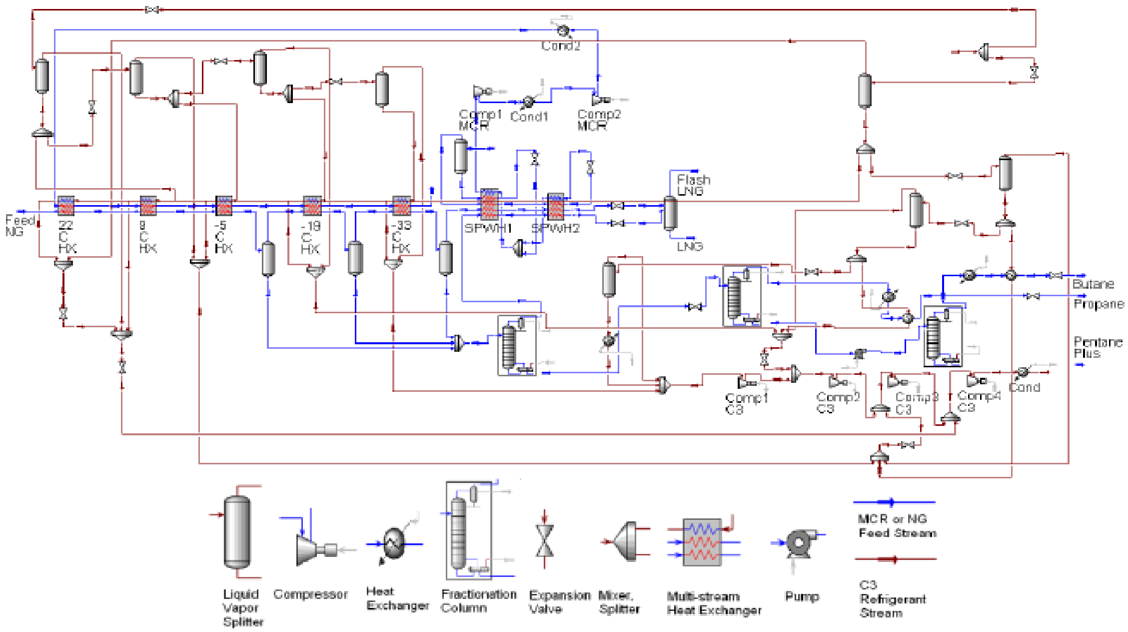


Figure 3-2 APCI base cycle modeled with HYSYS (Mortazavi et al., 2010).

3.3 Open cycles

The refrigerant which is used as cooling agent in liquefaction can be considered as a part of the gas stream in open cycles. General outline of an open cycle process can be seen in Figure (3-3). The feed gas is compressed with a compressor (CP in figure 3.3) and then cooled down to ambient temperature via heat exchanging units (HE in figure).

Cooled gas liquefaction is achieved via a turbo expander (TEX in figure), and work which can be utilized within the process is produced during expansion. Finally, liquefied gas is sent to a flash tank in order to remove its N2 content.

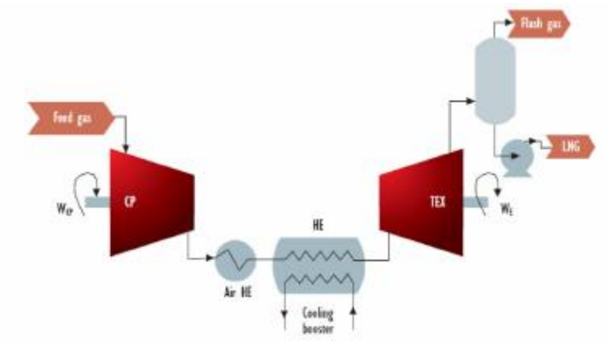


Figure 3-3 Open cycle (Petterson et al, 2007)

3.4 Closed cycles

In contrast to open cycles, the refrigerant is not a part of the gas stream in closed cycles. The refrigerant is supplied externally. General outline of a closed system can be seen in Figure 3.4. The refrigerant is compressed first (CP in figure), then cooled down via a heat exchanger (HE in figure) and cooled further in a cryogenic heat exchanger (MCHE in figure). Refrigerant leaving the cryogenic heat exchanger is expanded (TEX or E-V in figure) to obtain low pressure refrigerant at low temperature and work is produced at the same time to drive the compressor.

The expansion can be achieved either by a throttle valve which simply acts as an isenthalpic orifice, or an isenthalpic expansion engine. The difference between these two is that throttling provides only cooling while an expansion engine produces work in addition to cooling.

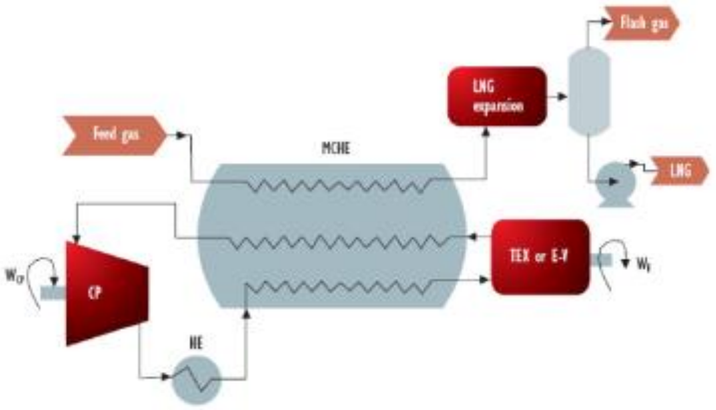


Figure 3-4 Closed cycle (Petterson et al, 2007)

3.5 Reductive C3MR base Process

The Peng-Robinson equation of state was selected for modeling the property of substances.

Since this thesis focuses on enhancing the energy efficiency of C3MR and from the base cycle we made some changes:

- Firstly we assumed that we are using a propane with conditions meet with the already used conditions in base cycle and thus we neglected the propane cycle (separators and compressors).
- We neglected the fractionation process because we used feed with
- (Methane –ethane) and less present of nitrogen.
- We assumed that the feed is firstly exchange heat with propane in heat exchanger unit (cold box), and the outlet feed from the heat exchanger unit enters multi component refrigerant unit (cryogenic column).
- Data assumed and selected was feed gas contains: (88.9% methane, 11% ethane and 0.1 nitrogen).
- Also for the C3MR process : (Feed Gas Temperature:30°C, Feed Gas Pressure:5bar, Natural gas pressure drop in heat exchangers

(cold box):0.5bar, Feed Gas Molar Flow rate: 12 MMSCFD, Natural Gas pressure Drop in cryogenic column: 0.45bar, Propane Feed Temperature: -20°C, Propane Feed Pressure: 50 bar, Propane feed Molar flow: 5 MMCSFD, Propane pressure drop in heat exchangers (cold box): 0.5 bar, Cooler pressure drop: 0.5 bar, MCR Feed Temperature: -121°C, MCR Feed Pressure: 38.5 bar and MCR Pressure Drop in cryogenic column: 3.5 bar).

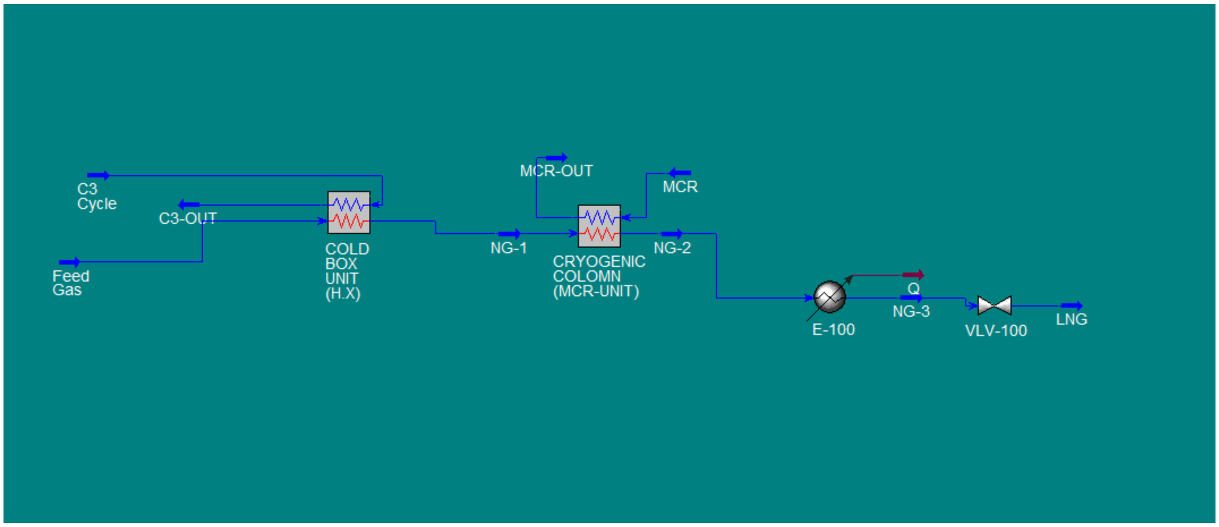


Figure 3-5 Reductive C3MR base Process modeled with HYSYS

To represent the above reduced C3MR in Aspen Hysys the first step is select components that we need in the cycle (methane, ethane, propane and nitrogen) to make a process flow diagram (PFD). In Simulation Basic Manager a fluid package is to be selected along with the fluid which is to be cycled in the process. Peng-Robinson is the fluid package. Now using an option “Enter to simulation Environment” PFD screen is started. Also select blue stream arrow twice, stream 1 for propane cycle and stream 2 for feed gas then enter specification and assumptions of feed gas and propane stream (temperature, pressure, molar flow rate and mole fraction).

Then select LNG heat exchanger (cold box unit): used in the simulation is a LNG H.E Where the hot fluid is feed gas and the cold is the propane.

After that the cold NG stream which coming out from the cold box exchange heat with the mixed component refrigerant in the cryogenic column (MCR unit).

3.6 The Proposed APCI liquefaction process

The APCI base cycle efficiency could be improved by replacing expansion valves with expanders. Liquid turbines or hydraulic turbines are a well-established technology. They are available with efficiencies over 90%. They can easily replace expansion valves used in the MCR cycle and the LNG expansion process. For the expansion valves used in the MCR cycle and the LNG expansion process, only two-phase expanders were considered.

- **Expander :-**

It a rotating device used for expansion of separated fluid in the splitter. The expansion process is assumed to be isentropic. Adiabatic efficiency of expander is varied from 70%-90%for different case studies.

After that we made a change in the reduced process, by replacing the expansion valve with turbine and adding a separator and mixture, then we simulated the new proposed process shown in figure (3.4) below.

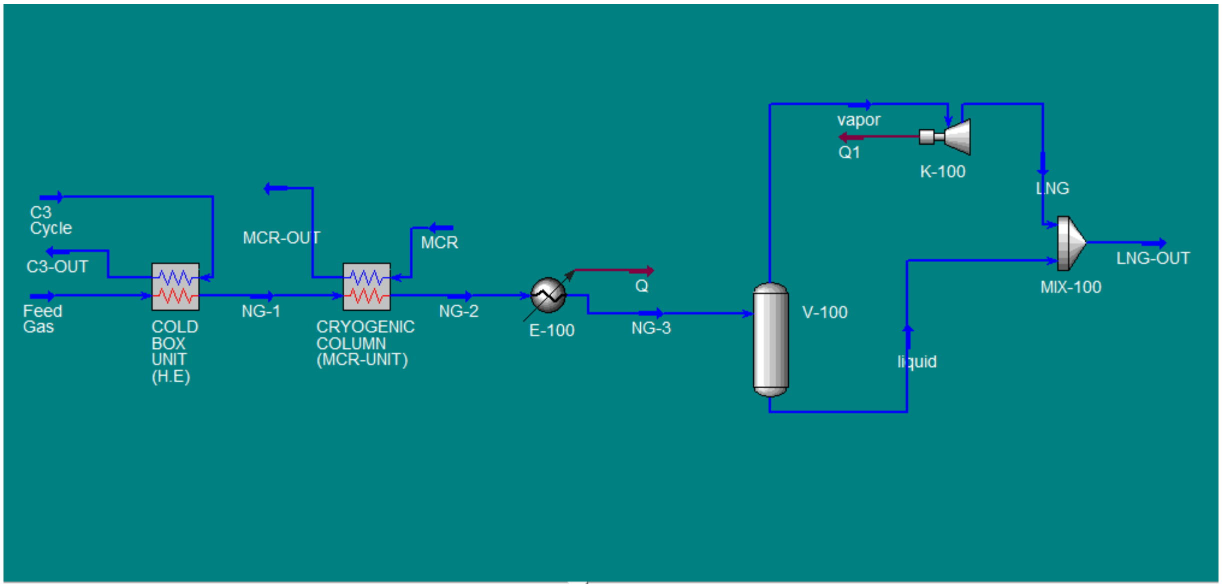


Figure 3-6 Proposed C3MR liquefaction process

Simulation results for the above C3MR cycle will be discussed in chapter-4. Also a Comparison between the base cycle and the enhanced cycle is done to show the more efficient process of liquefaction.

Chapter Four

4 Result and discussion of energy consumption

4.1 Base C3MR cycle results

Table 4-1 BASE C3MR energy consumption

Propane compressor power	43.7 MW
MR compressor power	66.5 MW
Propane cycle cooling capacity	115.5 MW
MR cycle cooling capacity	67.6 MW

These results all energy consumptions of the base cycle from the preparation of the propane, MCR, and the liquefaction area of the cold box and cryogenic column.

The results obtained from the basic cycle showed that the whole process needs about 293.3 MW.

Base cycle energy consumption in liquefaction area per amount of natural gas

Table 4-2 Energy consumption in liquefaction area per amount of natural gas

Propane cycle cooling capacity	115.5 MW	$415.8*10^6$ KJ/hr
MR cycle cooling capacity	67.6 MW	$243.36*10^6$ KJ/hr
Total	183.1 MW	$659.16*10^6$ KJ/hr

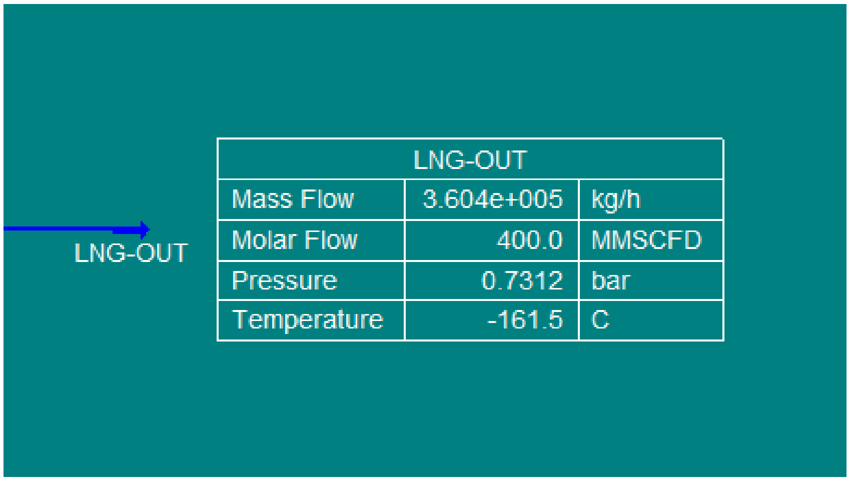
Energy needed to convert NG to LNG:

Feed = 100 kg/s NG = 360000 Kg/hr

E= $659.16*10^6$ KJ/hr / 360000 kg/hr = 1831 kJ/kg.

The simulation showed energy consumption about 1831 kJ/kg in the heat exchange area between the NG with propane and MR respectively.

Produced LNG specification from base cycle simulation



LNG-OUT		
Mass Flow	3.604e+005	kg/h
Molar Flow	400.0	MMSCFD
Pressure	0.7312	bar
Temperature	-161.5	C

Figure 4-1 Produce LNG specification

We made the simulation using hysys software instated of aspen plus used in base cycle and that led to a small difference in the base results. (Mortazavi et.al. 2011) [10]

Reduced C3MR with valve results

Table 4-3 Reduced C3MR with valve results

Propane compressor power	14.6 MW
MR compressor power	66.5 MW
Propane cycle cooling capacity	15.8 MW

MR cycle cooling capacity	6.92 MW
Cooler cooling capacity	23.3 MW

These results all energy consumptions of the reduced C3MR from the preparation of the propane, MCR, and the liquefaction area of the cold box and cryogenic column respectively.

The results obtained showed that the whole process needs about 127.12 MW.

Note: propane compressor power is less than the base by 33% approximately because we are using propane with -20 °C.

Reduced C3MR with valve energy consumption in liquefaction area per amount of natural gas

Table 4-4 Energy consumption in liquefaction area

Propane cycle cooling capacity	15.8 MW	$5.69*10^6$ KJ/hr
MR cycle cooling capacity	6.92 MW	$2.49*10^6$ KJ/hr
Cooler cooling capacity	23.3 MW	$8.4*10^6$ KJ/hr
Total	46.02 MW	$16.58*10^6$ KJ/hr

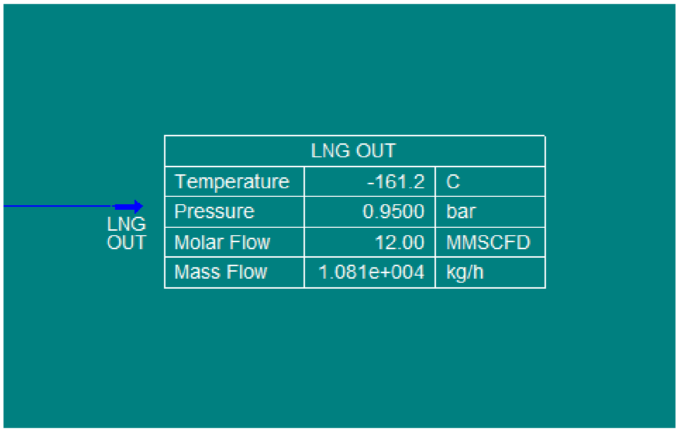
Energy needed to convert NG to LNG:

Feed = 3.003 kg/s NG = 10810 Kg/hr

E= $16.58*10^6$ KJ/hr / 10810 Kg/hr = 1533.77 kJ/kg.

The simulation showed an energy consumption about 1533.77 kJ/kg in the heat exchange area between the NG with propane and MR respectively.

Produced LNG specification from reduced C3MR with valve



LNG OUT		
Temperature	-161.2	C
Pressure	0.9500	bar
Molar Flow	12.00	MMSCFD
Mass Flow	1.081e+004	kg/h

Figure 4-2 Produced LNG specification from reduced C3MR with valve

4.2 Proposed C3MR with turbine (expander)

Table 4-5 reduced C3MR with turbine energy consumption

Propane compressor power	14.6 MW
MR compressor power	66.5 MW
Propane cycle cooling capacity	15.8 MW
MR cycle cooling capacity	6.92 MW
Cooler cooling capacity	23.3 MW
Turbine recovery	-1.56 MW

These results all energy consumptions of the reduced C3MR from the preparation of the propane, MCR, and the liquefaction area of the cold box and cryogenic column respectively.

The results obtained showed that the whole process needs about 125.56 MW.

Note: the turbine recovery is a gained energy and thus it is subtracted from the process with the valve and that why it is in negative sign.

Proposed C3MR with turbine energy consumption in liquefaction area per amount of NG

Table 4-6: Energy consumption in liquefaction area

Propane cycle cooling capacity	15.8 MW	$5.69*10^{6}$ KJ/hr
MR cycle cooling capacity	6.92 MW	$2.49*10^{6}$ KJ/hr
Cooler cooling capacity	23.3 MW	$8.4*10^{6}$ KJ/hr
Turbine recovery	-1.56 MW	$-0.6*10^{6}$ KJ/hr
Total	44.46 MW	$15.98*10^{6}$ KJ/hr

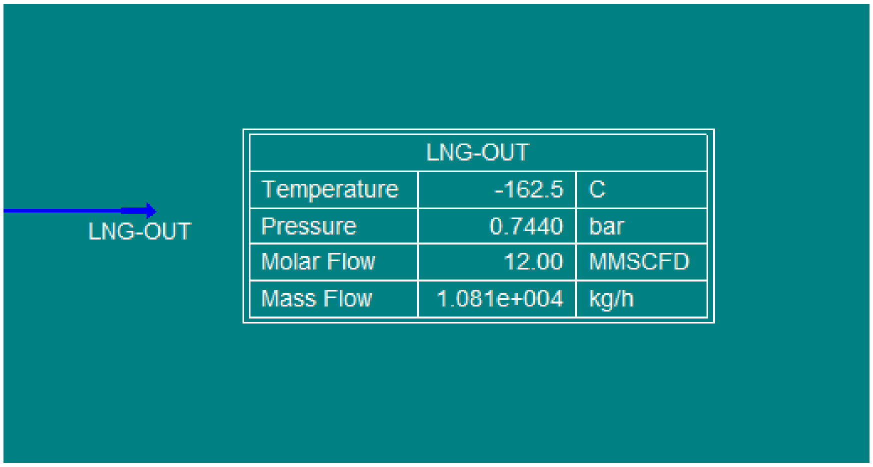
Energy needed to convert NG to LNG:

Feed = 3.003 kg/s NG = 10810 Kg/hr

E= $15.98*10^{6}$ KJ/hr / 10810 Kg/hr = 1478.3 kJ/kg.

The simulation showed an energy consumption about 1478.3 kJ/kg in the heat exchange area between the NG with propane and MR respectively.

Produced LNG specification from proposed C3MR with turbine



LNG-OUT		
Temperature	-162.5	C
Pressure	0.7440	bar
Molar Flow	12.00	MMSCFD
Mass Flow	1.081e+004	kg/h

Figure 4-3 produced LNG specification

Chapter Five

5 Conclusion and Recommendation

Natural gas is generally considered a nonrenewable fossil fuel. Natural gas is called a fossil fuel because most scientists believe that natural gas was formed from the remains of tiny sea animals and plants that died 200-400 million years ago, Natural gas is what is used to describe a gas composed of a mixture of different hydrocarbons, compounds made of carbon and hydrogen, being pulled from the ground, The global energy demand is increasing and the natural gas (NG) has obtained relevance as a clean fuel but there was a problem of delivering the natural gas to consumers and thus it become a nessacery to liquefy the NG for ease of transportation and storing.

LNG is natural gas that has been cooled to the point that it condenses to a liquid, which occurs at a temperature of an approximately (-256℉-161℃) at atmospheric pressure. Liquefaction reduces the volume of gas by approximately 600 times thus making it more economical to store natural gas where other forms of storage do not exist, and transport gas over long distances for which pipelines are too expensive or for which other constraints exist, Total global natural gas demand is estimated to have grown by about 2.7% per year since 2000 however; global LNG demand has risen by an estimated 7.6% per year over the same period, almost three times faster. LNG demand growth is, however, expected to be even stronger, particularly through 2020.

Liquefied natural gas (LNG) plants consume a great amount of energy. In order to enhance LNG plant energy efficiency, Liquefaction is the most capital and energy intensive component of the LNG value chain. It consists of processes that chill natural gas to the point where it becomes converted to a liquid, i.e., at an average temperature of minus 161 ºC (minus 258 ºF). In order to achieve this low temperature, the gas transfers heat to a refrigerant fluid that has been previously chilled in a cooling cycle so that, in effect, this fluid steals the heat from natural gas until it is liquid. This is a process with an intensive consumption of energy; also there are many processes for preparing NG to be liquefied.

There are many processes of liquefaction but the APCI (Air Products and Chemicals Inc.) process, also called Propane Pre-cooled Mixed Refrigerant Process (PPMR) currently holds 80% of the liquefaction plants on the market many studies and researches had been done one this cycle from changing the refrigerants and changing the size of exchangers, and in our project we used the aspen hysys software to obtain a proposed processes that increase the efficiency in terms of reduction in energy consumed and we result in that we have to use turbines instead of expansion valves and that led to an energy saving opportunity by 19 % according to the results of the simulator.

Recommendation:

We recommend that more studies should be done in modeling the base APCI (C3MR)

cycle to obtain more precise result and thus better proposed cycle .

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