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Energy Saving and Performance Enhancement of propane pre-cooled mixed refrigeration cycle in LNG plants

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Abstract

Production of liquefied natural gas (LNG) requires a huge amount of energy, therefore Enhancing the plant's energy efficiency is one of the most significant issues in a natural gas liquefaction facility. This study aims to improve the energy efficiency of the propane pre-cooling mixed refrigerant (C3MR) process by two approaches. first by minor structural modification of the existing cycle to reduce the shaft power of the compressor as it is the major energy-consumption unit in LNG plants by about 2.2 (MW/MTPA LNG) that results in increasing coefficient of performance (COP) of the refrigeration cycle. The Second approach investigates the feasibility of applying a hybrid modification of the AP-X process, designed by Air Products and Chemicals Incorporation (APCI), and a comparative study between conventional and modified cycles. The case study is a plant existing in Egypt and it is simulated by Aspen HYSYS version 11. The simulation results show two advantages after implementation of cycle modification: a reduction in total specific power by 12.5% by reduction in the flow rate of propane and mixed refrigerant by 26.1% and 40.8 % respectively. Another feature is increasing LNG production capacity to about 8 MTPA.

Keywords: *Liquefied Natural Gas (LNG); Mixed Refrigerant (MR); Energy Efficiency; Expansion Process; Simulation.*

1. Introduction

Natural gas is one of the cleanest, safest, and most useful of all energy sources as it is considered the most energy-efficient fossil fuel and it is gaining a growing share in the global energy market [1]. The demand for natural gas has recently increased due to the fact that natural gas is one of the cleanest fossil fuels and it is an environmentally friendly energy source so, it is desirable for countries seeking to reduce greenhouse gas emissions (CO_2 emissions) due to its lower carbon content when compared to other fossil fuels as the world moves towards a lower carbon economy.

The two major traditional methods of transportation of natural gas for long-distance are via pipeline or by liquified natural gas (LNG). Currently, liquefied natural gas technology is the most common method of transporting natural gas as it offers greater trade flexibility than the pipeline method. LNG plants consume a great amount of energy, as the liquefaction of 1 kg of natural gas needs about 1188 kJ of energy [2] depending on the liquefaction cycle and site conditions.

There are various liquefication processes with different refrigeration systems, The main three cycles are cascade, mixed refrigerant, and expansion cycle. A general closed refrigeration cycle consists of four components: compressor, condenser, expansion valve, and evaporator. Most of the LNG plant's energy consumption occurs in the compressor drivers where fuel energy is converted to mechanical work. There are several ways to improve cycle efficiency such as optimizing the refrigerant composition, pressure, and mass flow rate, or improving cycle components such as expansion valves and heat exchangers [3].

This study represents the propane pre-cooling mixed refrigerant cycle(C3-MR), developed by Air Products and Chemicals Incorporation (APCI) [4], as it accounts for a very significant portion of the world's base load LNG production capacity, and it is the most predominant cycle in the LNG industry among all available cycles [2]. So, it is essential to improve its energy efficiency and enhance performance.

Although there are many publications on the analysis and enhancement of LNG plants, only limited refrigeration cycles have been studied in the open research literature such as the single mixed refrigerant (SMR) which is the simplest LNG mixed refrigerant liquefaction cycle for LNG production at small scale.

The main objective of this study is to investigate and evaluate the performance of the conventional propane pre-cooling mixed refrigerant cycle and the modified cycle and then make a comparison in terms of energy saving, capacity, and cost. Finally, select the most effective refrigeration cycle configuration.

Risk analysis for LNG Plant units is highly effective in identifying risky operations and necessary precautions. The more profitable LNG plant is achieved after applying the risk assessment method [5].

2. Methodology

The study of existing and modified cycles was conducted using Aspen Hysys (Version-11) simulation software to detect the effect of propane pre-cooling mixed refrigerant cycle modification. The Peng-Robinson (PR) equation of state (EOS) is widely used in the oil and gas industry and research to model liquefaction processes for LNG production. Also, the Peng–Robinson Stryjek-Vera (PRSV) equation of state gives the lowest deviation percent to the actual data [6].

2.1. Case study

Egypt has a lot of key drivers that make LNG a growing industry. This work represents an existing Damietta LNG plant which was the first facility of its type in Egypt and is one of the world's largest capacity single-train facilities. The composition and condition of feed natural gas and mixed refrigerant, used in this study, is presented in Table 1 & 2 respectively.

Table 1. Condition of feed natural gas

Feed natural gas	
Inlet temperature, °C	21.8
Inlet pressure, bar	63
Mass flow, kg/h	639324
Composition	Mole%
CO_2	0.16
N_2	0.43
C1	98.23
C2	1.07
C3	0.09
i-C4	0.01
n-C4	0.01

Table 2. Condition of mixed refrigerant

Mixed refrigerant (MR)	
Inlet temperature, °C	18.2
Inlet pressure, bar	62.2
Mass flow, kg/h	1352966
Composition	Mole%
N_2	7.62
C1	43.46
C2	41.16
C3	7.76

2.2. Simulation of the (C3-MR) process

The (C3-MR) process as shown in Figure 1 has two refrigerant cycles, the first cycle is the pre-cooling closed loop which uses a pure propane refrigerant in a series of three heat exchangers at different pressure levels, as shown in Figure (2) to supply refrigeration cooling to natural gas feed and mixed refrigerant to -30°C. After that is the liquefication cycle by using a mixture of nitrogen, methane, ethane, and propane which is known as a mixed refrigerant that is sent to a flash drum to separate into a vapor stream (LMR: the stream contains lighter components) and liquid stream (HMR: the stream contains heavier components) [7]. then passed through a multi-stream heat exchanger to liquefy feed gas which is directly sent to the main cryogenic heat exchanger (MCHE) that consists of warm and cold bundles to provide the sufficient surface area needed for a close temperature approach between natural gas and mixed refrigerant. Finally, the natural gas is liquefied and cooled down to −160 °C when it comes out from the MR cooling system. Its pressure is reduced to atmospheric pressure by passing through an expansion valve.

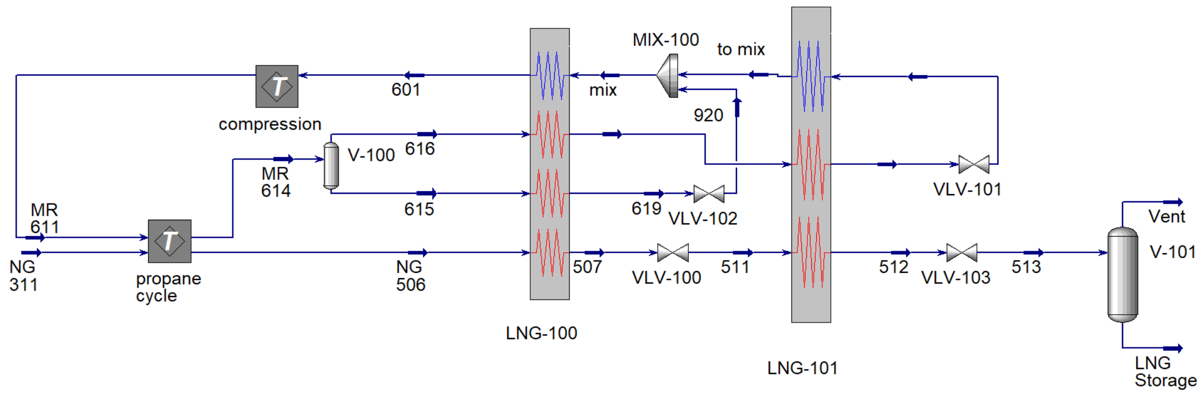


Figure 1. C3-MR process

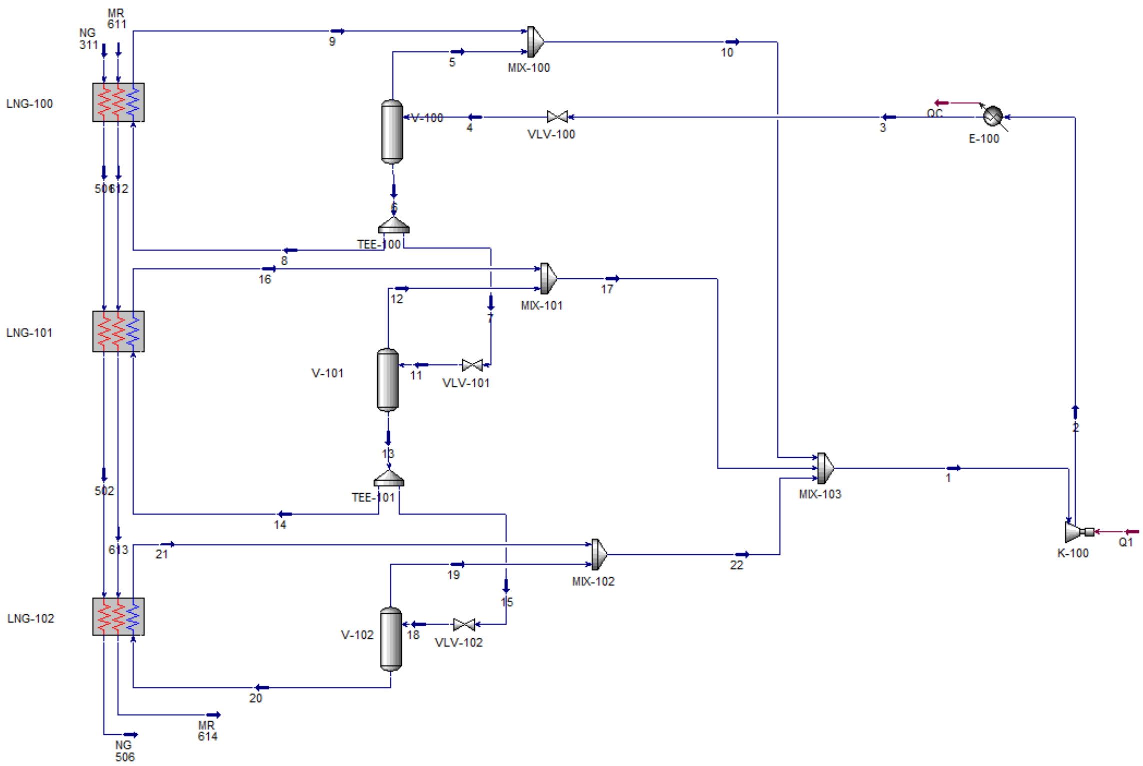
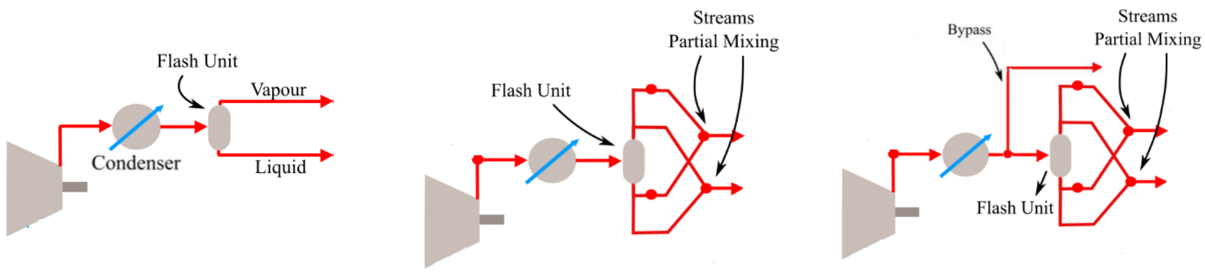


Figure 2. Propane pre-cooling closed loop

2.2.1. Configuration modification

This first contribution of this work is to investigate structural change to (C3-MR) cycle. The objective is to minimize shaft work demand which depends on the refrigerant flow rate, composition, pressure, and temperature. There are three options as presented in Figure (3) [8-9]. These cycles are: the Pre-Flash base cycle (Figure 3-a), the CryoMan cycle (Figure 3-b), and bypass cycle (Figure 3-c).



(a) Pre-Flash cycle (b) CryoMan cycle (c) Bypass cycle

Figure 3. Structural modification: a) Pre-Flash cycle; b) CryoMan cycle; c) Bypass cycle (modified [7-8])

In the Pre-Flash cycle, a phase separator is used to split the refrigerant to form the liquid and vapor phases as the two streams of refrigerant. in the CryoMan cycle the separated liquid and vapor streams are partially mixed to form the two refrigerant streams that provide cooling in the MCHE. In contrast to the CryoMan cycle, the Bypass cycle structural modification consists of an additional refrigerant stream that goes around the phase separator. This bypass stream's composition is identical to that of the overall refrigerant stream.

This modification results in different composition of the light and heavy mixed refrigerant and the important parameter is the outlet temperature. The temperature resulting from mixing of two refrigerant streams is calculated from an enthalpy balance around the mixing point [10-11]. It is well-known from Thermodynamics that the compression work is proportional to the specific volume and the amount of work needed to compress a gas can be reduced by lowering the inlet gas temperature [12].

According to the conceptual modifications that can be implemented in the C3-MR process, only designs that show shaft power savings are considered for optimization of their operating variables [13]. Since there are many variables involved in designing the APCI LNG plant, the optimization problem is, computationally, very expensive [14]. So, optimization is not considered in this study as it is considered future work after the development of the modified cycle.

2.3 Simulation of the (AP-X) process

The AP-X^{TM} process cycle is an improvement to the C3-MR process in that LNG is subcooled using a simple, efficient nitrogen expander loop instead of mixed refrigerant [15]. The AP-X process as illustrated in Figure 4 has three refrigeration cycles: a propane pre-cooling cycle, a mixed refrigerant liquefaction cycle, and a nitrogen sub-cooling cycle.

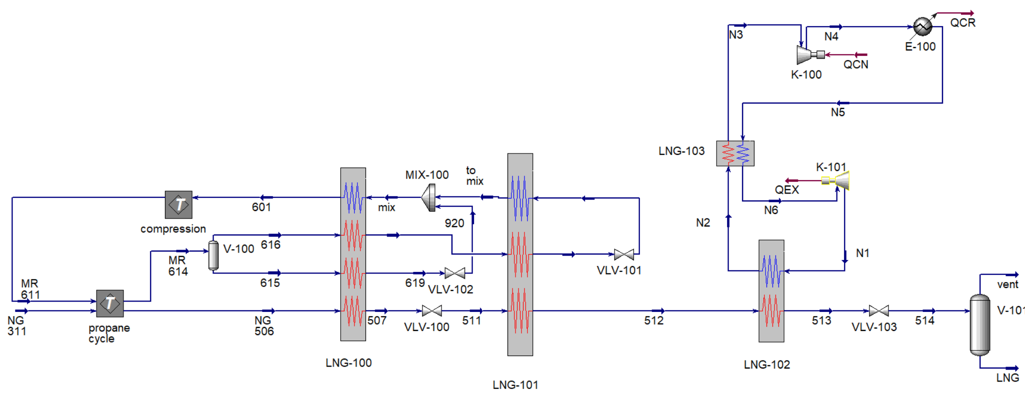


Figure 4. AP-X process

To reach LNG conditions, a certain amount of energy is required for each step. Similar to the C3-MR process the propane cycle cools down natural gas and mixed refrigerant from ambient temperature to (-30°C) in LNG exchangers, however, natural gas is partially sub-cooled in the liquefaction cycle with a mixed refrigerant in the MCHE and the temperature exiting is about (-105°C to -117°C), and finally A sub-cooling refrigerant that is composed of pure nitrogen to liquefy the natural gas to (-160°C) by using expander loop. After that reduction in pressure by an expansion valve to reach the atmospheric pressure of the LNG stream which is introduced to the storage unit.

AP-X process is complex and involves many design variables that always interact with each other: optimisation of the process requires variables to be optimized simultaneously [16]. This work represents the possibility and feasibility of applying the AP-X process and its effect on the conventional process. A thermodynamic-analysis-based study is required for evaluation and possible improvement of a general NG liquefaction process [17].

3. Results and discussion

3.1. Structural modification

In the case study presented the shaft work for compression mixed refrigerant in the base case is equal to 118.7 MW, for the CryoMan cycle this work can be reduced by an amount of 2.2(MW/MTPA LNG), For the bypass process, the shaft work demand can also be reduced to 115.8 MW. It is a minor energy-saving but still a good attempt for enhancing energy efficiency.

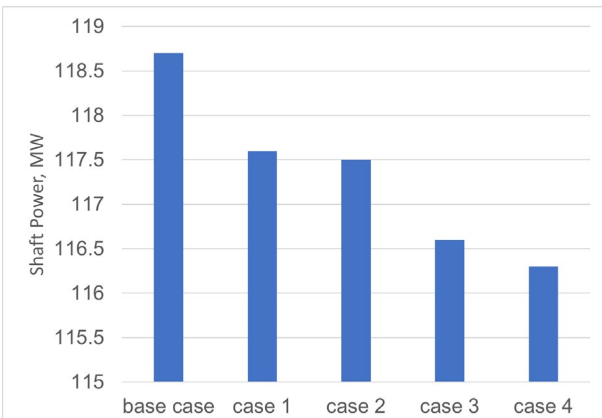


Figure 5. Shaft power for four cases in CryoMan process

Figure 5 represents the shaft power of the four cases for different partial mixing ratios. As the vapor phase is highly composed of the light components in the refrigerant mixture (60% is methane compared to only 1.7% of propane). on the other hand, for the liquid stream (38% is methane compared to 9.5% of propane). The shaft power varies according to the composition of each stream after mixing and also the inlet temperature to the compressor that leaves MCHE. The function of partial mixing is getting an intermediate composition of light mixed refrigerant (LMR) and heavy mixed refrigerant (HMR) as shown in Table 3 for the four cases.

Table 3. Composition of refrigerant streams after mixing for four cases and the inlet temperature to the compressor

Base case		Case 1		Case 2	
LMR 100% vapor	HMR 100% liquid	LMR 50% vapor 50% liquid	HMR 50% vapor 50% liquid	LMR 70% vapor 50% liquid	HMR 30% vapor 50% liquid
C1=0.6046	C1=0.3837	C1=0.4346	C1=0.4346	C1=0.449	C1=0.4173
C2=0.2104	C2=0.4719	C2=0.4116	C2=0.4116	C2=0.3946	C2=0.432
C3=0.0169	C3=0.0958	C3=0.0776	C3=0.0776	C3=0.0724	C3=0.0838
N2=0.1681	N2=0.0486	N2=0.0762	N2=0.0762	N2=0.084	N2=0.0669
Temperature= -48.45°C		Temperature= -52.22°C		Temperature= -52.49°C	

Case 3		Case 4	
LMR 70% vapor 20% liquid	HMR 30% vapor 80% liquid	LMR 70% vapor 60% liquid	HMR 30% vapor 40% liquid
C1=0.4968	C1=0.406	C1=0.4409	C1=0.4242
C2=0.338	C2=0.4455	C2=0.4042	C2=0.4239
C3=0.0554	C3=0.0878	C3=0.0753	C3=0.0813
N2=0.1098	N2=0.0607	N2=0.0796	N2=0.0706
Temperature= -55.32°C		Temperature= -55.37°C	

3.2. AP-X process

This work investigates the effect of implementation of AP-X as a modified cycle in the retrofitting or expansion of the case study, an existing Damietta LNG plant, to improve the performance. The simulation results show a reduction in the total shaft power by about 10 MW for fixed parameter such as feed condition and compressor efficiency this energy saving, represents 12.5% for total specific power, results from reduction in propane and mixed refrigerant by 26.1% and 40.8% respectively as illustrated in Figure 6 for propane and Figure 7 for mixed refrigerant, in this case the feed gas flow rate remains the same as in base cycle.

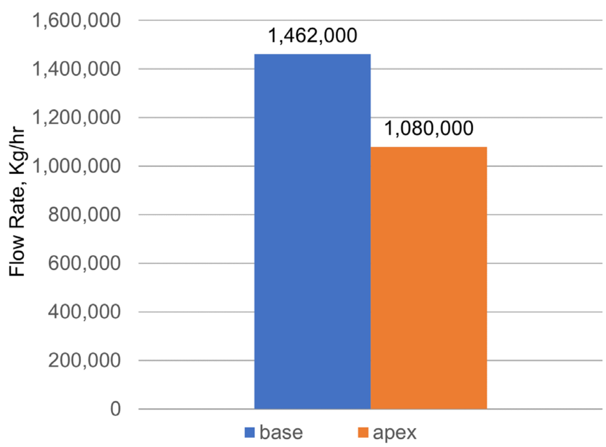


Figure 6. Reduction in flow rate of propane

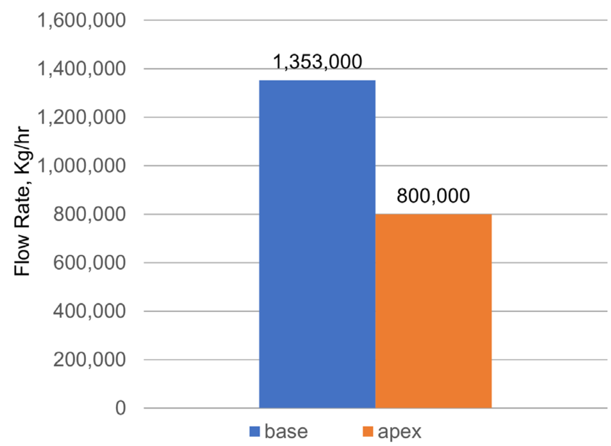


Figure 7. Reduction in flow rate of mixed refrigerant

Another feature of AP-X process is increasing the capacity, so the power saving will be utilized to increase LNG production rate, in this case there are some parameters that will be changed such as feed gas flow rate and nitrogen flow rate. A comparative study between conventional C3-MR cycle and modified AP-X cycle is done as shown in Table (4). The final evaluation parameter is the total specific power, in the case study represented the mass flow rate of feed gas increased by about 20% thus the LNG production rate increase by 28.6% and a reduction of total specific power by 2.72% is achieved.

Table 4. A comparative study between conventional C3-MR cycle and modified AP-X cycle

Parameter	Base cycle C3-MR	Modified cycle AP-X
Feed gas flow rate, Kg/hr	639324	767200
Temperature outlet from MCHE, °C	-132	-104
Total power, kW	161370	201820
LNG production rate, ton/day	12190	15680
Total specific power, kW/(ton/day)	13.23	12.87

4. Conclusion

The refrigeration cycles related to LNG production require a significant amount of shaft work for refrigerant compression, thus a reduction in power consumption could bring substantial operating cost savings to the LNG plant. It is necessary to enhance the plant's energy efficiency of the C3-MR process as it is the preferred option in LNG plants. Based on the findings of this study, the following conclusions can be drawn.

1- The structural modifications of mixed refrigerant cycles can yield significant savings in shaft work demand from 118.7 Mw to about 115.8 Mw, this is a minor percentage but still a good attempt for enhancing energy efficiency.

2- Expansion of existing plant capacity can benefit from economies of scale and improved efficiency due to lower capital cost per unit of production and better refrigeration power regeneration efficiency.

3- Possibility of applying AP-X Process plant in C3-MR mode by addition of Nitrogen sub-cooling loop to reduce the total specific power by 12.5%.
4- The simulation results of AP-X process show a significant reduction in mass flow rate of mixed refrigerant by 40.8% and also mass flow rate of propane by 26.1% of that required by the conventional C3-MR process.
5- The Feasibility study of the presented modified process revealed good plant profitability and a short payback period of less than one year.

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