OPTIMIZATION OF OPERATING PARAMETERS IN LNG AP-X PROCESS

By

Ho Nguyen Tuan Anh

Dissertation submitted in partial fulfillment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
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Approved by,

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(Assoc. Prof. Dr. Shuhaimi B Mahadzir)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
December 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the reference and acknowledgements, and that the original work contained herein has not been undertaken or done by unspecified sources or persons.

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HO NGUYEN TUAN ANH

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LIST OF ABBREVIATIONS

C3MR	**Propane mixed refrigerant**
NG	**Natural gas**
LNG	**Liquefied natural gas**
MCHE	**Main cryogenic heat exchanger**
Mta	**Million ton per annum**
SMR	**Single mixed refrigerant**

LIST OF FIGURES

ABSTRACT

Natural gas (NG) has been known as the cleanest fossil fuel since it releases low level of harmful products when being burnt. Natural gas can be transported either in pipelines or in liquefied natural gas (LNG) carriers. In LNG carriers, LNG is liquefied to the temperature of -162 degree Celsius at atmospheric pressure so that its volume can be reduced up to 600 times. There are a lot of techniques available for liquefying natural gas. The most potential technique developed by APCI is AP-X process. This is an improvement from C3MR process by using nitrogen in the sub-cooling loop at the end of the process. It is very beneficial to know the optimum refrigerant flow rate for the purpose of saving energy consumed in the process. Moreover, the operating refrigerant flow rate also is optimized with subject to the compensation with the compressor load and the energy efficiency. HYSYS software is utilized to model the nitrogen loop of AP-X process. LNG flow rate, compressor load and heat duties exchanged are taken from HYSYS model. In this study, the optimum pure nitrogen flow rate was found to be at around 2500 kg/h. Besides, the flow rate for 5% methane mixed refrigerant is 2375 kg/hr, so that the process is most beneficial in term of revenue as well as energy efficiency. The optimum capacity of LNG plant using AP-X process is found at 9.1 MTPA, according to around 13.5% increase in train capacity compared with the current operating train capacity in Qatar.

ACKNOWLEDGEMENT

The past 28 weeks of my enrolment in this final year project have been truly a valuable experience to me. Hence, I would like to take this opportunity to express my sincerest gratitude to a number of people that have helped me throughout this project.

First and foremost, I would like to extend my heartfelt gratitude and appreciation to AP. Dr Shuhaimi B Mahadzir, my supervisor, who has supervised me throughout my project period. His ever willingness to teach and guide me has helped tremendously in achieving the goals of my final year project. On top of that, he was constantly supportive of the decisions that I make and is always there to share his knowledge and experiences with me. Besides that, I also would like to thank all the lab technicians and chemical engineering department staffs who have contributed to my project.

Last but not least, special thanks to my friends and family, and to anybody who has contributed directly and indirectly towards accomplishing the objectives of this final year project. In short, I feel blessed to have successfully completed my final year project.

CHAPTER 1

INTRODUCTION

1. BACKGROUND OF STUDY

Natural gas (NG) has been known as the cleanest fossil fuel since it possesses many advantages such as giving off a great deal of heating energy when being burnt and emits lower levels of potentially harmful by-products. Usually, NG is transported either in pipelines or in liquefied natural gas carriers after exploration and treatment.

The liquefied natural gas (LNG) is produced by refrigerating NG sources from ambient temperature to around −162 °C. Liquefying natural gas can reduce its volume by 600 times, in such a form that NG can be shipped more economically worldwide. The earliest LNG liquefaction plants consisted of fairly simple liquefaction process based on either cascaded refrigeration or single mixed refrigerant (MR) and could process with train capacities less than one million tons per annum (MTPA). Air Products and Chemicals Inc. (APCI) developed the two-cycle propane pre-cooled mixed refrigerant (C3MR) process which became the dominant liquefaction process technology by the late 1970s. It is still competitive in many cases, although Shell Inc. claims that there are inherent limitations of using a single component refrigerant for pre-cooling in the C3MR design, and the Shell double mixed refrigerants (DMR) process could overcome such limitations. Recently, three-cycle processes such as the AP-X™ and the ConocoPhillips Optimized Cascade have been selected for some new LNG projects.

Although C3MR process possesses the seat of the preferred option in many cases, there still is substantial developing demand for larger train sizes. For example, trains using multiple GE Frame 7 or Frame 9 gas turbine drivers or large electric motors can be configured. While there still is potential to further increase train capacity with a C3MR process, new designs must be developed for several major equipment items at capacities exceeding 5.0 Mta. For example, the propane and centrifugal MR compressors are approaching single casing flow limits at current world scale LNG plant production levels. In response to continuing customer demand for increased LNG train capacity and lower unit cost, Air Products has developed and patented [2] the AP-XTM LNG Process. The AP-XTM process cycle is an improvement to the C3MR process in that the LNG is sub-cooled using a simple, efficient nitrogen expander loop instead of mixed refrigerant. Other embodiments include a dual MR version where another MR refrigeration loop is used for pre-cooling and nitrogen is likewise used for sub-cooling.

Besides improving the efficiency, the nitrogen expander loop makes greatly increased capacity feasible by reducing the flow of both propane and mixed refrigerant. Volumetric flow of mixed refrigerant at the low-pressure compressor suction is about 60% of that required by the C3MR process for the same production. Mass flow of propane is about 80% of that required by the C3MR process. With the new AP-XTM process, train capacities in excess of 8 Mta are feasible in tropical climates, in existing compressor frame sizes, without duplicate/parallel compression equipment, and using a single spool-wound MCHE of a size currently being manufactured.

The nitrogen expander loop is a simplified version of the cycle employed by Air Products in hundreds of air separation plants and nitrogen liquefiers worldwide. Experience has shown these plants to be simple to operate and very reliable. Many of these plants are remotely operated, including shutdowns and restarts. The nitrogen cycle has also been employed by Air Products with similar success in small, stand-alone LNG peak-shaving plants.

The AP-XTM process cycle is depicted below in Figure 1. As is the case with C3-MR process, propane is used to provide cooling to a temperature of about -30 °C. The feed is then cooled and liquefied by mixed refrigerant, exiting the MCHE at a temperature of about -120 °C. Final sub-cooling of the LNG is done using cold gaseous nitrogen from the nitrogen expander. Figure 1 shows the equipment layout for the liquefaction and sub-cooling sections of an AP-XTM train. Coil-wound heat exchangers are used to liquefy and subcool the LNG, while the nitrogen economizer uses brazed aluminum plate-fin heat exchangers.

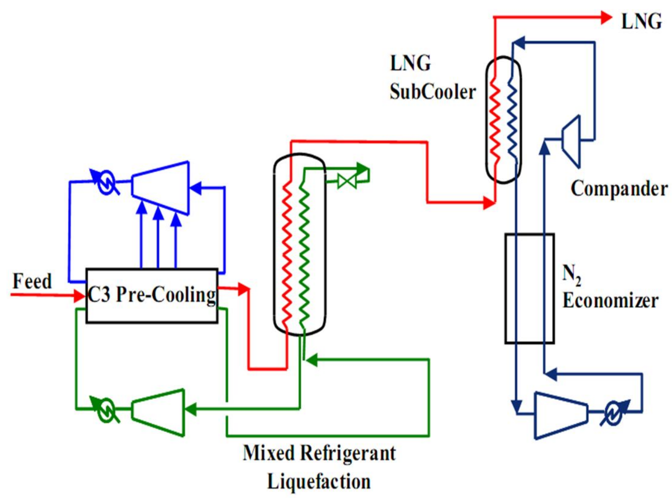

Figure 1: AP-X process

2. PROBLEM STATEMENT

LNG process is energy intensive. Methods for saving energy in LNG process have been studied by a few papers, in accordance with as many LNG processes currently exist. Some authors focus on the design of the process. Some focus on operating aspect of the process. However, most studies concentrate on some popular LNG processes such as APCI C3MR process, Prico process, Shell process.

AP-X is an improvement of APCI processes. The enhancement of AP-X over C3MR process is LNG is sub-cooled using a simple, efficient nitrogen expander loop instead of mixed refrigerant. The inlet LNG temperature of the nitrogen sub-cooling loop is around 115^{o}C. It is predicted AP-X will become the most popular process for producing LNG. Although it has a great potential to have an important role in LNG industry, there are not many studies about AP-X process. The flow rate of nitrogen has not been studied, even it is a very important factor in determining the energy consumption of the whole process. Therefore, it would be beneficial if a study to optimize the flow rate of nitrogen in the sub-cooling loop of the AP-X LNG process can be done.

3. OBJECTIVES

- ✓ To build up the sub-cooling loop of AP-X process into HYSYS for further study.
- ✓ To optimize the flow rate of pure nitrogen as well as mixed refrigerant in AP-X process.

4. SCOPE OF WORK

The focus of this study will be put into the nitrogen sub-cooling loop of AP-X process, including nitrogen economizer and compander. The propane pre-cooling loop and main cryogenic heat exchanger are similar to C3MR process which is studied widely by previous researches. By looking into details the nitrogen loop which is the enhancement of AP-X process over other processes, we can withdraw some beneficial conclusions for LNG energy consumption saving purpose for AP-X process specifically, and other LNG processes in general.

CHAPTER 2
LITERATURE REVIEW

LNG process is energy intensive. Therefore, there have been a lot of studies doing energy optimization in order to minimize the energy consumption in LNG process.

Wang, Zhang and Xu (2012) discussed a new methodology for LNG liquefaction synthesis targeting energy consumption minimization. The authors built up an appropriate superstructure for LNG liquefaction process synthesis. From the superstructure, an MINLP model for energy consumption minimization is generated. Aspen Plus version 7.3 is employed to generate the regression data when simplifying thermodynamic functions and conduct optimization result validation thereafter. Next, the optimization problem is solved by LINDO Global solver (LINDO Systems Global Solver, 2009) in GAMS (GAMS, 2009). Finally, the optimization results are further validated through rigorous simulations. The authors found that the methodology could effectively reduce the energy consumption by 13% with the case study of C3MR process.

Mortazavi, Somers and Hwang (2012) discussed about potential energy consumption reduction in LNG process. The authors employed Aspen Plus software to model APCI C3MR LNG process with the property package of Peng–Robinson–Boston–Mathias equation of state used. From this base model, four different expansion loss recovering options were modelled and compared with the base model in terms of energy saved, work and production. The authors found that the compressor power reduction, expansion work recovery, and LNG production increase can be achieved by as much as 2.68 MW, 3.82 MW, and 1.24%, respectively, through there placement of conventional expansion processes with expanders. Moreover, the expansion work recovery is an important option to be implemented in the LNG plants. The power consumption per unit mass of LNG could be reduced by 7.07% and 3.68% with and without considering deduction of the recovered power from the total required power respectively.

Lee and Tak (2012) discussed to optimize the energy consumption of compressors in LNG C3Mr process. The authors modelled C3MR process with pure refrigerant cycle onto HYSYS and optimized the compressor energy for different case studies. The authors found that the simulation of case studies showed energy consumptions mainly depend on both compressing ratios and pressure levels. The study has achieved the energy consumption savings by 27.7% through different case studies with an emphasis on compressing ratios and pressure levels.

Xu, Liu, Jiang and Cao (2012) discussed about the determination of mixed refrigerant (MR) composition in the PRICO process when working condition is changed. The authors utilize Aspen Plus model as a server while the genetic algorithm search method as a controller in the optimization frame work. The Aspen Plus simulation model is called by the genetic algorithm and supplies network consumption of MR process for calculating the fitness of the genetic algorithm. The search engine was programmed using Visual Basic for Applications (VBAs) in Microsoft Excel. Linear regression was performed on the MR composition to derive a set of functions, which were then validated for feasibility and energy efficiency. The authors found that when the ambient temperature increases, the concentrations of methane, ethylene and propane should decrease, and iso-pentane should increase.

Mokarizadeh and Mowla (2010) discussed about energy consumption in the gas peak shaving plant. The authors defined the sum of compressors energy consumption as a parametric function that is flexible for every layout of single-stage mixed refrigerant (SMR) process. This parametric function is generated by using thermodynamic relations and properties calculation of process streams in the MATLAB file that is used in Genetic Algorithm (GA) to achieve optimal condition of key design variables and minimum compressors energy consumption. The case study was a single-stage mixed refrigerant (SMR) cryogenic cycle with two compression stage LNG process. The authors found that their study saved up to 25% energy consumption compared to the commercial Prico SMR process.

Aspelund, Gundersen and Nowak (2010) discussed about an optimization-simulation model for a simple LNG process. They built up a gradient free optimization-simulation method for processes modelled with the simulator ASPEN HYSYS. Values are given to HYSYS, which is then started and runs until it either converges or warns that it is unable to. The tool is based on a Tabu Search (TS) and the Nelder-Mead Downhill Simplex (NMDS) method. The local optima that result from the TS are fine-tuned with NMDS to reduce the required number of simulations. The author found out the tool has been successfully applied to optimize the Prico LNG process with 7 independent variables applying three different methods for selecting the heat exchanger area. The objective function value is improved from the initial feasible solution with 23–36% for the investigated cases.

Abdullah and Amir (2011) discussed about energy optimization in LNG C3MR process. The authors utilized HYSYS to model the C3MR LNG plant. The power consumption comes from the compressors and seawater pumps are calculated by HYSYS. This model was connected with MATLAB for optimization purpose. The model in HYSYS is treated as a black box in the optimization. Optimization process was carried out in two stages. First, MCR cycle optimization and then Propane cycle optimization were conducted. The optimization constraint is that the Propane cycle pre-cools the MCR cycle. The authors found the total power consumption was reduced by 9.08% in their optimization.

Rodgers, Mortazavi and Eveloy (2012) discussed about the efficiency and production capacity of the propane cycle in the LNG plants utilizing sea water for process cooling. The author investigated several propane cycle enhancement approaches which rely on the use of gas turbine waste heat powered water/lithium bromide absorption cooling to either subcool propane after the propane cycle condenser, or reduce propane cycle condensing pressure through pre-cooling of condenser cooling water. Aspen Plus was employed to predict the amount of waste heat available from gas turbine exhaust gases over a range of operating conditions and to quantify the improvements in propane cycle performance obtained. The authors found that with the study case of LNG plant in the Persian Gulf, sub-cooling propane after the condenser by approximately 21^{o}C relative to the base cycle was found to enhance the propane cycle total coefficient of performance and total cooling capacity by 13% and 23%, respectively. On the other hand, reducing propane cycle condensing pressure by reducing condenser cooling water temperature from 35^{o}C to 15^{o}C, resulted in enhancements in propane cycle total coefficient of performance and total cooling capacity of 63% and 22%, respectively.

Prue, Rajab and Ali(2011) discussed a systematic analysis of optimisation formulations for LNG process. The authors utilized the sensitivity analysis to find the optimal operation and design parameters. They categorised objective functions in two groups, operation and design, and tested their efficiency in finding optimal conditions of 12 of the most critical identified parameters of a C3/MCR process. The authors found that the most effective operation optimization is the minimisation of the major operating cost, and for the design point of view the minimization of Net present value is favoured.

Tak and Lim (2011) discussed to find out the optimal process condition for the purpose of saving LNG liquefaction energy consumption. The authors built up a model of LNG single mixed refrigerant process onto HYSYS and utilized non-linear program model for simultaneous optimizations of the key operation variables such as pressure level, refrigerant flowrate, and refrigerant composition. The authors found that refrigerant composition is a major key variable and half of energy consumption can be reduced by changing operating conditions and refrigerant composition only.

From another view point, energy saving can be achieved by focusing on design and control. Finn, Ivar and Berit(2011) discussed to build up a methodology for integrated process and control design in order to better the design and operability of gas processing plants. By considering the disturbances that act on the plant and the constraints in the plant equipment, which are two important factors determining the steady state optimal performance and the optimal closed loop behaviour of process plants, the authors built up an integrated procedure including 8 critical steps, and did the testing, clarifying the procedure on TEALARC LNG process. The author succeeded in suggesting the procedure which enhances process and control design. A capacity increase, moving the plant bottleneck from a compressor to the NG flow rate , gives a different optimal combination of measurements as controlled variable.

Skaugen, Gjovag and Neksa (2010) discussed about the static flow instabilities happening in the heat exchangers of cryogenic services. The authors developed the simulation rating programs S-FIN for PFHE and S-PLATE for PHE at SINTEF Energy Research. These tools was incorporated in process simulation environments Aspen HYSYS, and thus be used as an integrated part when doing process energy simulation and optimization. A Ledinegg instability analysis is shown using the developed programs. With the well-known single mixed refrigerant process as a case study, a thermally valid plate-fin heat exchanger was designed that was subjected to Ledinegg instability. The authors found that for the selected case, the compressor power increased by 14% going from an unstable to a stable design/operation.

Nogal and Kim (2008) discussed about the approach for the optimal design of mixed refrigerant cycles. The authors considered multistage refrigerant compression, full enforcement of the minimum temperature difference in heat exchangers, simultaneous optimization of variables, consideration of capital costs, and the use of stochastic optimization (genetic algorithm) to overcome local optima in their research. Non linear programme optimization problems were built up and solved by generic algorithm. The methodology was applied to previously published liquefied natural gas case studies. The author found that considering multistage compression and capital costs during optimization are very important in optimization which makes their work better than the previous ones, and the application of genetic algorithms in the design of mixed refrigerant cycles permits a greater confidence in the optimality of the results.

Jensen and Skogestad (2009) discussed abouth determining the steady-state controlled variables that need to be selected. The authors utilized MATLAB in order to observe the response of the system when keeping the selected variables at constant set points in 2 modes of given feed and maximum feed in the single-cycle mixed-fluid LNG process. The authors found that for both mode I (given feed) and mode II (maximum feed), operating close to surge and at maximum compressor speed is optimal for the nominal operating point and in some of the disturbance regions. The selection of controlled variables is equally important if one uses a model-based control structure such as model predictive control (MPC).

Besides studies doing energy saving by optimizing the current LNG techniques, there are some papers talking the enhancement of LNG technology also aiming to energy optimization as well as capacity improvement.

Yu, James and Joseph(2011) discussed about the ultimate strength of AP-X LNG process. The authors make a comparison on capacity, refrigerant volume, flexible configuration of the process, LPG recovery ability to reflect the advantages of AP-X process. The authors showed that AP-X has a capacity up to 7-10 Mta and capital saving is greater than 10% compared with C3MR process.

Pearsall and Schmidt (2012) mentioned about the great potential of AP-X process in producing LNG. By discussing 3 main design innovations in AP-X process which are significant scale up to produce the most LNG in a single liquefaction train. robust high pressure LNG subcooler heat exchanger with a stainless steel shell, and utilization of new, large, reliable nitrogen companders for final sub-cooling, they conclude that AP-X process will safely and reliably bring significantly more natural gas to market, enabling natural gas to be utilized for diverse applications and helping to meet rising demand caused by higher energy prices and more stringent environmental regulations.

Castillo and Dorao(2010) discussed a procedure for defining a selection criterion for remote small LNG plants. The authors considered scenarios, LNG technologies as well as some economic tools such as CAPEX, OPEX, value present, internal rate of return, sensitivity analysis in the procedure. The authors found that area plays a major role in economical evaluation, but other factors have to be put into consideration as well for the selecting process.

Hongbo and Baocong (2010) discussed the cold energy recovery, specially cold storage characteristics and heat transfer in LNG refrigerated vehicle. The authors set up an experiment with ambient temperature of 10^{o}C, two types of copper tubes with and without internal fins were tested. The authors concluded thermal resistance inner the tube was dominated for the total thermal resistance of the conjugated heat transfer with smooth tube, and ice layer increase in radial direction with time going.

CHAPTER 3
METHODOLOGY

The methodology framework contains the major tasks: nitrogen loop analysis, HYSYS model development, optimization function development and validation data.

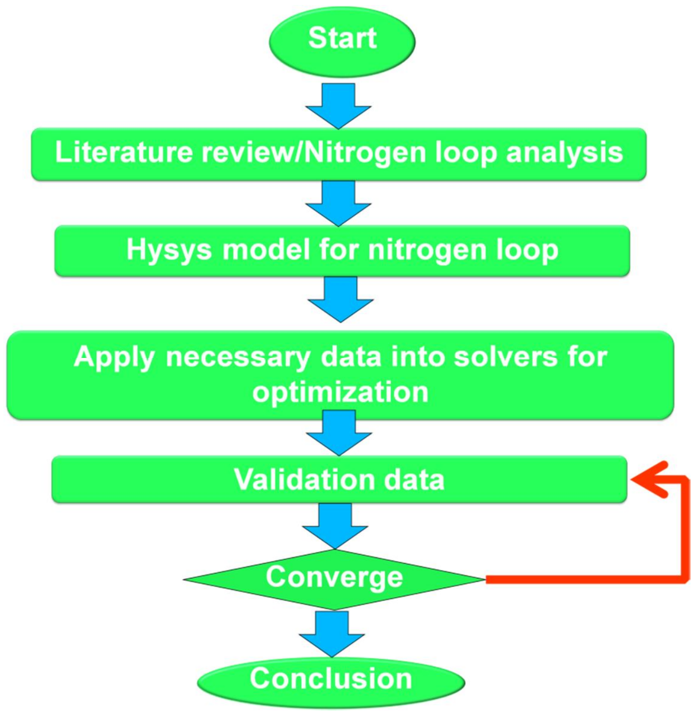

Figure 2: Frame wok

In the first stage, literature review has been done thoroughly in order to understand the the advancement of AP-X process. The focus will be put into nitrogen loop, including compander and nitrogen economizer. Important enhancements of nitrogen sub-cooling loop such as power consumption requirement, capacity enhancement of AP-X process over other processes would be emphasized. Operating parameters of nitrogen loop such as temperature, pressure would be clarified for further study.

The AP-XTM cycle enhances LNG production capacity by augmenting the C3-MR cycle with a nitrogen-expander refrigeration system to accomplish LNG subcooling. The refrigeration load absorbed by the nitrogen-expander system alleviates the need to increase the size and quantity of the propane and MR system equipment. Air Products has extensive experience in nitrogen refrigeration systems used for air separation, nitrogen liquefaction, and LNG peak shaving cycles worldwide.

Besides improving the efficiency, the nitrogen expander loop makes greatly increased capacity feasible by reducing the flow of both propane and mixed refrigerant. Volumetric flow of mixed refrigerant at the low-pressure compressor suction is about 60% of that required by the C3MR process for the same production. Mass flow of propane is about 80% of that required by the C3MR process. With the new AP-XTM process, train capacities in excess of 8 MTPA are feasible in tropical climates, in existing compressor frame sizes, without duplicate/parallel compression equipment, and using a single spool-wound MCHE of a size currently being manufactured.

The AP-XTM process cycle is depicted in the Figure 3. Similarly to the case with C3-MR process, propane is used to pre-cool natural gas to a temperature of about -30°C. The feed is then cooled and liquefied by mixed refrigerant in the MCHE. However, final sub-cooling is not done in the MCHE and the temperature exiting the exchanger is about -115^{o}C rather than -150^{o}C to -162^{o}C.

The final stage of sub-cooling is done using a nitrogen expander loop. Nitrogen is compressed to a high pressure and then cooled to near ambient temperature. The high pressure nitrogen is then cooled with low pressure nitrogen returning to the compressor, expanded to a lower pressure further reducing its temperature. The nitrogen provides refrigeration for sub-cooling LNG.

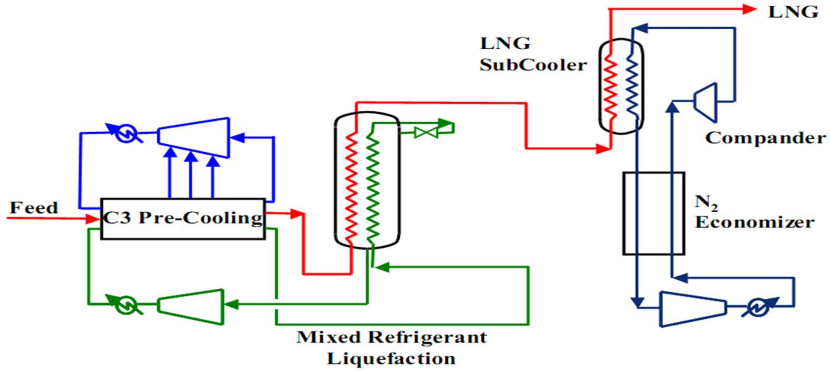

Figure 3: AP-X configuration

Nitrogen is chosen as the preferred working fluid because it has a vapour pressure of 17 to 23 bara at the required natural gas liquefaction temperature. This results in a relatively small volumetric flow rate in the low pressure nitrogen circuit, therefore decreasing the size and the cost of the associated equipments. Besides, elevated pressure improves the efficiency by reducing the effect of pressure drop losses.

The advancement of AP-X LNG process is displayed at the expandable and flexible characteristics. We can operate the AP-X plant with the C3MR mode (without the nitrogen loop) at a reduced production rate of about 65%. Vice versa, we can upgrade our C3MR plant to AP-X plant by adding the nitrogen loop with a certain increase in production rate. This gives us more options in operation the plant. Besides, the power split between C3, MR and Nitrogen is flexible, and manipulated by changing the temperature range of the three refrigerant loops. This facilitates machinery configuration and gives flexibility in matching compressor driver sets as well.

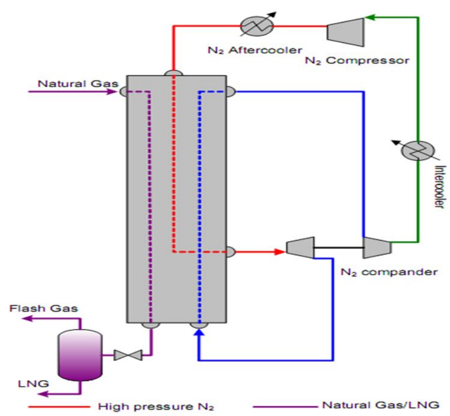

Figure 4: Nitrogen loop

According to Marak and Neeraas (2011), there are some nitrogen cooling loop configurations such as Single N2 expander, Dual N2 expander, Statoil Dual N2 expander. Each configuration contains its own pros and cons. Base on our purpose, we can choose the appropriate one. The simplest nitrogen loop is single N2 expander as depicted in Figure 4.

Continuously, in the second stage, a HYSYS model of nitrogen loop will be developed for detailed study. With HYSYS model, mass and energy balance of the nitrogen loop can be performed quickly and precisely. Responses of certain input changes can be simulated. From important parameters such as LNG flow rate, compressor load, heat duties exchanged acquired from HYSYS model, graphs representing the data relationship are built up, and precious conclusion could be drawn. With the support of either Excel or GAMS simulation software, the optimization and validation data for the flow rate for nitrogen loop can be done at the final stage.

CHAPTER 4
RESULT AND DISCUSSION

The working principle can be illustrated by the model acquired in Figure 5: Nitrogen is compressed to a high pressure and then cooled to near ambient temperature. The high pressure nitrogen is then cooled with low pressure nitrogen returning to the compressor, after which it is expanded to a lower pressure further reducing its temperature. The nitrogen provides refrigeration for sub-cooling LNG. Coil-wound heat exchangers are used to liquefy and subcool the LNG, while the nitrogen economizer uses brazed aluminum plate-fin heat exchangers.

In the cycle, we can see that, the energy required mostly at the compressor K-100 since the compressor K-102 is using the energy released from turbine K-101. Coolers E-100 and E-101 are absorbing heat from the process. Therefore, our concern will be put into the compressor.

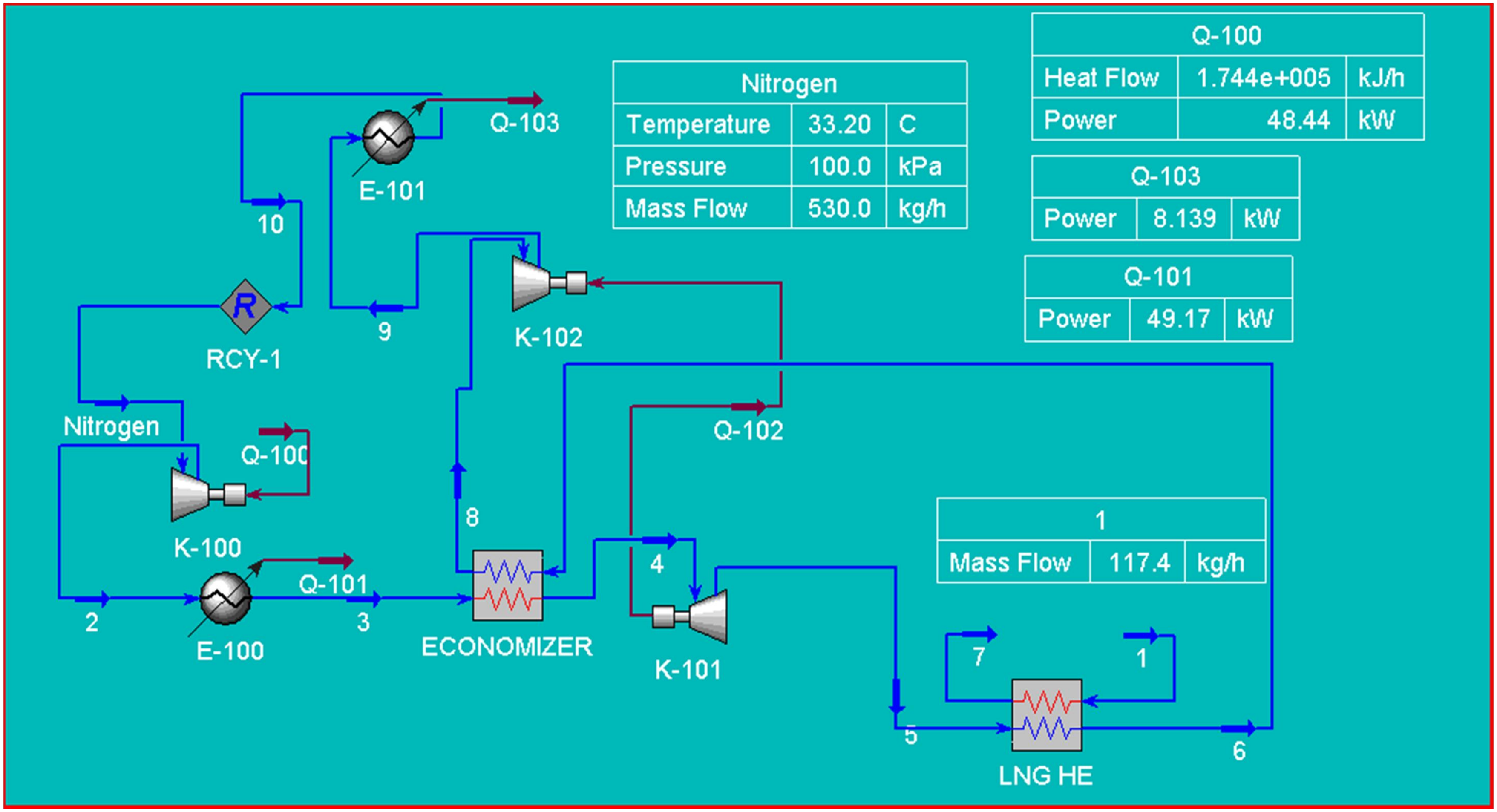

Figure 5: Hysys model for nitrogen sub-cooling loop

1. Case 1: Fixed output temperature of LNG stream

1.1 Pure nitrogen loop

When the output temperature of LNG stream is maintained at -162°C, the revenue from product stream, the compressor work cost from the compressor as well as the recovery efficiency (ratio between heat duty exchange in the LNG heat exchanger and compressor work) were acquired and plotted onto graphs according the change of the nitrogen flow rate.

Figure 6 illustrates the data of fixing LNG output temperature. As we can see from the graph, when nitrogen flow rate increases, the revenue and compressor work cost increase as well in linear relationships. The linear relationship can be understood through the formula:

$$\dot{W} = \frac{\dot{m} C_p T_1}{\eta_c} \left[\left(\frac{P_2}{P_1} \right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1 \right]$$

where: W: Compressor work load (kW)

m: Mass flow rate (kg/h)

Cp:Specific heat (kJ/K)

P: Pressure(bar)

T: Temperature(K)

γ: Specific heat ratio

When others are fixed, the relationship between compressor load and the mass flow rate of nitrogen is linear.

Similarly, the formula for the heat duty exchanged in the LNG heat exchanger is :

$$Q = m_{N2} * C_{P1} * \Delta T_1 = m_{LNG} * (C_{P2} * \Delta T_2 + \Delta H_{phase\ change})$$

Where Q: Heat duty (kW)

m_{LNG} , m_{N2}: Flowrate of Nitrogen ,LNG(kg/hr)

C_{P1} ,C_{P2}; Specific heat of Nitrogen, LNG(kJ/kg.K)

$\Delta H_{phase\ chang}$: Specific phase change enthalpy for LNG

ΔT_1, ΔT_2: Temperature change of Nitrogen, LNG(K)

The relationship between flow rate of nitrogen and LNG is linear also, as we can observe from the above equation.

The cost functions for compressor is :

$$C(\$) = W * \text{operating time (hr)} * \text{price of electricity/hour (\$/hr)}$$

And the revenue for LNG is :

$$R(\$) = m_{LNG} \text{(kg)} * \text{price of LNG (\$/kg)}$$

Therefore, we have the linear relationships between Nitrogen flow rate and Compressor work cost and Revenue of LNG.

It seems there is no clear trade-off between the revenue and the cost in this case. However, as we observe, the recovery efficiency is fluctuating along the range of nitrogen flow rate. This is a very important factor showing the ability to operate benificially of the cooling process. It shows us how much energy we can get back out the the total energy we have spent in the process.

From the Figure 6, the highest recovery efficiency happens when the flow rate of nitrogen is at around 2500 kg/h. Therefore, we can say that, with consideration of the compressor work cost, the revenue of LNG product and the recovery efficiency, the optimum nitrogen flow rate is at about 2500 kg/h, thoughout the operating range of nitrogen which is in accordance to the operating range of LNG from 8 MTPA to 10 MTPA.

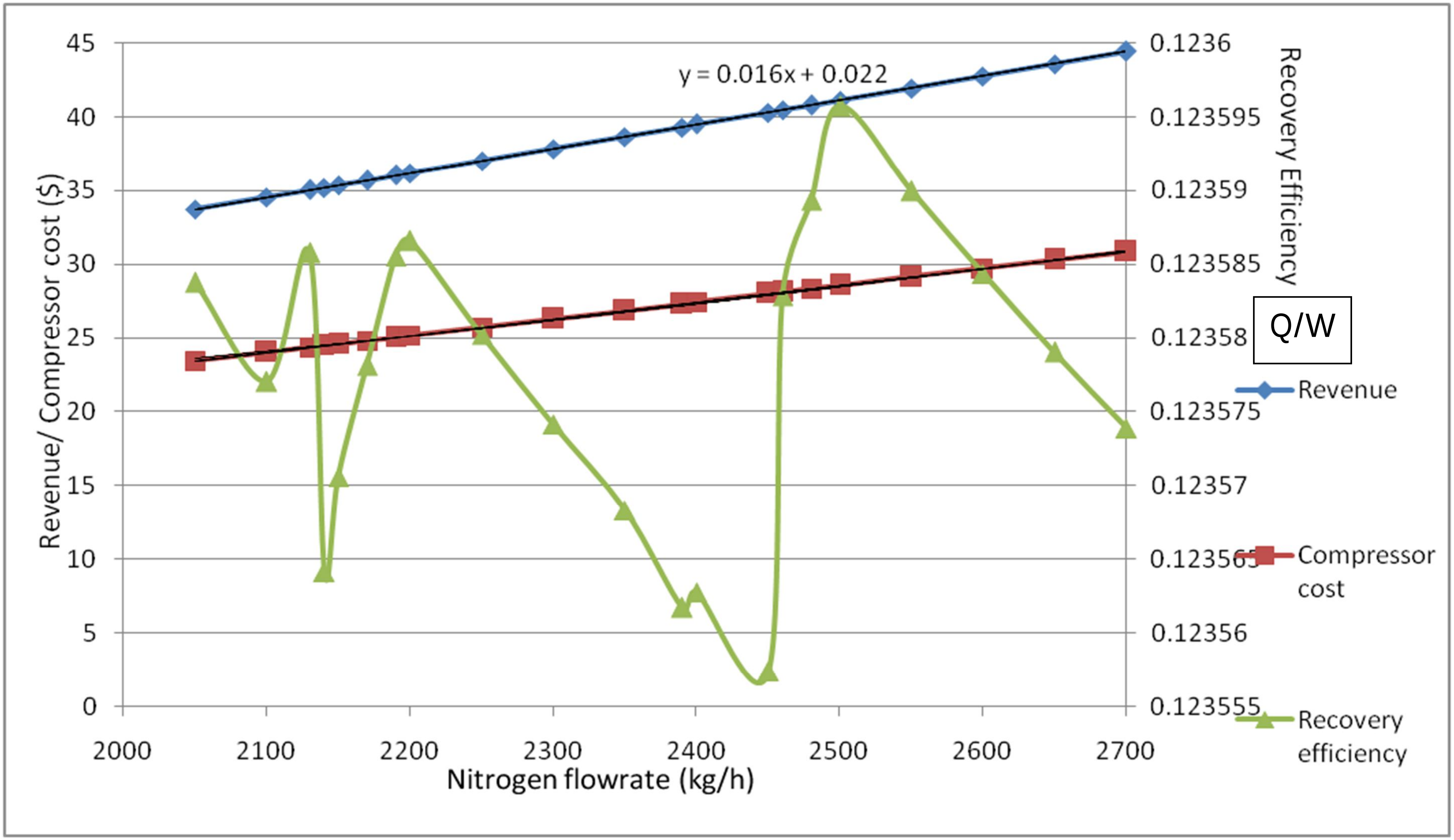

Figure 6: Data of fixing LNG output temperature

1.2 Mixed refrigerant

Using pure nitrogen is a good choice with many advantages, however it possesses a disadvantage is that the flow rate of nitrogen is relatively high, which results in high compressor work load. The possibility to use a small portion of other refrigerant to mix with pure nitrogen is benificial. The option of using methane as the second refrigerant in the mixture seems to be a good choice since methane has a relatively low boiling point (at -164°C at 1atm) and methane is available in the LNG plant.

Following that idea, the mas flow rate of refrigerant flow together with the energy reccovery ratio Q/W is obtained according to the change in the composition of the mixture with the LNG flow is fixed at 100 kg/hr. The result is shown in Figure 7:

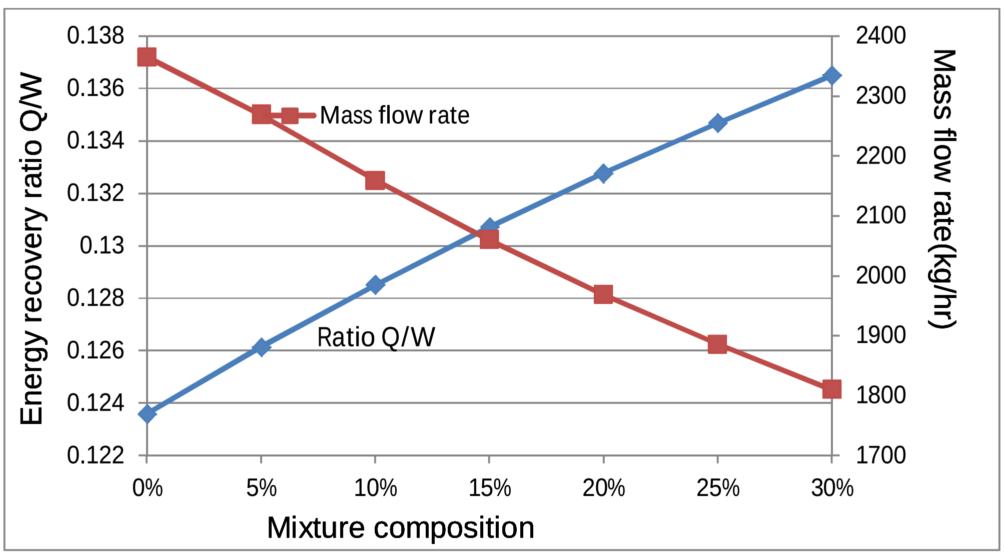

Figure 7: Mass flow rate/ Energy recovery ratio vs Mixture composition

The graph shows the advantages of the mixture of refrigerant over the pure nitrogen referigerant. Following the increasing trend of composition, the mass flow rate of the refrigerant mixture decreases linearly, leading to the reduction in compressor work load and as a result, the energy recovery ratio between the heat duty and compressor work load increase. This means that using refrigerant mixture is giving us more chance to get back the energy spent in the process.

However, adding adding much methane into the pure nitrogen flow will loose the stability which is the most advantage of pure nitrogen refrigerant. Thus, mixture of less methane is preferable, such as 5% mass composition refrigerant mixture.

The effectiveness of the 5% mixture of refrigerant versus the pure nitrogen refrigerant is shown in the Figure 8:

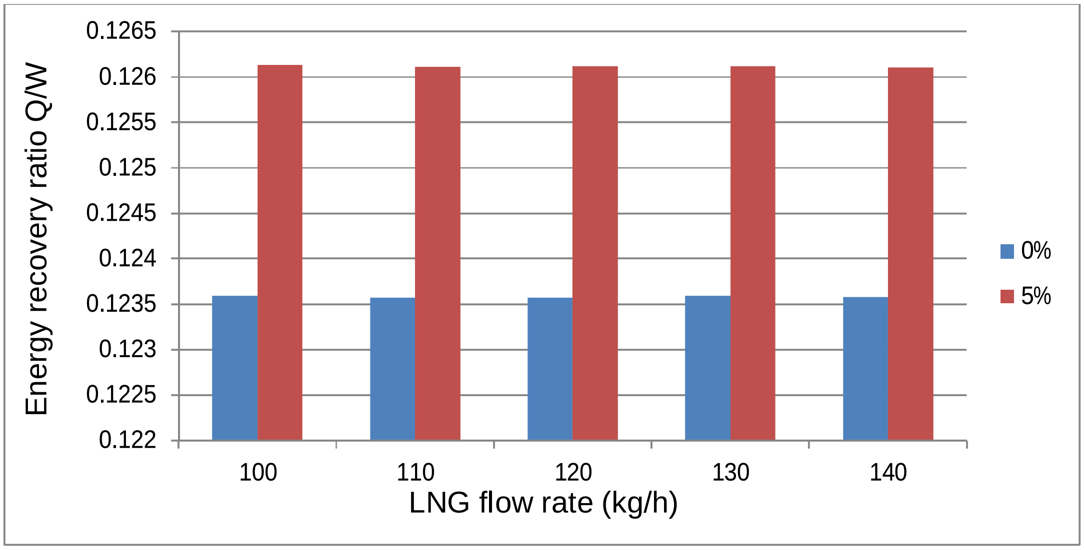

Figure 8: Comparison between pure nitrogen vs 5% mixture of refrigerant

The ultimate strength of the mixture of refrigerant is shown in the graph. For different flow rate of LNG stream, from 100 kg/hr to 140 kg/ hr, the energy recovery ratio Q/W of the mixture is always higher then that of the pure nitrogen case. This gives us the conclusion that using mixture between methane and nitrogen is better than using pure nitrogen for AP-X process. However, the portion of methane should be relatively small in order to sustain the stability of the whole process which is the most advantage of AP-X process.

For the case of 5% mixture of refrigerant, the optimum flow rate of the mixture for the production of LNG is also the ultimate purpose. For the range of producing LNG of 8 MTPA to 10 MTPA, the energy recovery ratio is plotted as we did for the pure nitrogen refrigerant.

The result from the graph is saying that, the highest energy recovery ratio happens at around 2375 kg/hr of the flow rate of the refrigerant. Therfore, we can say that, the optimum refrigerant flow rate is 2375 kg/hr. This is the refrigerant flow rate according to the capacity of the plant is 9.1 MTPA. In the case of pure nitrogen, the optimum flow rate of nitrogen happens at 2500 kg/hr at the capacity of the plant is 9.1MTPA as well. Therefore, we can see clearly the relationship between the optimum flow rate and the optimum capacity of the plant in term of energy recovery. The optimum capacity of the plant should be around 9.1 MTPA in term of energy recovery. This is according to 13.5% increase in the train capacity compared with the train capacity currently in Qatar.

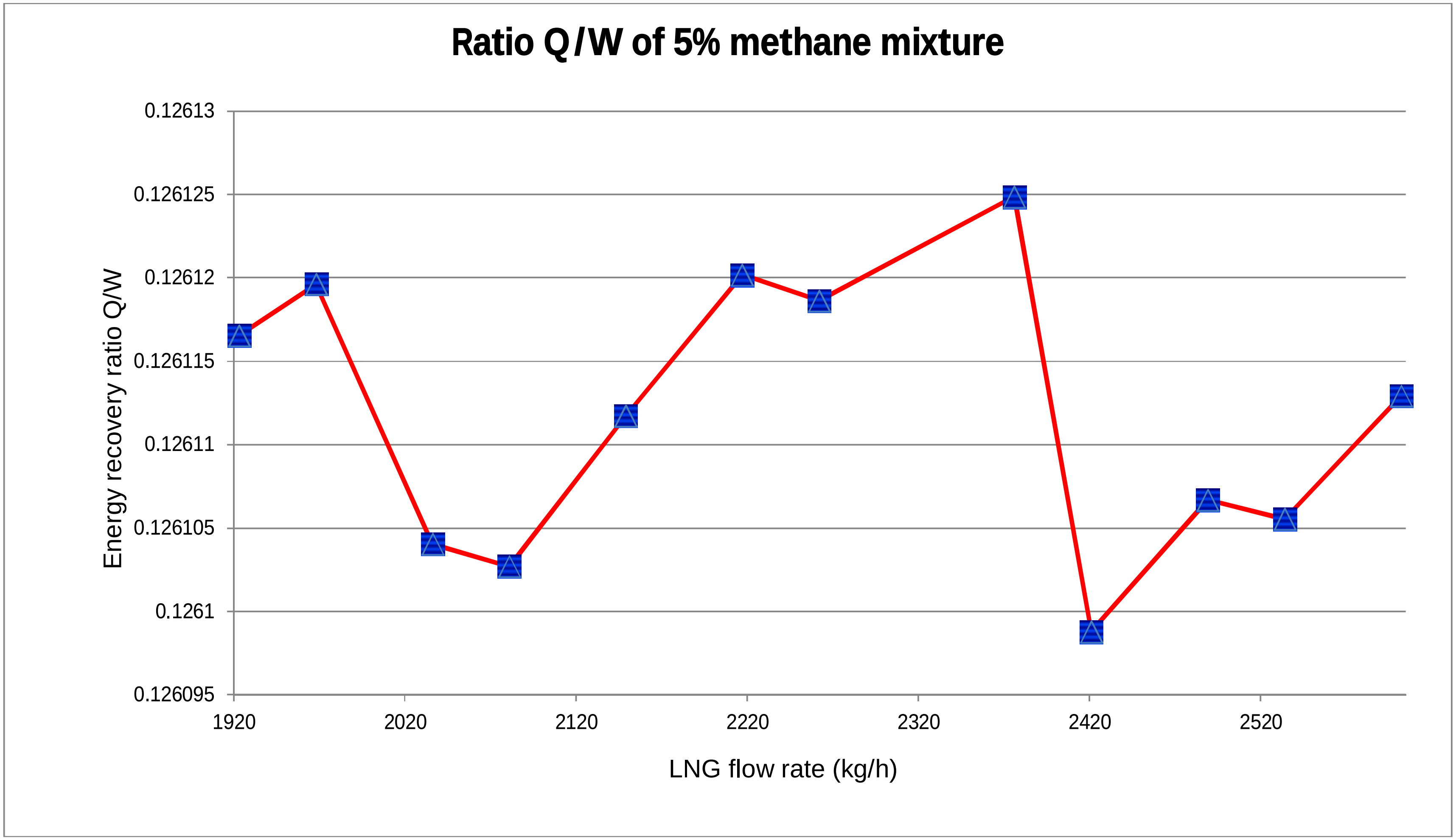

Figure 9: Energy recovery ratio vs LNG flow rate

2. Case 2: Fixed LNG flow rate:

After conducting trial run on HYSYS model, with the fixed flowrte of LNG is 100kg/hr, for different temperatures of output LNG stream, we can have the necessary data for LNG temperature and compressore work load.

Plotting those data onto the graph we can have the result:

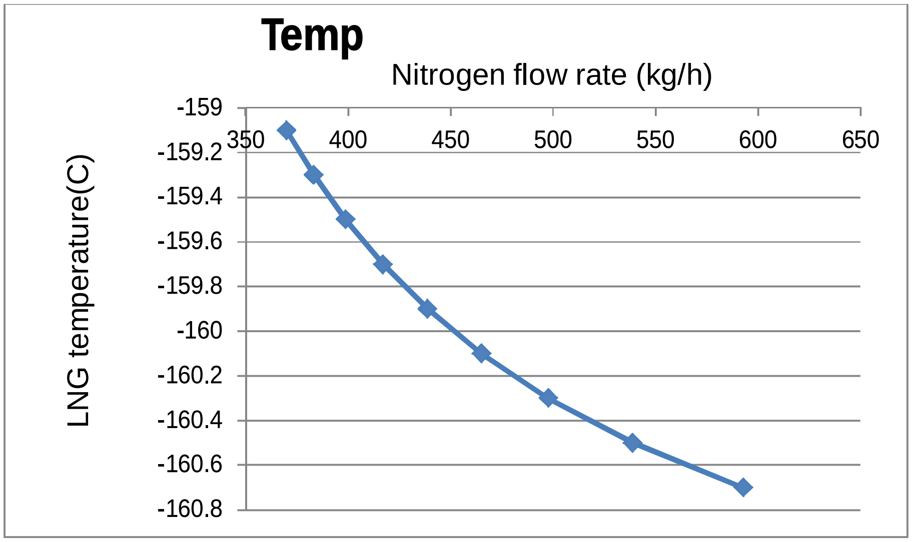

Figure 10: LNG temperature vs Nitrogen flow rate

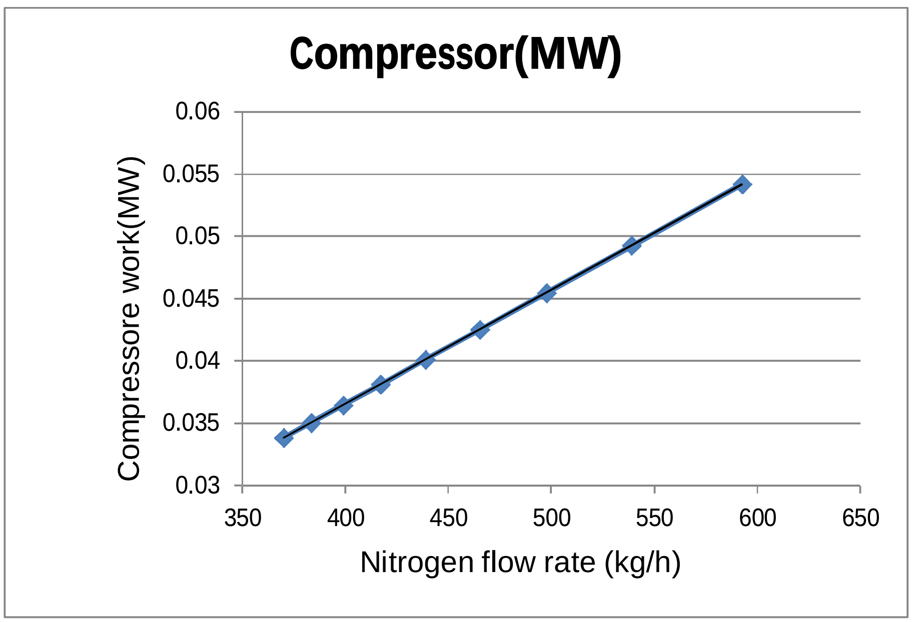

Figure 11: Compressor work load vs Nitrogen flow rate

It is easy to understand the common trend of the data acquired. The more the flowrate of nitrogen is, the more work has to be done by the compressor, and the lower the temperature of the output LNG stream.

The remarkable point is following the increasing trend of nitrogen flowrate, the compressor work increases linearly, while the output LNG stream temperature decreases polynomially.

From Figure 10 and Figure 11, we can see the trade-off between LNG temperature and the compressor work load. The more nitrogen, the more energy we have to spend. In another viewpoint, the more nitrogen, the lower temperature of LNG. In term of safety, the lower LNG product leads to the safer transport of LNG due to lower probability of the presence of LNG vapor which could lead to fire and explosion. In term of economic viewpoint, the lower temperature of LNG product will give us flexible design for LNG container, facilitate the choice of materials for design purpose.This is an interesting point which could lead to another interesting result of the minimum flow rate of nitrogen. However, in order to compare correctly, the scale of the two graphs have to be the same, which means we have to compare them in the same basis. This process is quite complicated since it requires us to introduce another variable which is equally derived from the compressor work load as well as the temperature of LNG stream. If this can be done, it would be great. This shows a bright future of this project with works ahead.

CHAPTER 5
CONCLUSION – FUTURE WORK

In a nutself, LNG process is energy intensive. Optimizing LNG energy consumption is such a interesting job that researchers have been doing. There are many techniques of producing LNG such as C3MR process, Prico process, Shell cascade process and accordingly, there are lots of researches studying about energy comsumption optimization for such techniques. However, even though possessing a great potential for becoming a dominant LNG production process in the near future, there are no research studying deeply about AP-X proccess. Thus, it is benificial if a study for optimizing flow rate of refrigerant inside AP-X process can be done, pushing the process of reducing energy consumption in LNG process a step forward.

The process has been following the schedule properly. The works of building the HYSYS model of the nitrogen loop, and further study have been done well. Trends of the process has been drawn up. Optimum flow rate of pure nitrogen in case of fixing the temperature of LNG output product was found at around 2500 kg/ h, and 2375 kg/hr for the mixture of 5% mass methane. The optimum capacity in term of the best energy recovery ratio is 9.1 MTPA. Trade-off has been found in the case of fixing LNG flow rate, showing an interesting direction for optimizing the flow rate of refrigerant.

To expand the work, it is proposed that a properly mutual scale for the compressor work load as well as the temperature to be determined. Besides, the best composition of the refrigerant mixture of nitrogen and methane may need to be further investigated in order to have a system which is as stable as AP-X process but has a higher energy recovery ratio as well as lower compressor work load.

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APPENDICES

Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
FYP I														
Literature review														
HYSYS review														
HYSYS model build up														
Nitroloop study														
FYP II														
Optimization model build up														
Validation data														
Final report														

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