Enhancing Propane Refrigerant Performance at Pre-Cooling Stage During Hot Climate Conditions at LNG Plants – Case Study from Egypt

By

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Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

____

Dr. Usama Mohamed Nour

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May 2013

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 references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Belal Magdy Fathalla

ABSTRACT

As a result of the growth of LNG markets, the LNG production capacity of liquefaction trains is increasing continuously. This is true not only for new projects, but also for the debottlenecking of existing trains.

When the propane refrigerant is condensed through air coolers, limitation of the variation in atmospheric temperature plays a vital role in the efficiency of the condensing system as it will be affecting the Natural Gas temperature and vaporization rates. That will increase the load on the Propane Compressor and Air Coolers till the condensing rate of the refrigerant is affected. That will result in limiting the ability of the Plant to go for full load when Propane-MR refrigerants are used as the Technology for Natural Gas liquefaction.

This study took the challenge in studying a cost effective solution to maintain a high efficiency performance of the condensing system of the Propane Refrigerant in LNG Plant during hot climate conditions, Temperature range of 25^{o}C - 35^{o}C.

Two approaches were examined through this study which are:

1. Effect of passing the propane feed from the discharge of the compressor to the recycle cooler before the main propane condenser during hot climate conditions. (Two Stages Condensing System)
2. Effect of changing the propane composition on the performance of the refrigerant.

This study is based on SEGAS LNG Plant in Damietta, Egypt where a mixed component refrigerant is pre-cooled by another refrigerant made up of propane.

At the end of the study, the following results were obtained:

1. Full condensation of the Propane Refrigerant when utilizing the two stages condensing system over Hot Climate conditions.

2. Pure Propane refrigerant showed the least power consumption and lower Air condensing duty against other compositions tested.

ACKNOWLEDGMENT

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NOMENCLUTURE

A	Area of heat exchanger
APCI	Air Products and Chemicals, Inc.
AP-X APCI's	nitrogen expanded high capacity process
C1	Methane
C2	Ethane
C3	Propane
C3MR	Propane precooled mixed refrigerant process
h	Enthalpy
LMTD	Logarithmic mean temperature difference
LNG	Liquefied natural gas
m	Mass flowrate
M	Molecular weight
MFC	Mixed Fluid Cascade
MR	Mixed refrigerant
MTA	Million Tonnes per Annum
P	Pressure
T	Temperature
U	Overall Heat Transfer Coefficient

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Over the last 30 years the C3-MR liquefaction process has imposed itself as the first choice of the majority of operating companies in the LNG Industry. Over 80% of LNG Plants around the world are producing through the APCI Technology.

When the propane refrigerant is condensed through air coolers, limitation of the variation in atmospheric temperature plays a vital role in the efficiency of the condensing system as it will be affecting the Natural Gas temperature and vaporization rates. That will increase the load on the Propane Compressor till the condensing rate of the Propane refrigerant is affected. That will result in limiting the ability of the Plant to go for full load when Propane-MR refrigerants are used as the Technology for Natural Gas liquefaction.

When Air coolers are used to condense the propane, accounting for variation in air temperature is important. While considering an increased number of Air coolers would be the easy solution to consider, this study is interested in studying a cost effective solution by utilizing the available equipment in the plant to improve the condensation duty and study different approaches of improving the performance of the refrigerant.

1.2 Problem Identification

In a normal C3MR Liquefaction Process, The propane refrigeration pre-cooling system utilizes propane evaporating at four pressure levels to different four Compressor Stages. The Compressed Propane is then condensed and supplies refrigeration to the feed circuit and the Mixed Refrigerant (MR) circuit. Refer to Figure (1) for a schematic of the Propane Refrigeration Process.

Propane from the discharge of the Propane Compressor (16-MJ04) is desuperheated and condensed by ambient air in the Propane Condenser (16-MC09) which is a fixed Speed Air Cooler consisting of 90 Fans.

The condensed propane is collected in the Propane Accumulator (16-MD06). The propane liquid from 16-MD06 is subcooled in the Propane Subcooler (16-MC10) before being supplied to the evaporators.

The primary functions of the Propane Compressor Recycle Cooler (16-MC11) are to cool the compressor discharge when it is in recycle operation and to provide feed to the compressor to avoid Surge. The Recycle Cooler is also Air Cooler but with a variable speed motor consisting of 9 fans.

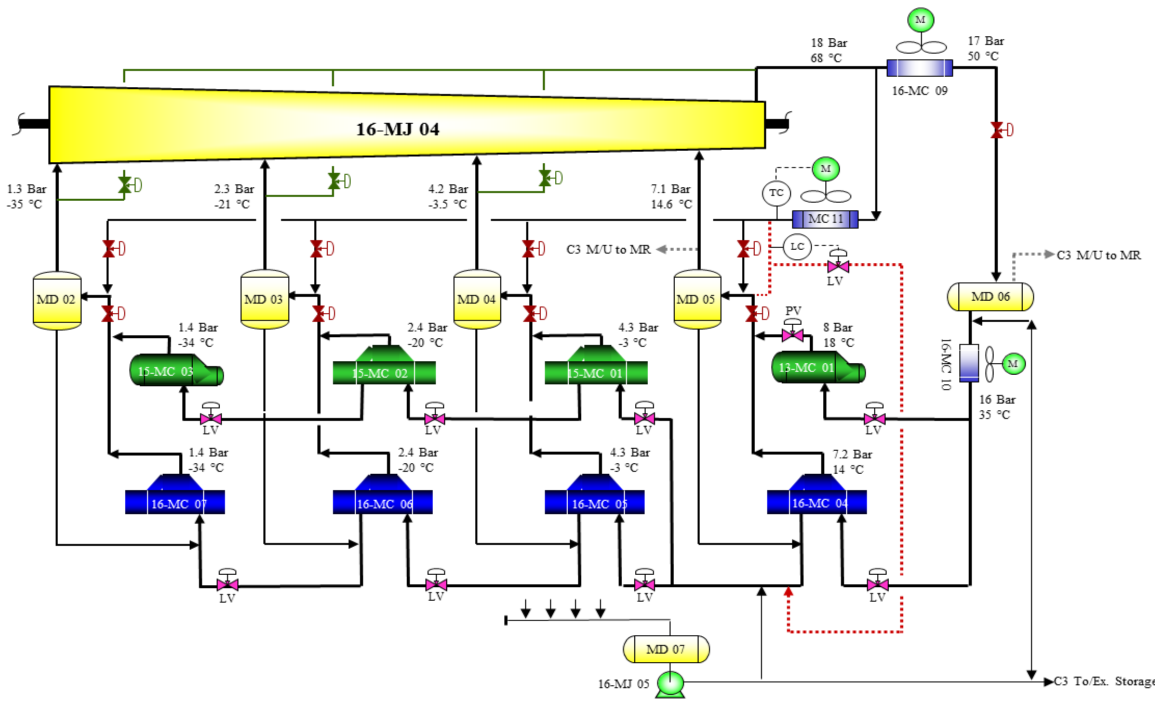


Figure 1: Propane Refrigeration Process

The Propane Condenser 16-MC09 design basis is on 24°C ambient air temperature. During summer, Ambient Air Temperature rises to 30°C ++ which means, the Plant is receiving the Natural Gas in higher temperatures conditions. The rise in ambient temperature as well causes a rise in the rate of Propane vaporization in the chillers and a rise in the suction temperature of each compressor stage. As more amount of Propane is being discharged from the compressor with higher temperatures conditions, not all Propane form the discharge of the Compressor 16-MJ04 is being condensed especially when considering an Air Cooler Performance will be highly affected by the ambient Air temperature.

As more vapors are not being condensed that will result in 2 major effects:

1. Rise in the Pressure of Propane in the compressor discharge above 18.0 bara and temperature rise above 68.4°C which make condensing the propane nearly impossible with the available air fan coolers capacity.

2. Head Pressure on the Propane compressor which would open the anti surge streams and that would escalate the problem by recycling more propane to the discharge of the compressor.

As a result of that, the DCS operator will have to decrease the amount of propane to the suction of the compressor by decreasing the level in the chillers which will divert the cooling load to the Mixed Refrigerant (MR). Instead of Cooling the MR to -37°C by Propane Refrigerant, it may be only cooled to -35°C or higher. That implies more MR is required to liquefy the Natural Gas (NG).

Less cooled MR refrigerant directly means that less amount of Natural Gas can be liquefied in the Main Cryogenic Heat Exchange (MCHE) causing a slower production rate at the Plant and making it impossible to operate full load.

Why the Propane Condenser cannot handle all the flow at higher temperature conditions?

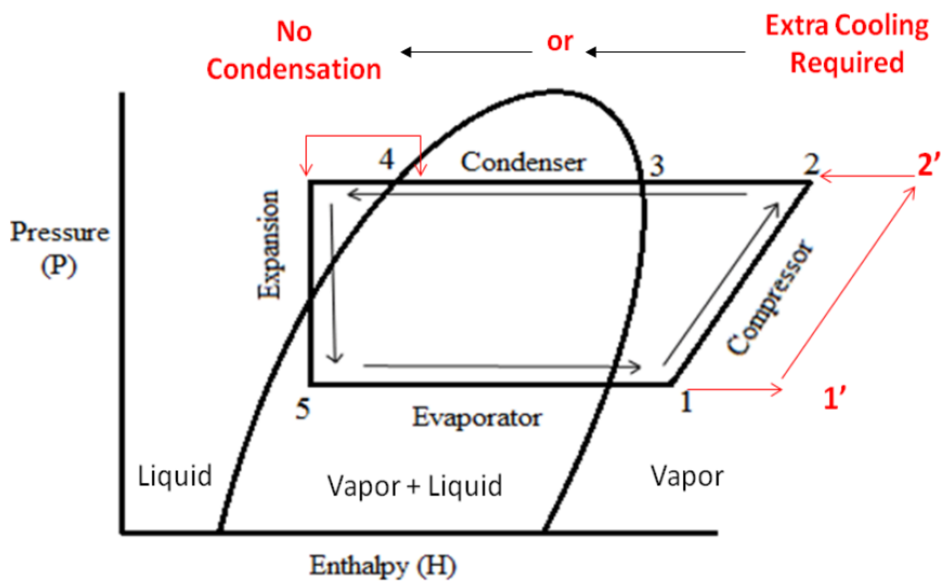


Figure 2: P-H Diagram

If we refer the P-H diagram, from the Rankine cycle which shows a clear representation of the problem. As the Vapor to the suction of the compressor increases (**1 >> 1'**), the discharge temperature will be also higher (**2 >> 2'**).

To reach the desired cooling temperature, extra cooling is required which the Propane condenser cannot provide as more cooling duty is being used to cool the vapor to the condensation temperature.

1.3 Problem Statement

During Hot climate conditions, the performance of the Propane Refrigerant is affected by the ambient air temperature resulting in increasing the difficulty of condensing all the amount of propane required as a Refrigerant.

In the Project we are studying the effect of bypassing the Propane discharge from the compressor to the Recycle cooler first to utilize its cooling duty and study the improvements achieved in the Performance of the Refrigerant

1.4 Objective of the Study

1. To simulate and validate the Propane Refrigerant Unit at SEGAS LNG Plant and study the effect of bypassing the Propane feed through the Recycle Cooler in the C3MR Process.
2. To investigate the performance of the propane refrigerant (C3MR Process) during hot climate condition (Temperature Range 25°C - 35°C).
3. To investigate the effect of modifying the Propane Refrigerant composition on its performance in terms of Compressor Power Consumption, Heat Exchanger UA Values and Air cooler duty.

1.5 Scope of the Study

This study is interested on studying the effect of two different way of cooling and improving the precooling process in LNG Industry. The two ways are:

1. Air Cooling – how would utilizing any excess of air cooling in the plant would contribute to the whole performance of the process during hot climate conditions?
2. Refrigerant composition – how would slightly changing the propane refrigerant composition would affect the performance of the refrigerant?

1.6 Using the Recycle Cooler as a stage in condensing

The Prime objectives of the Recycle Cooler are:

1. To partially cool the propane flowing to the suction of the compressor from its discharge in case of surge condition.
2. To be used during Total Recycle Case.

When talking about operating the plant at full production capacity, the compressor is not expected to go for surge as maximum flow of propane is flowing to the compressor ideally. However, the recycle cooler will operate over empty flow to account for any emergency condition.

The approach here is to use that waste of cooling duty from the Recycle Cooler during the need of operating with full production capacity where the condensing duty of the air condenser is limiting the plant to do so.

1.7 Significance of the Project

In LNG Industry, availability of the refrigerant is an essential factor in maintaining the operations of the plants to meet the energy demands.

Since LNG Plants that face hot climate conditions will be facing the problem of limited availability of refrigerants at the specified conditions resulting in not being to operate at full load at those conditions. By improving the behavior of the refrigerant or finding cost efficient ways to increase the cooling duty of the unit to meet the refrigerant specified conditions, which will definitely be very beneficial for the industry.

The Middle East and Africa for example where countries like Qatar, Omar, Egypt, Algeria, Nigeria and other producing a huge portion of the World's LNG Production are all facing such kind of problem as they are all designed on the basis of Warm Climate and using Frame 7 Compressors.

CHAPTER 2: LITERATURE REVIEW

Keywords: Air Cooling – Refrigerant Composition

In this section we are interested in reviewing published literature on the two keyword studied. So we will start with important engineering understanding for each keyword then analyze available data.

It is also important to note, that no published research where found studying the Hot Climate conditions which is the focus of this study. All published papers found where on Warm Climate or Cold Climate conditions as they are the design basis of LNG Plant in the industry. However, some papers studying the Warm Climate are presented in this section as the closest conditions to the Hot climate conditions. It is expected that Hot Climate conditions research papers are confidential.

2.1 Air Cooling

2.1.1 Basic understanding

Air-cooling systems use ambient air to cool fluids. Air cooled exchangers are classified as forced draft type (tube section is located on the discharge side of the fan) or induced draft (tube section is located on the suction side of the fan). Below is a comparison between advantages and disadvantages of each type.

Table 1: Comparison between Induced and forced draft fans

	Advantages	Disadvantages
Induced draft	- Better distribution of Air across the section. - Less possibility of	- Higher horsepower requirements since fans are located in the hot air.

	the hot effluent air recirculation around to the intake of the sections. - Less effect of sun, rain since most of the face of the section is covered - Natural stack effect is much greater with induced draft so it will show increased capacity in the event of fan failure.	- Effluent air temperature should be limited to 200°F to prevent potential damage to fan blades, bearings, V-belts or other mechanical components - Fan drive components are less accessible for maintenance
Forced Draft	- Less horsepower requirements since fan is in cold air side. - Easier accessibility for maintenance. - Easily adoptable for warm air recirculation for cold climates.	- Poor distribution of air over the section - Increased possibility of hot air recirculation due to low discharge velocity. - Low natural draft capability during fan failure. - Full exposure of tubes to sun, rain and hail

Since Air cooling is highly affected by the variation in ambient air temperature different approaches are used to control the cooling temperature such as by varying the amount of air flowing through the tube section. This can be accomplished by using multiple motors, 2-speed drives, variable speed motors, louvers on the face of the tube section, or variable pitch fans.(1)

2.2 Refrigeration

A refrigeration system is used to lower the temperature of a fluid to a desired a temperature that is not possible to reach through cooling with water or air at ambient conditions.

Refrigeration systems are common in the natural gas processing industry where selection of the refrigerant is governed by temperature requirements, availability, and economics. For Natural gas, ethane and propane are the most common used refrigerants.[(2)]

2.2.1 Refrigeration Cycle

Referring to the P-H Diagram, the refrigeration cycle can be expressed in the following four stages:

a. Expansion – The temperature and pressure of the liquid refrigerant is reduced through an expansion valve. The lowered Pressure is determined base on the desired refrigerant temperature.

   Since the expansion step happens across an expansion valve and no energy has been exchanged the process is considered to be isenthalpic. As point B is inside the envelope, vapor and liquid coexist. In order to determine the amount of vapor formed in the expansion process, let X be the fraction of liquid at pressure PB with an enthalpy h_{LB}. The fraction of vapor formed during the expansion process with an enthalpy h_{VB} is (1-X). Equations for the heat balance and the fraction of liquid formed are:

$$(X)h_{LB} + (1 - X)h_{VB} = h_{LA}$$

$$X = \frac{(h_{VB} - h_{LA})}{(h_{VB} - h_{LB})}$$

$$(1-X) = \frac{(h_{LA} - h_{LB})}{(h_{VB} - h_{LB})}$$

b. Evaporation - Heat is absorbed from the process by the evaporation of the liquid portion of the refrigerant.

This process is a constant temperature, constant pressure step (B-C) where the latent heat of vaporization of the refrigerant play a vital role.

The evaporation step happens in a heat exchanger referred to as a chiller or evaporator. If the enthalpy of the vapor at point C is referred to as h_{VB} , the refrigeration flow rate is given by:

$$m = \frac{Q_{ref}}{(h_{VB} - h_{LA})}$$

c. Compression - The refrigerant vapors leave the chiller at the saturation pressure Pc an Temperature Tc and is then compressed isentropically to a pressure P_A.

d. Condensation – The Compressed vapor refrigerant is then cooled through a cooling media such as Air or water. The condensed refrigerant is usually subcooled using the same cooling media in a later stage .[3]

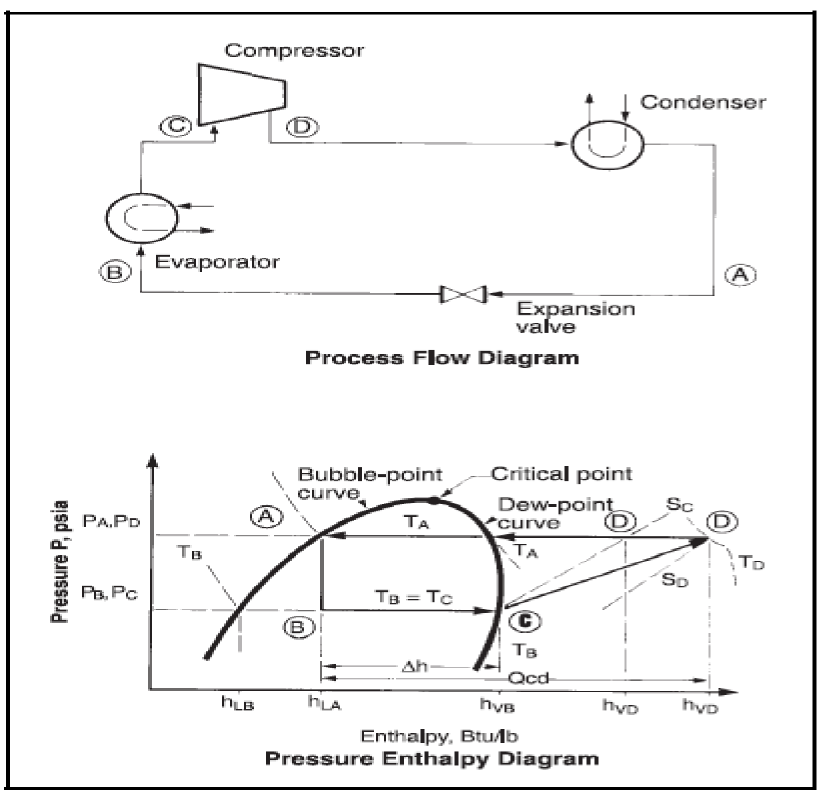


Figure 3: Process Flow Diagram and Pressure-Enthalpy Diagram

2.2.2 Choice of Refrigerant

The ideal refrigerant is nontoxic, noncorrosive, has PVT and physical properties compatible with the system needs plus a high latent heat of vaporization.
Propane is usually used at chiller temperature above -40^{o}C and methane or ethane used at cryogenic temperatures.
Propane is a popular choice in the gas processing application for its availability, inexpensive value and it has a good vapor pressure curve.(4)

2.2.3 Mixed Refrigerants

Mixed Refrigerants are a mixture of two or more components where the light components lower the evaporation temperature and the heavier components allow condensation at ambient temperatures.
Mixed Refrigerants are advantageous in terms of thermal efficiency as refrigeration is always provided at the warmest possible temperature.(5)

2.2.4 Propane Pre-ccoled Phase Separator (C3-MR) Process

The process using propane to pre-cool the natural gas before being liquefied is the most used process in the world nowadays. Propane is evaporated at three or four pressure levels to desuperheat the natural gas and condense the Mixed Refrigerant (MR) before the Liquefaction Process. The number of stages where propane is vaporized at depends on the climate conditions of each plant and the cooling media either air or water. Four stages are usually suitable for warm climate conditions.
The Vapor Propane is then compressed at a three or four pressure level compressor. Propane is normally superheated at the entry of the 1st stage compressor. Calculations show that the maximum energy loss among the pre-

cooling compressor stages happens at the 4th stage compressor and as nearly the same as the other three compressors combined. That happens since the flow rate and temperature is the highest through the fourth stage compressor.(6)

2.2.5 APCI Liquefaction Technology for Today's LNG Business

APCI has been the leading supplier for Natural Gas Liquefaction technology for over 30 years. The APCI Technology focuses on Propane precooled , Mixed Refrigerant (C3MR) and MCR Wound Coil Heat Exchanger.

To meet increased demand of LNG Production capacity which requires stronger refrigeration process to avoid LNG Vaporization, APCI uses 2 Propane Frame 7 compressors casings for production of 5 - 7.5 MTA LNG. When production capacity is increasing up to 10 MTA LNG and beyond the Refrigeration required can be achieved using a single Frame 9 compressor casing for mixed Refrigerant and Nitrogen. While production capacity of 7.5 MTA and above can be achieved by using the AP-X™ Technology where the number of propane compressors casing in increased to two as for the C3MR Process. In the AP-X™ Technology, Nitrogen expander is used for the sub-cooling of LNG.(7)

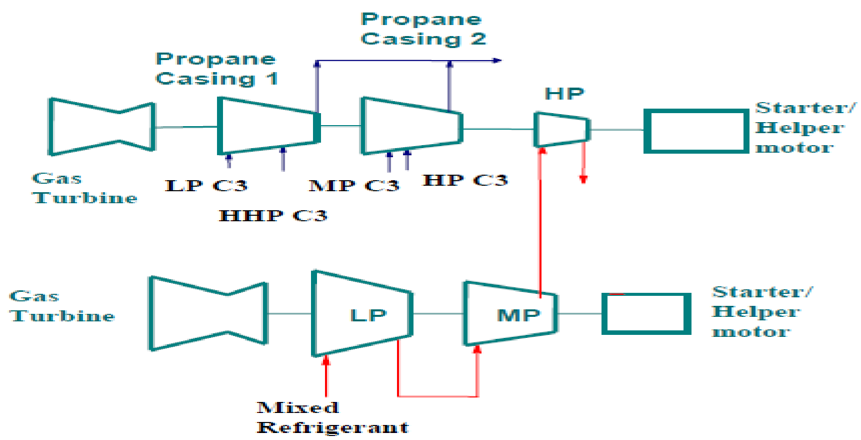


Figure 4: APCI Technology using 2 Compressors Casings.

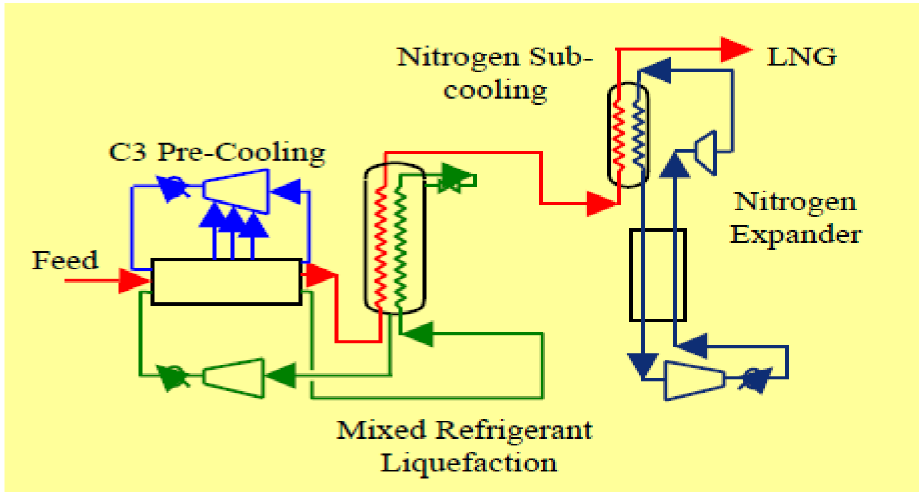


Figure 5: APCI AP-XTM Technology

2.2.6 Performance of C3MR Refrigerant during Warm climate.

The C3MR Refrigerant represents the biggest portion of the installed LNG Plants in the world. This process consists of two main refrigerant cycles which are the Pre-cooling Cycle and the Liquefaction-Sub Cooling Cycle. The Pre-cooling Cycle uses pure Propane refrigerant to cool the Natural Gas to -35^{o}C or depending on the Technology used. The Liquefaction and sub cooling stages uses a Mixed Refrigerant (MR) consisting mainly of N2/C1/C2/C3.

In a recent study on the Pre-cooling stages for different LNG Processes [4], the study compared the performance of C3MR Refrigerant to the performance of Mixed Fluid cascade (MFC) which uses a Mixed Refrigerant in the Pre-cooling stage as well.

Under Warm Climate conditions (25^{o}C), using the C3MR Refrigerant Process showed less power requirements comparing to the MFC Process. The mixed refrigerant precooling cycle with two stage (MR-C3MR) gives a power consumption about 10% larger than the C3MR. The UV values for Heat exchanges were also less when using the C3MR Refrigerant compared to the MFC Refrigerant.(8)

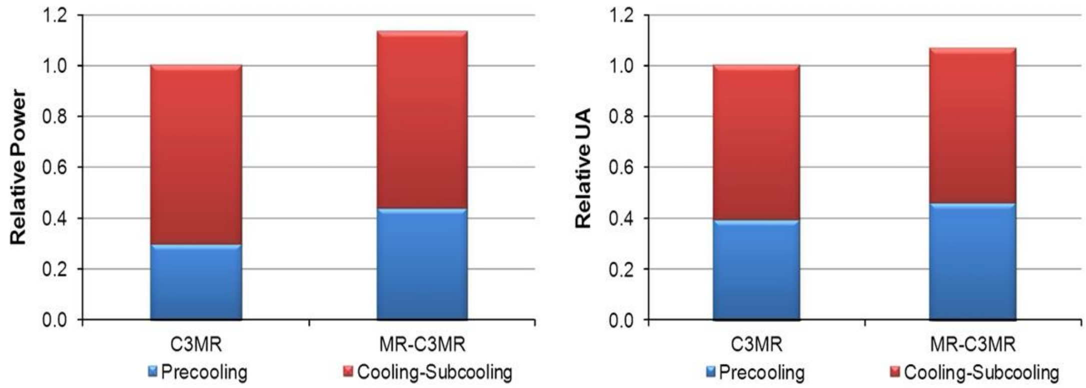


Figure 6: Design variable for the C3MR and MR-C3MR processes at warm climate

Those results show that using a mixed refrigerant instead of pure Propane in the Precooling stage is not beneficial for the process in terms of energy efficiency or UA Values. We can also notice that adding the light components increases the power consumption.

2.2.7 Evaluation of Different LNG Precooling Processes.

In a recent Master thesis done in the Norwegian University of Science and Technology, different configurations of the Precooling Process were examined. The Results showed that the Pure Propane Refrigerant performs better compared to other Precooling Configurations as temperature increases. The figure below shows the compressor duty with different configuration.

From the figure below, pure propane showed the lowest power consumption among other configurations. Taking Propane as a reference, we notice that the mixed refrigerant configuration with n-butane gives only 0.88% higher power consumption while other mixed refrigeration configurations shows higher power consumptions due to using lighter components.[9]

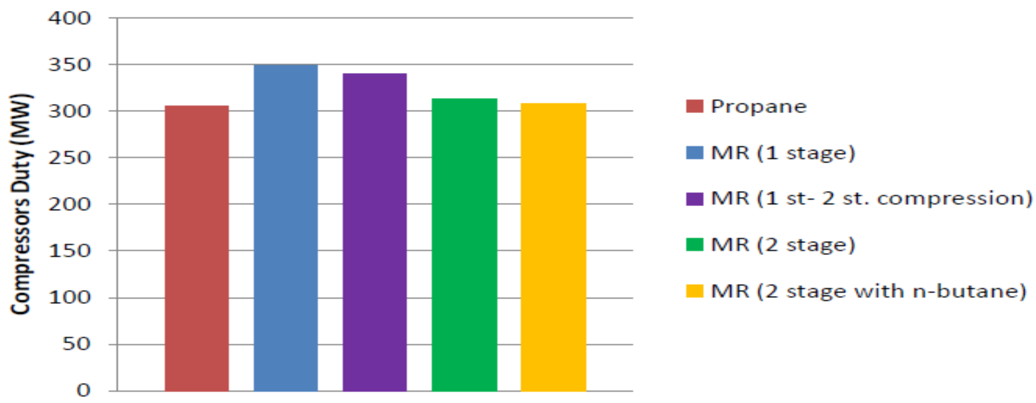


Figure 7: Compressor Duty with different configurations applied, Warm Climate

The results also showed that, the propane refrigerant showed the lowest UA Values for Heat exchangers as shown in the figure below.

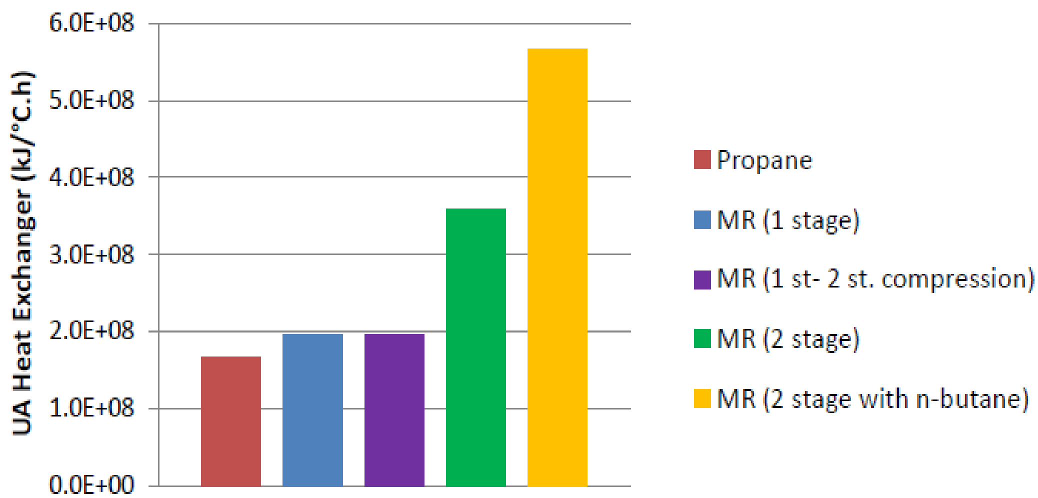


Figure 8: Heat Exchangers UA Values for different configurations, Warm Climate

As shown in the figure above, all mixed refrigerant compositions showed higher UA values comparing to the pure propane configuration. It is also noticeable that the mixed refrigerant with n-butane shows quiet bigger UA Value.

From the overall results shown for different refrigerant compositions, pure propane still proves to be the best option in comparison to other configurations in terms of UA Values or power consumption under warm climate conditions.

In this study, we are going to examine the effect of slightly changing the composition of pure propane and examine its effect on compressor power consumption, Heat Exchanger UA Values and Air Cooler duty.

2.2.8 Heat Driven Absorption Chillers

Heat Driven absorption is a different approach in tackling the problem of refrigerant performance. This approach is briefly described below.

A Heat Driven Absorption Chiller is a cooling machine using thermal energy (steam, hot water) instead of mechanical compressors consuming electricity or valuable fuel gas.

The main benefit of Heat Driven Absorption machine is to make use of low level thermal energy otherwise cooled by external cooling media or release to atmosphere.[10]

In hot climate conditions a chilled water loop (7ºC) can be used to cool down process fluid lower that available ambient temperature cooling media.

In a study published in 2009, it was shown that a single effect Amonia-Water Absorption Refrigeration System could provide the cooling duty provided by the propane chillers and completely replace it.

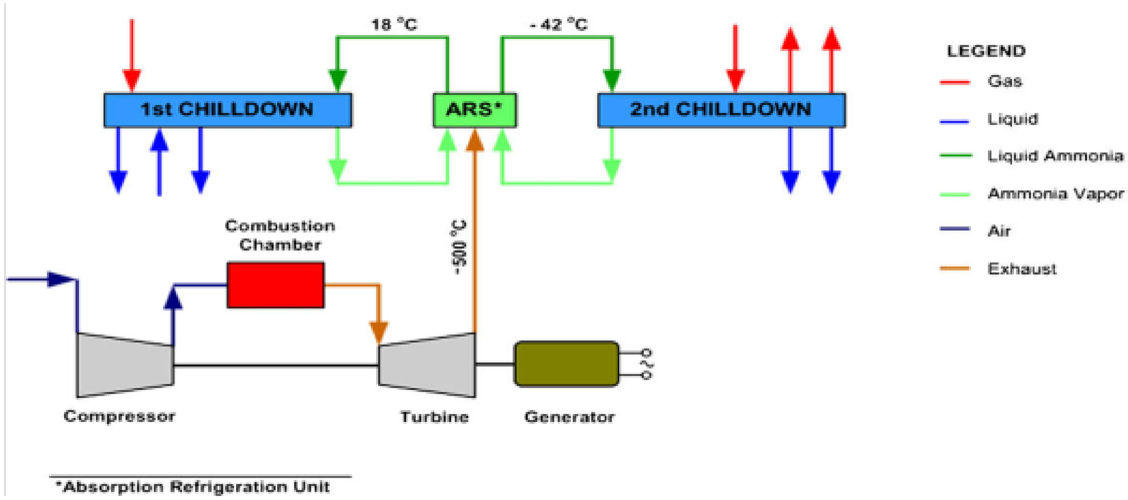


Figure 9: Amonia –Water Absorption Refrigeration System.[(11)]

In another study published in 2010, it was shown that using a Water/Lithium – Bromide Absorption chiller Replacing 22 ^{o}C and 9 ^{o}C evaporators and cooling the condenser of propane at 14 ^{o}C cycle and inter-cooling the compressor of mixed refrigerant cycle with absorption chillers using a scaled gas turbine the compressor power demand could be reduced by 21.3% which also leads to reduction of gas turbine fuel consumption by 21.3.[(12)]

CHAPTER 3: METHODOLGY

3.1 Research Methodology

The research project is carried out through computational simulations using Aspen HYSYS® where, the effect of the modification proposed can be examined and a comparison between different proposed solutions can be made.

The First stage of the Project is focusing on examining the possible literature available for tackling the challenge of the Increased Refrigerant demand in the LNG Industry nowadays. The Literature Review examined is a head start to build a deep understanding for the problem and allowing us to see the big picture of the issue through comparison of different approaches studied

The second stage of the project is focusing on two aspects:

1. Testing Actual data from SEGAS Plant on utilizing the Recycle cooler as a first stage to cool the discharged propane from the compressor before diverting the feed to the main the Propane Condenser.

   In this Scenario, not to disturb the operations of the plant we will look into scenarios where the plant was in Total Recycle case or Start up during Summer time. That is beneficial because

   - During Total Recycle Case or start up of the plant, the propane from discharge of the compressor is always diverted to the recycle cooler then back to the suction of the compressor. From that we can study how big is the temperature drop that the recycle cooler can cause
   - Testing during summer is aligned with our FYP Study to examine the behavior during hot climate conditions above 25^{o}C.

2. Building the simulation model for the examined unit and study the effect of using the Recycle cooler as Pre-cooler first stage on the performance of the refrigerant during Hot climate condition. This Stage is focusing on optimizing the process but utilizing a potential waste cooling duty that does not impose a major change in the process to be used.

The Third stage of the project will examine the effect of modifying the composition of the refrigerant on its performance using a simulation model as well.

The following Parameters to be considered:
Main refrigerant : Propane (C3)
Possible components to be added : Methane (C1), Ethane (C2)

The Hot Climate in this study refers to temperature profile of 25^{o}C – 35^{o}C which is 10^{o}C above the Warm Climate condition.

The Last part of the project will be to compile all the findings and report them.

3.2 Expected Results

Table 2: Expected Results

	Test Scenario	Expected Results
1	Diverting the C3 feed to the Recycle cooler before the Propane Condenser	- Temperature Drop in the propane stream before entering the Propane condenser which will increase the cooling duty of the system - Will that temperature drop be enough to handle the increase in temperatures

		dues to hot climate conditions? • Test is limited to the actual temperature condition at the time of the test.
2	Simulating using the recycle cooler as a first stage cooling in condensing the Propane through Aspen Hysys.	- We would be able to test the amount of temperature drop throughout the whole temperature range (25^oC-35^oC) - Will the Recycle cooler be able to provide the needed extra cooling throughout the whole temperature range.
3	Simulating the effect of modifying the composition of the C3 Refrigerant on its performance in Aspen Hysys.	- Effect of the composition on the heat transfer in the Chillers and compressor power consumption. - Will it improve from using pure C3 refrigerant?

3.3 Main Milestones achieved:

1. Completed Literature Review. Developed a deep understanding of the LNG Industry and refrigerants.
2. Co-operation with an Actual LNG Plant in Egypt to validate our data.
3. Testing actual data from the plant for using the recycle cooler over some specific temperature conditions.
4. Aspen Hysys Practice.
5. Plant Data Collection.
6. Building and Validating the Simulation Model.
7. Testing Propane Performance During Hot Climate Conditions.
8. Testing the approach of Two Stage Condensing System.

9. Testing the approach of modifying the Propane Refrigerant Composition.

3.4 FYP Gantt Chart

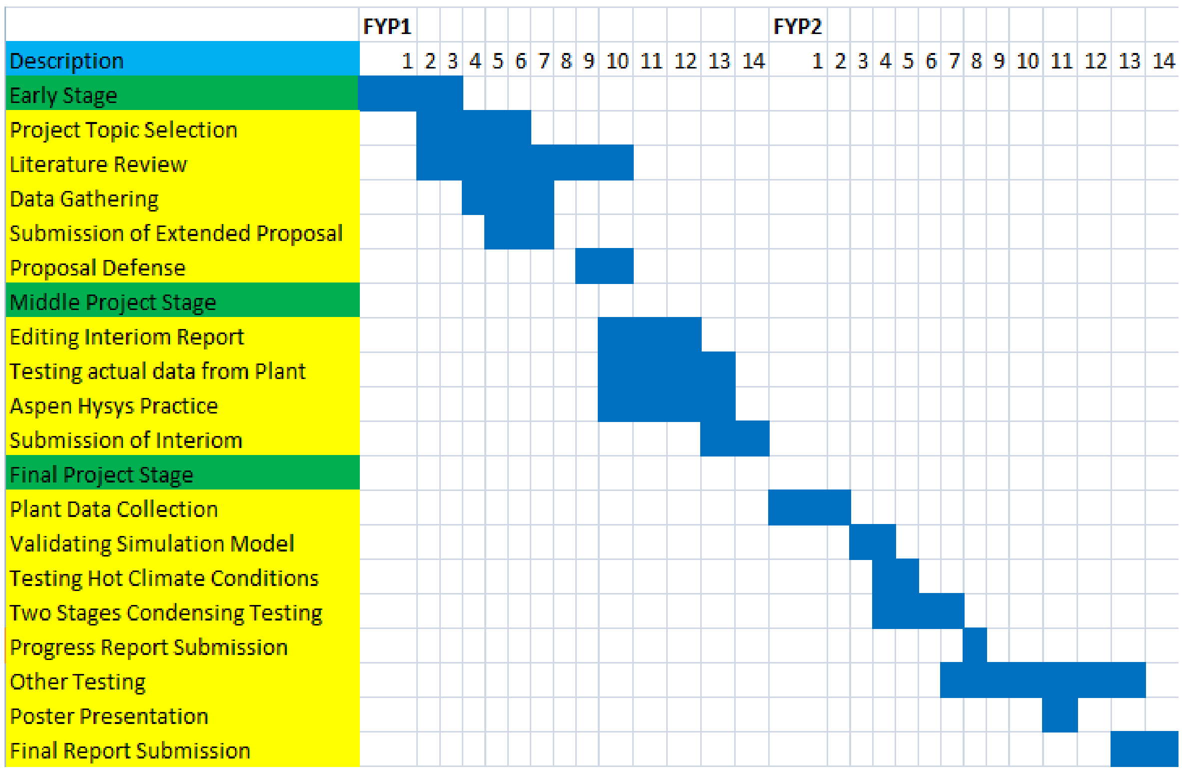
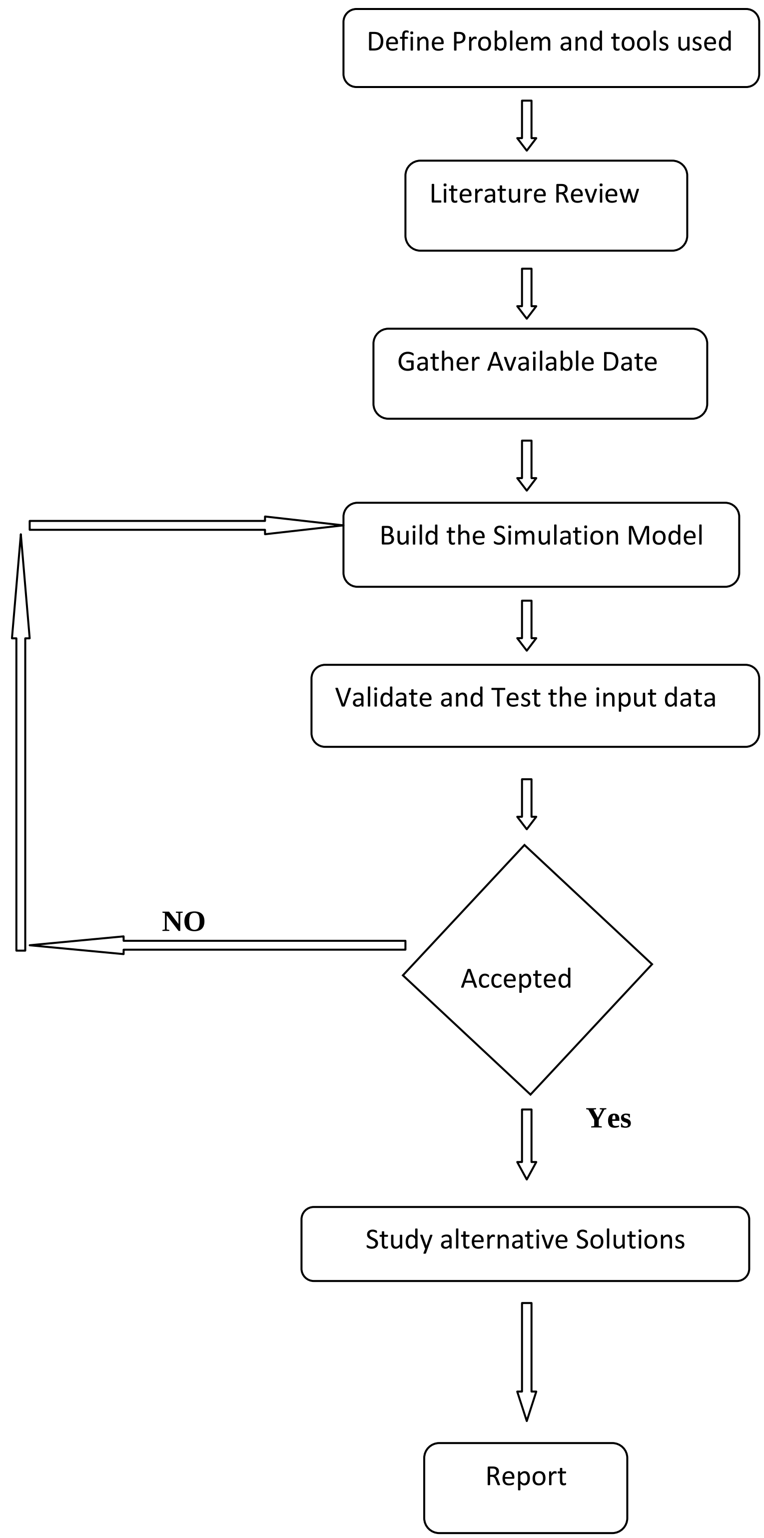


Figure 10: Gantt chart – FYP

3.5 Research Process:



CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Actual Plant data review

Since one of the proposed solutions is to utilize the cooling duty of the recycle cooler to add up to the actual Propane condenser where both of them are Air coolers, actual performance data in SEGAS Plant were studied

The Recycle Cooler at SEGAS LNG Plant (16-MC11) consists of 9 variable speed fans with a design duty of 52398 KW. Temperature drop in propane flow was examined in cases of Total recycle of the plant where all the propane from the discharge of the compressor is only passing through the recycle cooler and then back to the suction.

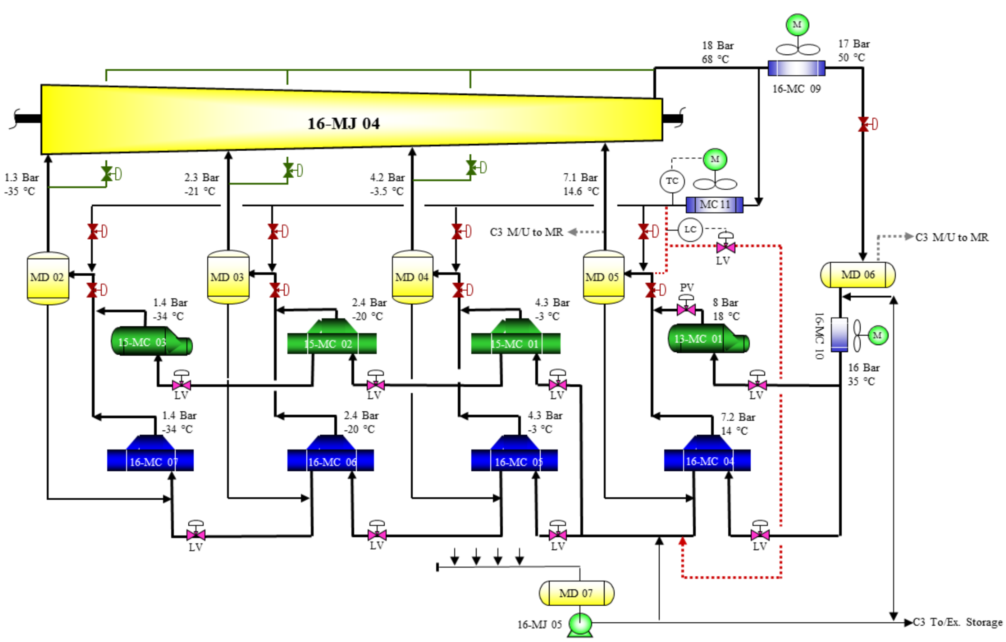


Figure 11: PFD of the Propane Unit at SEGAS LNG Plant

The Following Numbering system is used:

Table 3: Numbering Tags at SEGAS LNG Plant

Number Tag	Unit / Indication
16-MJ 04	Propane Compressor (4 Stages)
16-MC 09	Propane Condenser (Air Cooler)
16-MC 10	Propane Sub Cooler
16-MC 11	Propane Recycle Cooler
16TI1217	Propane From Compressor Discharge Temperature Indicator
16TIC1242	Propane at the outlet of Recycle Cooler Temperature Indicator
16TI1424	Air Intake Temperature Indicator
16UY2310	Propane Mass flow Indicator at the Discharge of the Compressor

The numbering system is adopted from SEGAS LNG Plant system.(13)

4.2 Actual Scenario Test Problem

During summer, as ambient air temperature will rise above 25^{o}C especially, the natural gas which is pre-cooled in the C3 chillers requires extra cooling, leaving the propane vapor at higher temperature conditions.

At SEGAS LNG Plant, the design discharge temperature of the propane compressor is 68.4^{o}C at warm climate conditions. In hot climate conditions when the temperature rises to 29^{o}C -30^{o}C the discharge temperature will increase to nearly 80^{o}C. That means an excess of 11.6^{o}C cooling is required. That limits the ability of the Propane condenser to condense the Propane in case of Full Plant load.

In SEGAS LNG Plant, there is a software names “PI System” where its prime objective is to monitor the operations of the plant. So it keeps records of all the operating parameter of the plant since its commissioning in 2003.

The Software was very useful in getting operating parameters during summer 2012 where the plant undergone total recycle cases and startups.

The following parameter were analyzed,

- Propane mass flow from the Discharge of the compressor.
- Propane Temperature drop across the recycle cooler.
- Ambient Air Temperature at the time of testing.

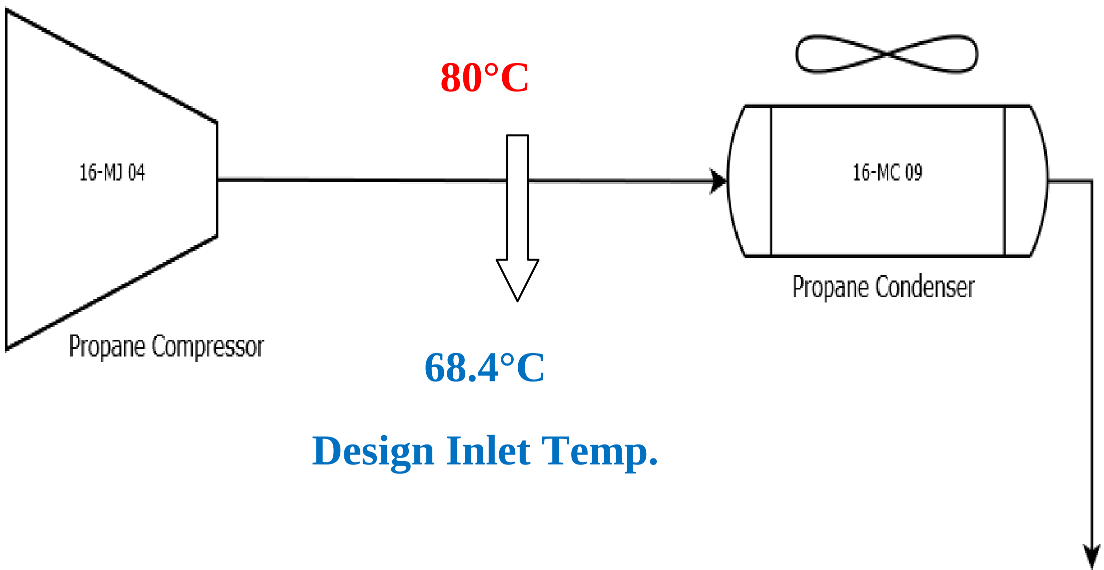


Figure 12: Propane Discharge Temperature Rise at 29^{o}C ambient Air Temperature

Data Test 1

In this test, we have nearly constant Flow of Propane [70% of maximum], Constant Temperature difference of 125°C between Propane inlet temperature and Ambient Air Temperature.

Table 4: Data Obtained from the PI System at SEGAS for a total Recycle Case

	16TI1217	16TIC1242	16TI1424	16UY2310	Column2	Column3	Column4
	PR COMP DISCHARGE	PROP COMP 16-MC11	16-MC11 INTAKE AIR	UIC-1198 MASS FLOW	ΔT	Temp Diff.	m%
	°C	°C	°C	kg/h	°C	°C	
17-Aug 15:40:00	155.75	115.50	30.95	1598648.572	40.25	124.79	70.10
17-Aug 15:50:00	155.95	115.54	31.19	1602442.181	40.40	124.75	70.27
17-Aug 16:00:00	156.10	115.92	31.49	1607113.284	40.17	124.60	70.47
17-Aug 16:10:00	156.30	115.98	31.20	1607119.198	40.32	125.10	70.47
17-Aug 16:20:00	156.40	116.04	31.25	1607527.12	40.35	125.14	70.49
17-Aug 16:30:00	156.47	116.16	31.21	1607254.918	40.31	125.26	70.48
17-Aug 16:40:00	156.48	115.93	31.21	1604734.113	40.55	125.27	70.37
17-Aug 16:50:00	156.32	115.68	31.15	1601631.106	40.64	125.17	70.23

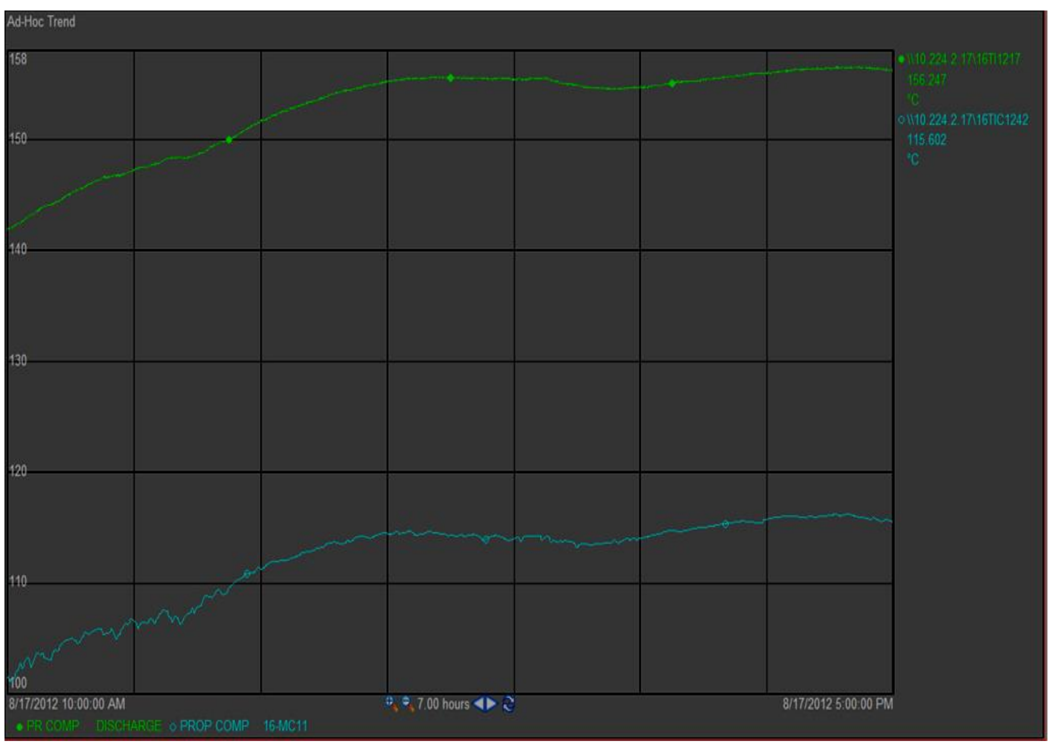


Figure 13: Temperature drop trend across the Recycle Cooler 16-MC11 [PI Graph]

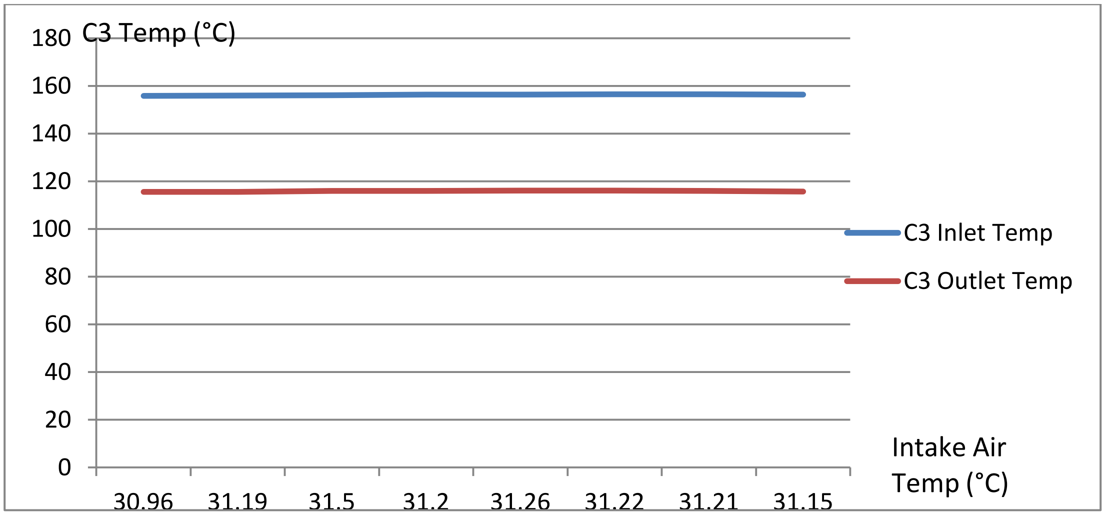


Figure 14: C3 Temp In/Out vs. Air Temp

So when the Temperature difference between Inlet Propane and Air Temp is 125°C, we can notice temperature drop across the total flow of 40°C.

In our First Calculations we showed that we can obtain 36.5°C temperature drop in the total flow.

In this example:

Since Mass flow = 70% of Maximum C3 Mass Flow.

$\Delta T_{obtained}$= 40°C

ΔT_{Total} = 0.70× 40 = 28°C

At TD= 125°C a total of 28°C Temperature drop in the compressed vapor propane can be obtained.

We also notice that at constant conditions of mass flow and temperature difference, the temperature drop behavior will be constant. Next Examples would also verify this.

Data Test 2

Table 5: Data Obtained from the PI System at SEGAS for a total Recycle Case

	16TI1217	16TIC1242	16TI1424	16UY2310	Column2	Column3	Column4
	PR COMP DISCHARGE	PROP COMP 16-MC11	16-MC11 INTAKE AIR	UIC-1198 MASS FLOW	ΔT	Temp Diff.	m%
	°C	°C	°C	kg/h			
17-Aug 06:00:00	114.04	78.72	25.73	1680337.302	35.32	88.30	73.68
17-Aug 06:10:00	113.96	79.06	26.33	1676876.097	34.90	87.63	73.53
17-Aug 06:20:00	114.09	79.13	26.33	1675362.34	34.95	87.76	73.46
17-Aug 06:30:00	114.08	79.21	26.35	1679041.617	34.87	87.73	73.62
17-Aug 06:40:00	114.24	79.27	26.32	1681654.167	34.96	87.92	73.74
17-Aug 06:50:00	114.27	79.46	26.36	1688139.584	34.80	87.91	74.02
17-Aug 07:00:00	114.53	79.90	27.40	1692409.165	34.62	87.12	74.21
17-Aug 07:10:00	114.72	80.03	26.92	1701891.533	34.69	87.79	74.63

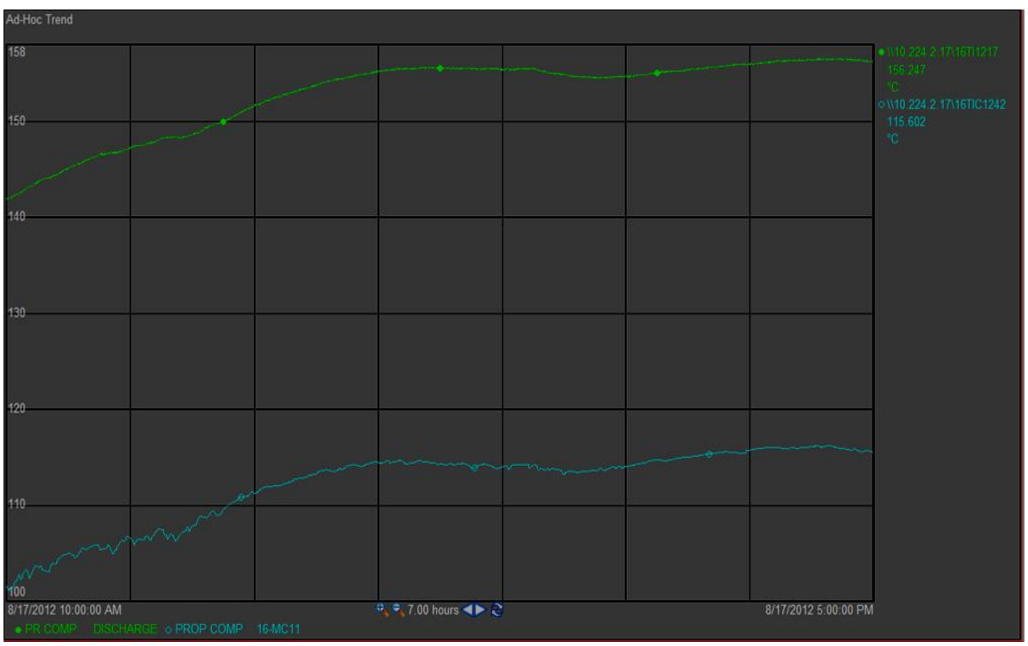


Figure 15: Temperature drop trend across the Recycle Cooler 16-MC11 [PI Graph]

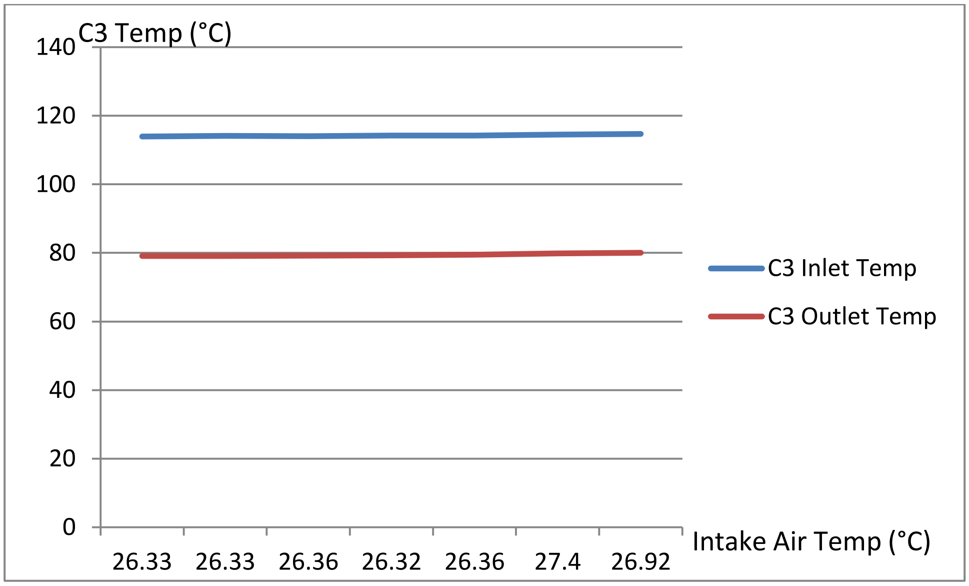


Figure 16: C3 Temp In/Out vs. Air Temp

As expected, when Temperature difference between Propane and Air Temp decreases, the losses in Propane Temperature will be less as the efficiency of Heat Transfer will decrease.

At Temperature Difference TD = 87°C, the Temperature Drop (ΔT) = 34°C

Noting that 73% of maximum Propane feed is passing through the Recycle Cooler in this case, the Total Temperature drop will be as follows:

ΔT_{total}= 0.73 × 34 = 25.185°C

As in the previous example, we notice that at constant conditions of mass flow and temperature difference, the temperature drop behavior will be constant.

Data Analysis 3

In this case we referred to a case that will show very similar conditions to the ones specified in our problem. We would expect the Propane Inlet Temp to be around 80°C ++ and the Air Temperature above the design temperature of 24°C.

In the Table below, we referred to Total Recycle case during August 2012 in SEGAS LNG Plant which is middle summer and we examined the behavior of the system at afternoon temperatures.

Table 6: Data obtained from the PI System for a total Recycle Case

	16TI1217	16TIC1242	16TI1424	16UY2310			
	PR COMP DISCHARGE	PROP COMP 16-MC11	16-MC11 INTAK E AIR	UIC-1198 MASS FLOW	ΔT	Temp. Diff	m%
	°C	°C	°C	kg/h	°C	°C	
20-Aug 13:21:00	88.75	58.04	29.22	1635183.1	30.71	59.53	71.70
20-Aug 13:22:00	88.71	58.01	29.43	1634464.6	30.70	59.27	71.67
20-Aug 13:23:00	88.66	58.12	29.63	1643250.5	30.54	59.03	72.06
20-Aug 13:24:00	88.59	58.09	29.48	1644294.8	30.50	59.10	72.10
20-Aug 13:25:00	88.58	58.04	29.39	1635715.4	30.54	59.19	71.73
20-Aug 13:26:00	88.58	57.98	29.59	1626961.5	30.59	58.99	71.34
20-Aug 13:27:00	88.59	58.02	30.15	1623442.0	30.56	58.43	71.19
20-Aug 13:28:00	88.56	58.08	29.83	1629603.9	30.48	58.72	71.46
20-Aug 13:29:00	88.56	58.11	29.54	1631034.4	30.45	59.02	71.52
20-Aug 13:30:00	88.57	58.09	29.70	1626845.2	30.48	58.86	71.34
20-Aug 13:31:00	88.54	58.06	29.79	1622931.4	30.48	58.75	71.16

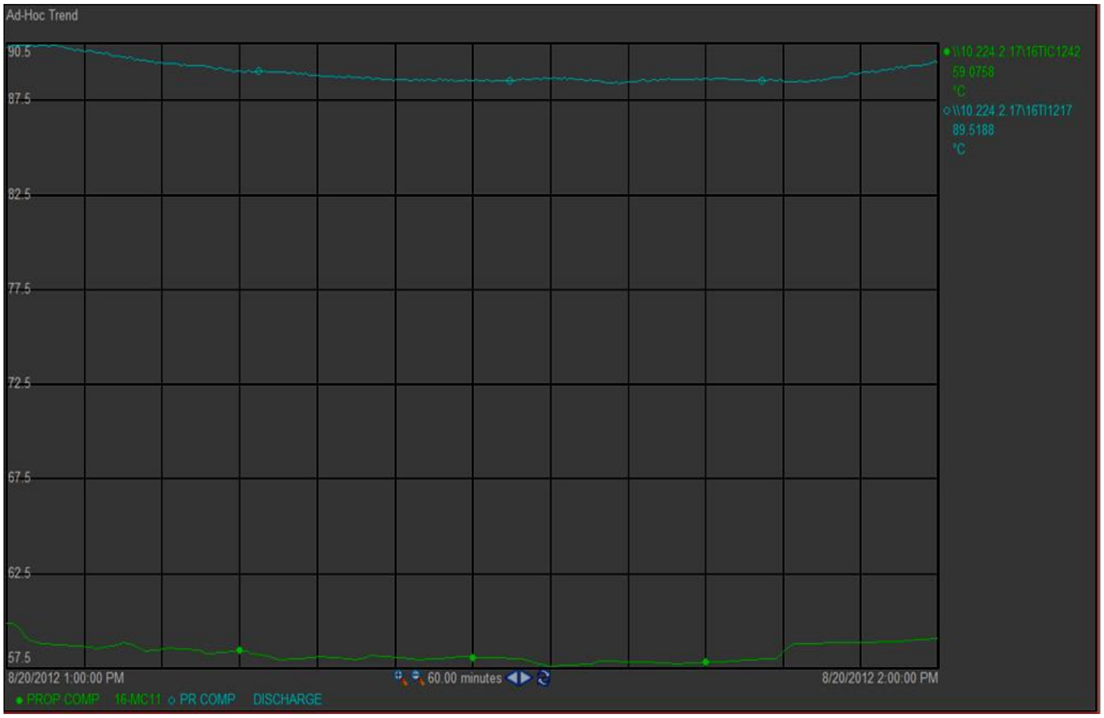


Figure 17: Propane Temp Drop – PI System- Aug 20

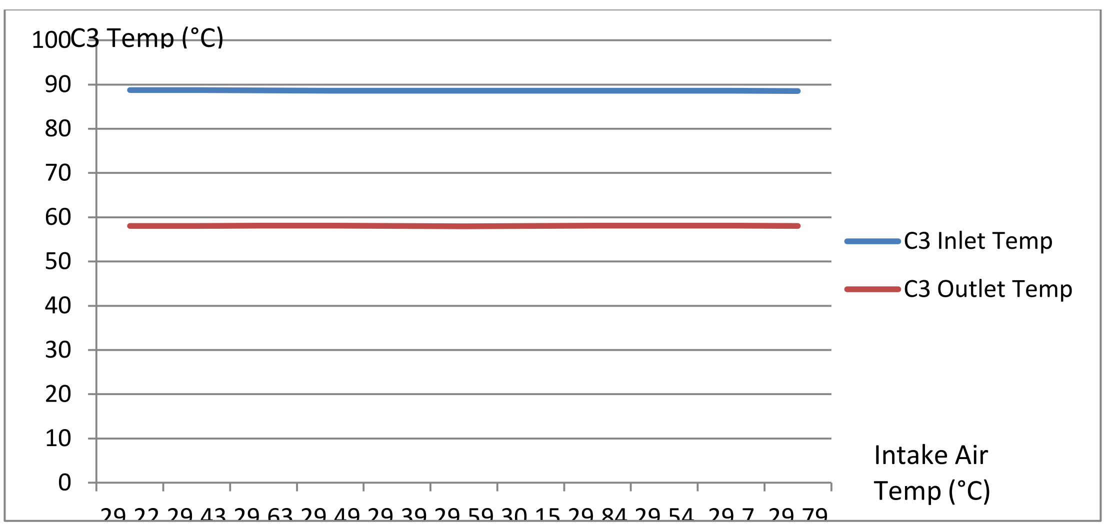


Figure 18: Propane Temp Drop vs. Air Temp

In this test, we noticed that the Temperature Difference between Inlet Propane and Air is reduced to 58°C with 71% of maximum Propane feed passing through the Recycle Cooler.

Since Mass flow = 71% of Maximum C3 Mass Flow.

$\Delta T_{obtained}$ = 30°C

$\boldsymbol{\Delta T_{Total}}$ = 0.71 × 30 = 21.3°C

At ΔT= 58°C a total of **21.3°C** Temperature drop in the compressed vapor propane can be obtained.

As shown in the tested condition above, the Recycle cooler was able to provide up to ***21.3°C cooling***.

4.3 Limitation of the tested results

Though the data shown above can show an actual plant data, we were not able to construct a whole understanding of the behavior of the Propane temperature drop across the whole range of Hot Climate conditions [25°C -35°C]. The test was limited by actual ambient air temperature at the cases of total recycle at the plant. We were also limited by the mass flow provided to the plant and we had no power to impose a change on it.

It also important to note that because of recycling the propane from the discharge of the compressor back to the suction, that causes continuous heating of the propane feed since the Recycle cooler is only designed to partially cool the propane feed and not completely cool it to the design suction temperature at normal operations.

In the next part, we will simulate the behavior across the whole range of the hot climate conditions Temperature through Aspen Hysys. We will be also able to control the parameters of mass flow, Temperature difference, Ambient Air Temp and Propane discharge temperature. That will give us concrete understanding of the behavior.

4. 4 Building and Validating the Simulation Model in Aspen Hysys.

The Propane Unit was simulated through Aspen Hysys 7.1 and the Data was validated through SEGAS LNG Plant Data from Egypt.

The simulation was carried out as a steady state case with the following consideration:

1. A 4-Stage Propane Compressor was simulated through 4 different Propane Compressors with a Mixer before each stage to include the flow from the previous stage with the flow from the chillers.
2. A Kettle Shape Heat Exchange was simulated through a normal heat exchanger followed be a separator to avoid liquid escapes to the compressor.
3. Discharge of each Heat Exchanger in each stage is sent to a separator where the vapor stream is sent to the Compressor suction and the liquid stream is sent to the next chiller stage.

Since the simulation model is conducted through steady state following is a comparison table to validate the data of the simulation model with the data obtained from the Process Flow Diagram (PFD) of SEGAS LNG Plant in Egypt.

Table 7: Validating the Simulation Model Data with SEGAS LNG Plant Data.[(14)] .[(15)] .[(16)]

No	Unit Tag Name	Tag No	Value	Plant Data	Hysys Data	%error
1	Propane Compressor	16-MJ04	Discharge Pressure	18 bar	18 bar	0
2	Propane	16-MJ04	Discharge	68.4 °C	70.89°C	3.6

	Compressor		Temperature			
3	Propane Condenser	16-MC09	Duty	192.797 MW	192.797 MW	0
4	Propane Condenser	16-MC09	Discharge Pressure	17.1 bar	17.1 bar	0
5	Propane Condenser	16-MC09	Discharge Temperature	50^{o}C	49.62^{o}C	0.76
6	Recycle Cooler	16-MC11	Duty	13.2 MW	13.2 MW	0
7	Propane Sub-Cooler	16-MC10	Duty	26.4 MW	26.4MW	0
8	Propane Sub Cooler	16-MC10	Discharge Temperature	35^{o}C	35^{o}C	0
9	Propane Sub Cooler	16-MC10	Discharge Pressure	15.7 bar	15.7 bar	0
10	MR Last Chiller	16-MC07	Discharge Pressure	61.1 bar	61.1 bar	0
11	MR Last Chiller	16-MC07	Discharge Temperature	-29.9^{o}C	-31.5^{o}C	5
12	NG Last Pre-Cooler	15MC-03	Discharge Pressure	61.4 bar	61.4 bar	0
13	NG Last Pre-Cooler	15 MC-03	Discharge Temperature	-29.7^{o}C	-29.2^{o}C	0.16

4.5 Propane Performance during Hot Climate Condition using original plant configuration.

The approach we are testing is to test utilizing the Recycle cooler as a first stage cooler to see if we are able to obtain a full propane condensation after the Propane condenser.

We are concerned to do the testing during Hot Climate Conditions through the Temperature Range of 25^{o}C - 35^{o}C ambient Air Temperature.

To simulate the Hot Climate condition at the steady state in Hysys we used an approach of 10^{o}C increase in the Outlet design temperature of the Propane Condenser. Since the PFD is set at 25^{o}C, an increase in the outlet Temperature up to 10^{o}C will allow simulating the Hot Climate condition up to 35^{o}C.

Table 8: Hot Climate Condition Approach

Ambient Air Temperature	Propane Condenser Outlet Temp
25^{o}C	49.62^{o}C
35^{o}C	59.62^{o}C

Case 1: Without using the Recycle Cooler

At normal plant operation where the Recycle Cooler is not used as a stage in the propane condensing process, during Hot climate condition there will be a failure in obtaining a full propane condensation.

In Figure 20, we have tested the propane condenser behaviour during hot climate condition at Ambient Air Temperature Range [25^{o}C - 35^{o}C]

From the figure we can observe a failure in fully condensing the Propane during hot climate conditions if the plant kept on operating full load. The System fails to maintain a Vapour fraction of 1.00 at the outlet of the condenser.

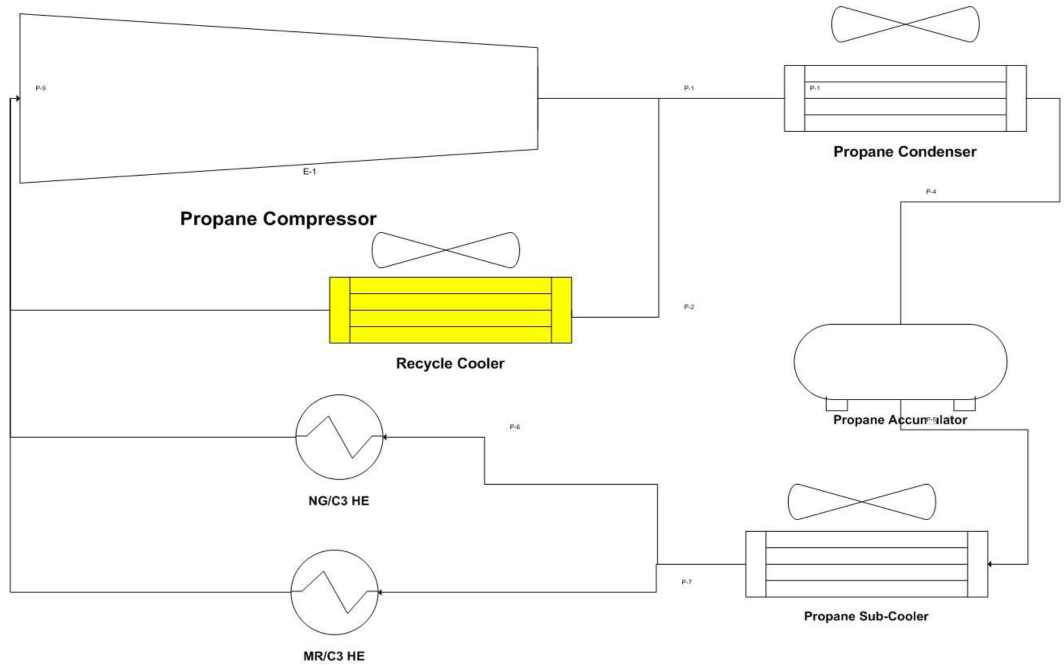


Figure 19: Propane Refrigerant Process

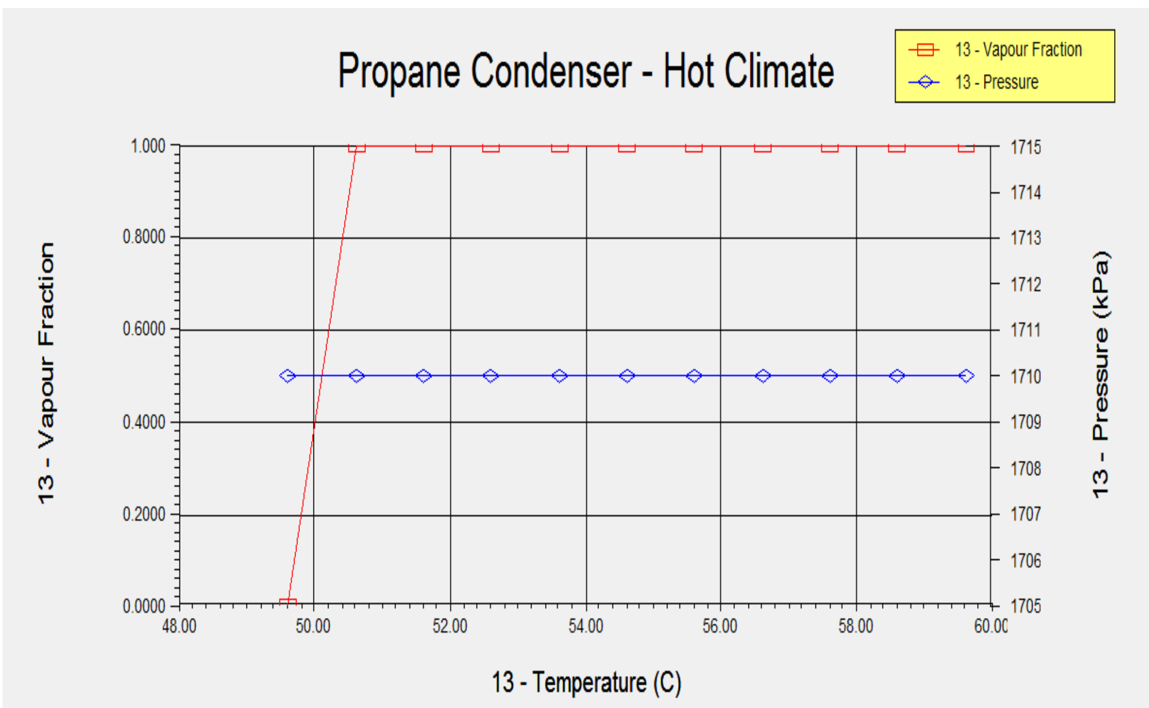


Figure 20: Vapor Fraction during Hot Climate condition

4.6 Two Stages Condensing System

Case 2: Utilizing the Recycle Cooler as a first Stage Condenser

To Test the performance of the Recycle Cooler and whether it is able to provide a full condensation for the propane was done utilizing the same temperature approach.

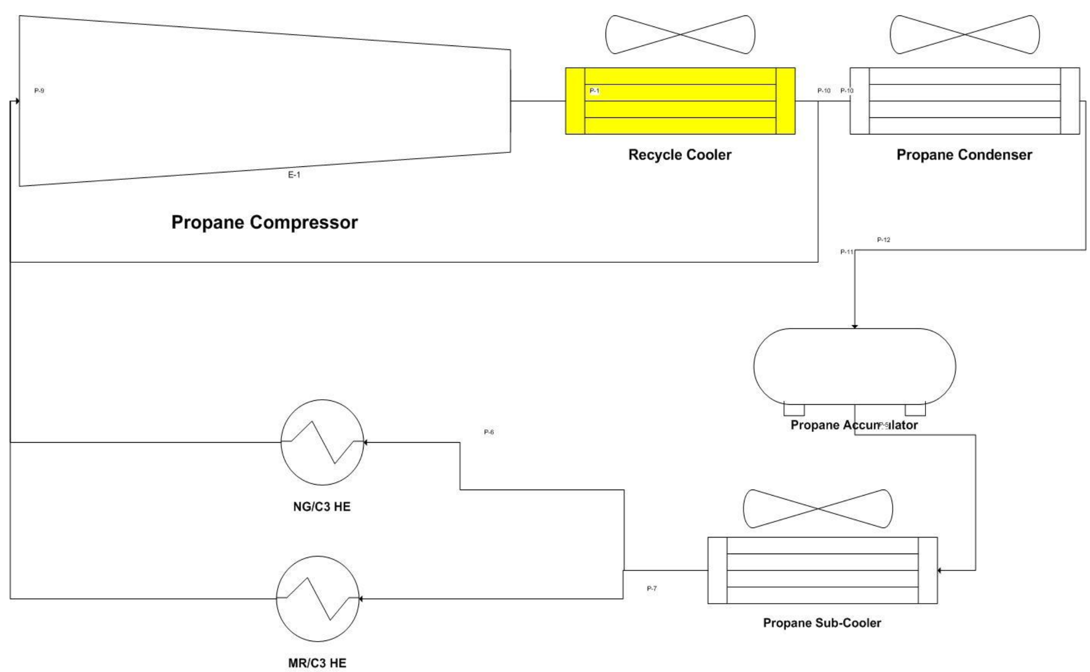


Figure 21: Two Stages Condensing Concept

Note that only 71% of Propane flow was set to pass through the Recycle cooler as the Plant Data Sheet for the Recycle Cooler suggests. The rest of the flow passes only through the Propane condenser.

The figure below shows the Vapor fraction of the Propane when utilizing the Two-Stages Condensing system.

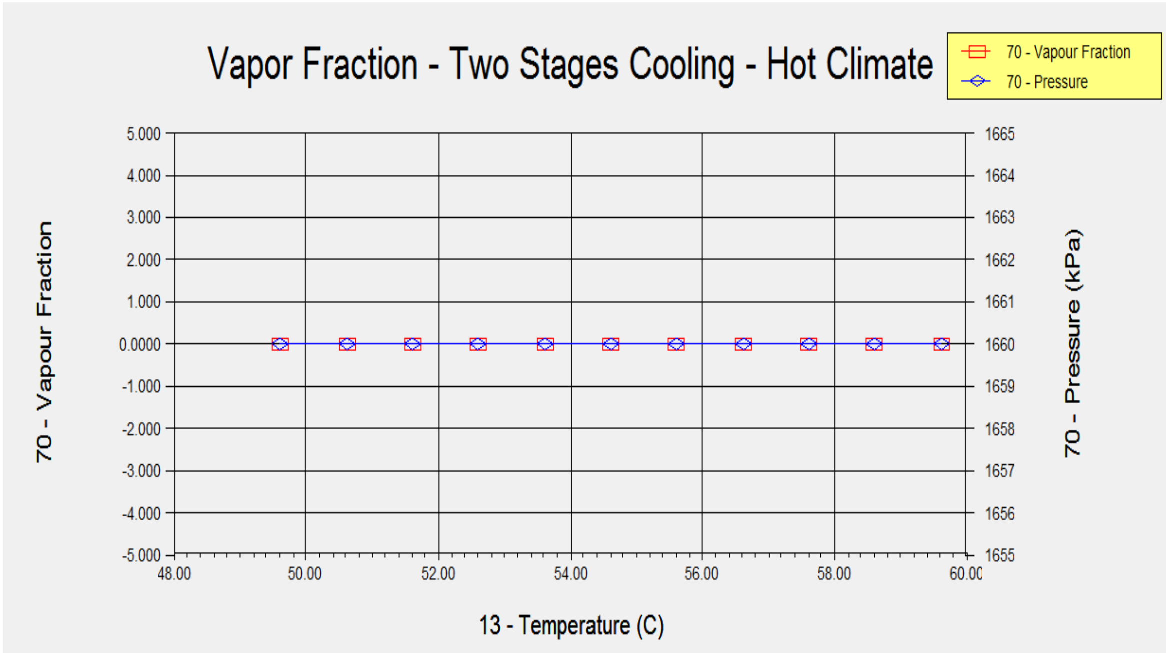


Figure 22: Propane Vapor Fraction after using the Two Stages Cooling System – Hot Climate

From the graph above we can observe a **full condensation of the propane refrigerant** when utilizing the Two Stages Condensing System (Recycle Cooler + Propane Condenser) during Hot Climate Condition over a temperature range of 25°C - 35°C.

4.7 Compressor Protection

Since the Prime objective of the Recycle Cooler is to recycle its outlet flow to the suction of the Propane compressor, it is important to avoid any liquid escapes as it will damage the compressor compartments.

It is important that the Vapour Fraction after the Recycle Cooler will always stay as 1.00 to avoid any liquid escapes or utilizing the Two-Stages Condensing

System will be inefficient and will cause major damage to the Compressor compartments.

The graph below shows the Vapour fraction of Propane after the Recycle Cooler at the same Temperature Range.

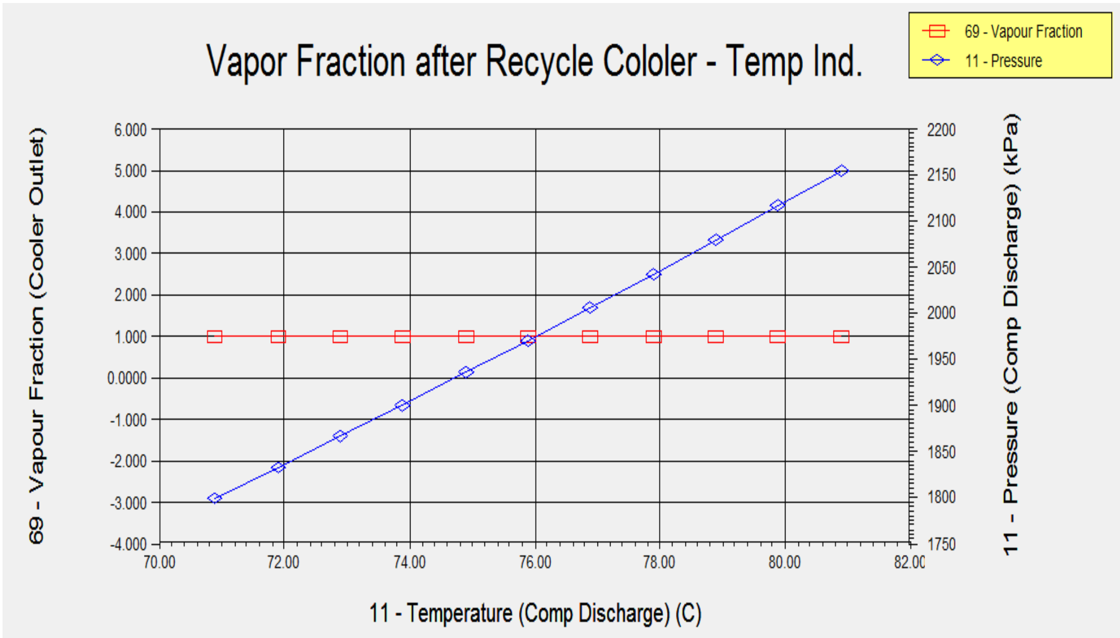


Figure 23: Vapor fraction after the Recycle Cooler – Hot Climate

From the graph above, we can observe a constant vapor fraction of 1.00 after the recycle cooler which is a guarantee that no liquid escapes will happen to the suction of the compressor in case of Compressor surge.

That concludes that utilizing the Two-Stages Condensing system is safe at the Compressor Compartment from that perspective.

4.8 Operating Line for Propane Refrigerant

Generating the phase envelop for the Propane is refrigerant will allow us to decide on the operating line for the Propane Refrigerant Unit. The table below shows the bubble point/dew points for propane at different temperature and pressure profiles.

Table 9: Propane Phase Envelop Table values

Pressure (kPa)	Temperature (°C)
50.6625	-56.90218082
107.2525133	-40.88263153
291.5425581	-14.95479265
792.4948378	17.9885526
2154.224317	60.58075114
3551.715453	86.4930377
3900.796305	91.7427494

From the table above we can generate the phase envelop diagram for the Propane where above the line, propane is in liquid phase and below the line propane is in vapour phase. That line accounts as the operating line for achieving full condensation of the propane refrigerant.

From the operating line figure, we can notice the improvements achieved by utilizing the Two Stages condensing system where failure to fully condense the propane happens during Hot Climate condition. By using the Two Stages condensing, we can shift back the propane line to the liquid state above the operating line.

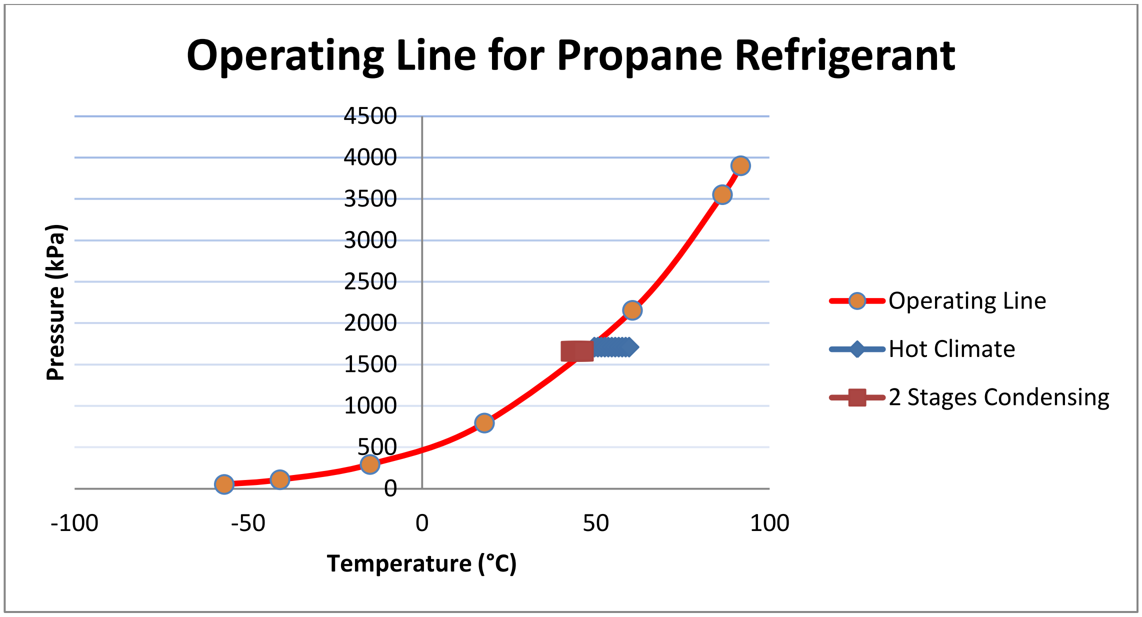


Figure 24: Operating line for the Propane Refrigerant

4.9 Modifying the Propane Refrigerant Composition

Our second approach in testing the performance of the Propane refrigerant during Hot Climate conditions is to test the performance of the refrigerant when introducing minimum amounts of lighter components to the refrigerant compositions. We will be comparing the Performance in terms of:

1. Compressor Power consumption
2. Heat Exchangers UA
3. Air Coolers Duty

Putting in mind, the first two points are the most important in judging the performance since they are the most important in terms of cost and performance considerations.

In our testing, we examined five different compositions for the refrigerant, maintaining the Propane composition above 95 mol% always. The table below shows the different compositions under investigation.

Table 10: Refrigerant Compositions

Case / Composition	Propane (mol%)	Ethane (mol%)	Methane (mol%)
Case 1	100	0	0
Case 2	98.2	1.8	0
Case 3	97	3.0	0
Case 4	98.2	1.2	0.6
Case 5	98.2	0.6	1.2

The previous compositions have been tested through the Aspen Hysys Model in the previously validated model with SEGAS Plant Data.

The following figures shows a comparison between the results obtained for the different cases in terms of Compressor Power consumption, Heat Exchangers UA values and Air Cooler Duties.

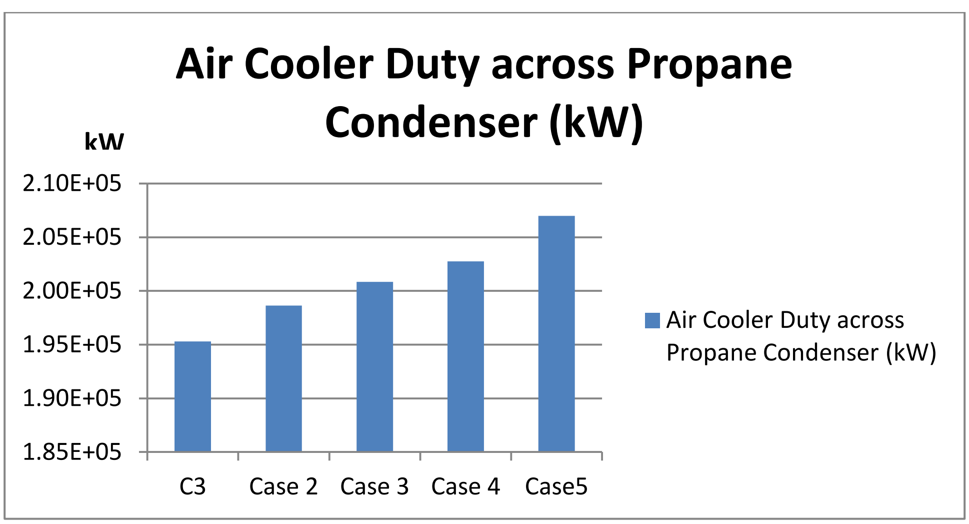


Figure 25: Air Cooler Duty Comparison after Propane Condenser

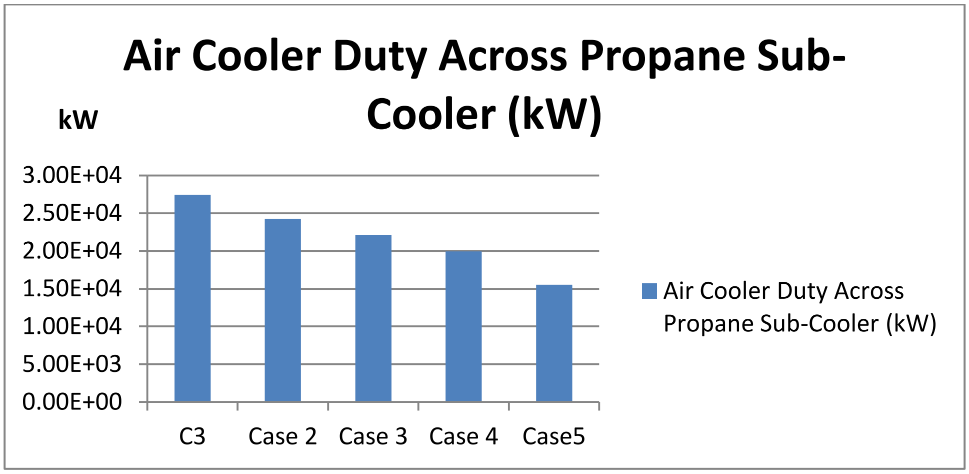


Figure 26: Air Cooler Duty Comparison after Propane Sub-cooler

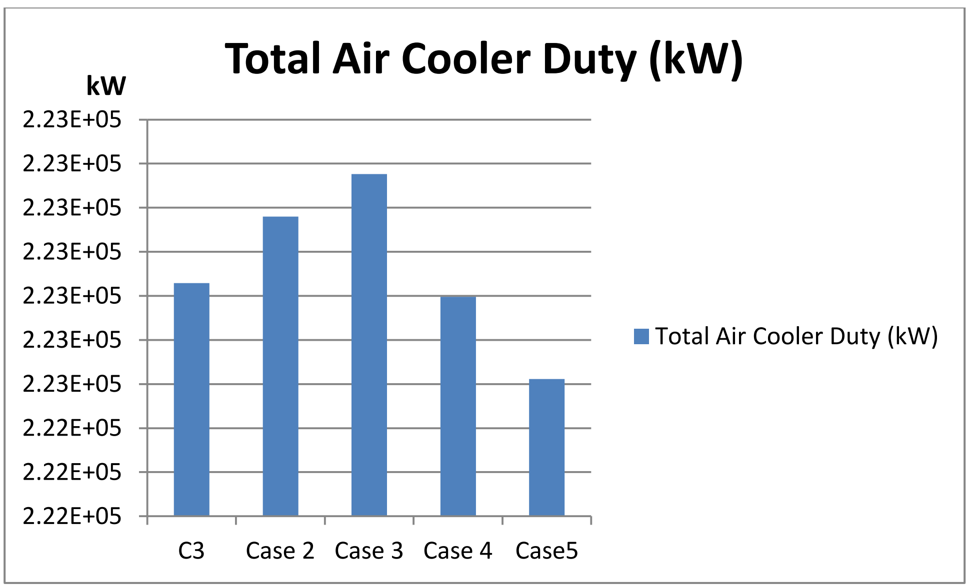


Figure 27: Total Air Cooler Duty Comparison

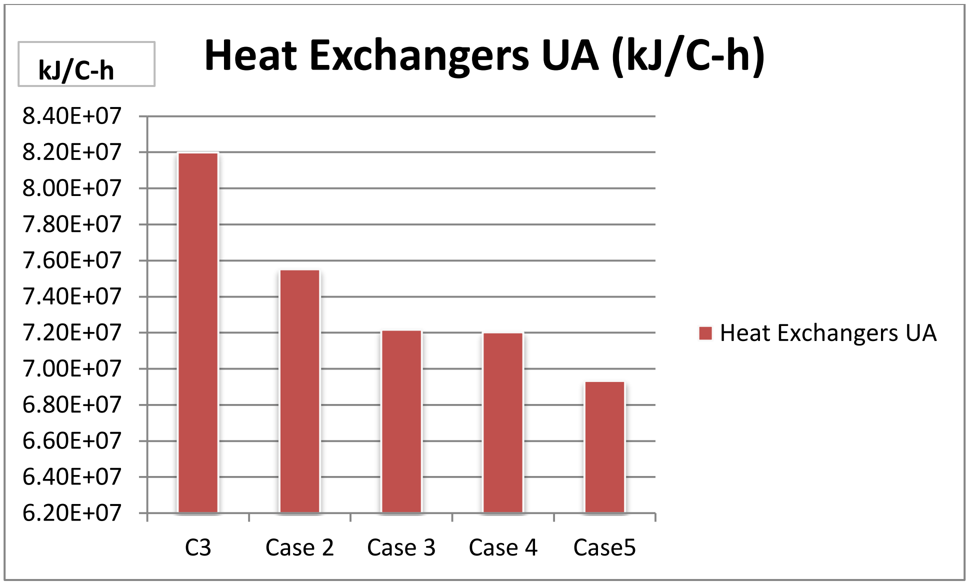


Figure 28: Heat Exchanger UA Values Comparison

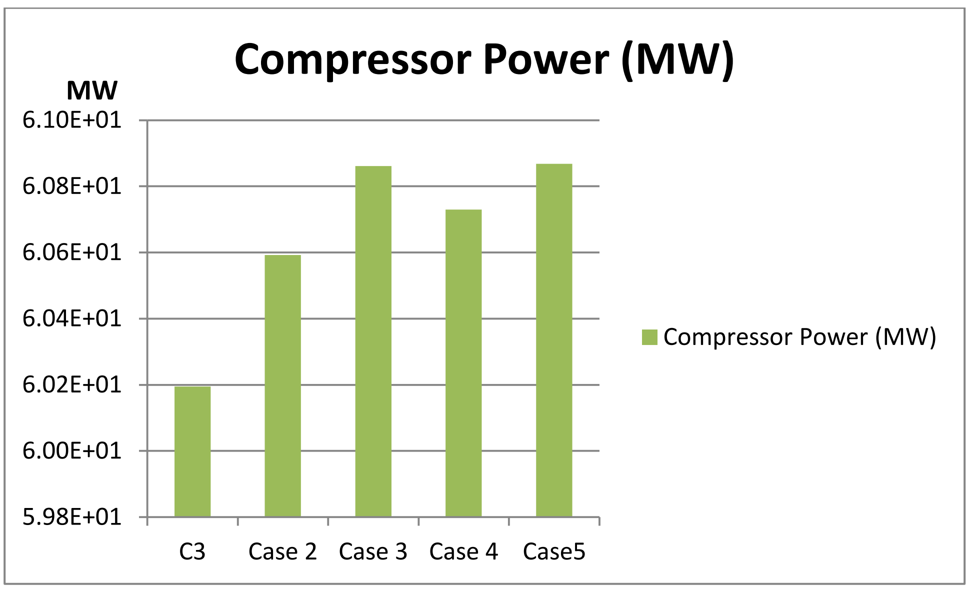


Figure 29: Compressor Power Consumption Comparison

From the figures shown above, we observe the following:

1. Adding lighter components to the refrigerant increased the condensation duty of the Air Cooler as a result of the higher heat of condensation required by lighter components (as shown in Fig. 25). However the duty of the Air cooler was

decreasing as the percentage of lighter components decreases (as shown in Fig. 26) as a result of a decreased Specific Heat Capacity (C_p).

The total Air Cooler Duty required to reach the specified condition by SEGAS LNG Plant showed improvements when introducing Methane in the refrigerant (As shown in Fig. 27). This change relates to the different mass flow of refrigerant required as the composition changes. However, our concern here is the duty of the Condenser.

2. Pure Propane refrigerant showed and increased Heat Flow or UA values across the Heat Exchangers in comparison to other refrigerant composition. Increasing the Percentage of lighter components showed a decrease in the total Heat flow. (As shown in Fig 28)

3. In terms of Compressor Power consumption, Pure Propane composition was the least in terms of Power consumption in comparison to the other compositions. (As shown in Fig. 29)

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

From the Literature review above, we were to able to identify different approaches in handling the increased requirement of LNG Production capacity which requires stronger Refrigeration process or suitable climate conditions and both conditions are limitations to the LNG production in order to meet the required demands of production.

While some studies focused on providing more compressor power to meet the increased demand of the refrigerant by changing to Frame 9 Compressors or using 2 Frame 7 Compressors, other studies focused on using alternative refrigerants or other refrigerant for sub-cooling such as Nitrogen.

Few studies did comparison between different Refrigerant configuration and Propane pre-cooling C3MR Process seems to be the most Energy efficient so far.

In our Study, we focused on improving the Propane C3MR process by utilizing any waste of cooling duty that may exist and look in depth into how the configuration of the Refrigerant composition of Propane without moving to a mixed refrigerant can improve the performance of the Refrigerant.

In FYP II, Two Stages condensing approach was tested through Aspen Hysys where the Recycle Cooler was used as stage in condensing the propane rather than only using it for recycling the feed to the suction of the compressor. The testing succeeded in obtaining 2 important results:

1. The ability to obtain full Propane Condensation over Hot Climate Conditions [25^{o}C-35^{o}C]
2. No liquid Propane was found at the outlet of the Recycle cooler at any pressure or temperature condition over the tested range. That makes the process safe on the Compressor compartment in case of Compressor Surge.

A second approach was tested in this study where modifying the composition of the Propane refrigerant and examining the effect on the Cooler duty, Heat Exchangers UA and Compressor Power consumption. The following results were obtained.

1. In terms of Air Cooler Duty, Pure propane showed the least Air cooler duty across the Propane condenser.
2. In terms of Compressor Power consumption, Pure Propane was the least in terms of power consumption in comparison of other refrigerant compositions.

From that we can conclude that pure propane is the best option to use to save on Compressor power consumption and Air Condensing Duty.

Recommendations

This study has examined certain approaches in improving the performance of the Propane refrigerant during Hot Climate conditions.

However further studies are to be considered for future work including:

1. Control System.
2. Piping and installation study.
3. Further Study on the (CCC) Surge Protection system of the Propane Compressor. Advised to be conducted in collaboration with the manufacturer (GE)

CHAPTER 6: REFERENCES

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CHAPTER 7: APPENDECIES

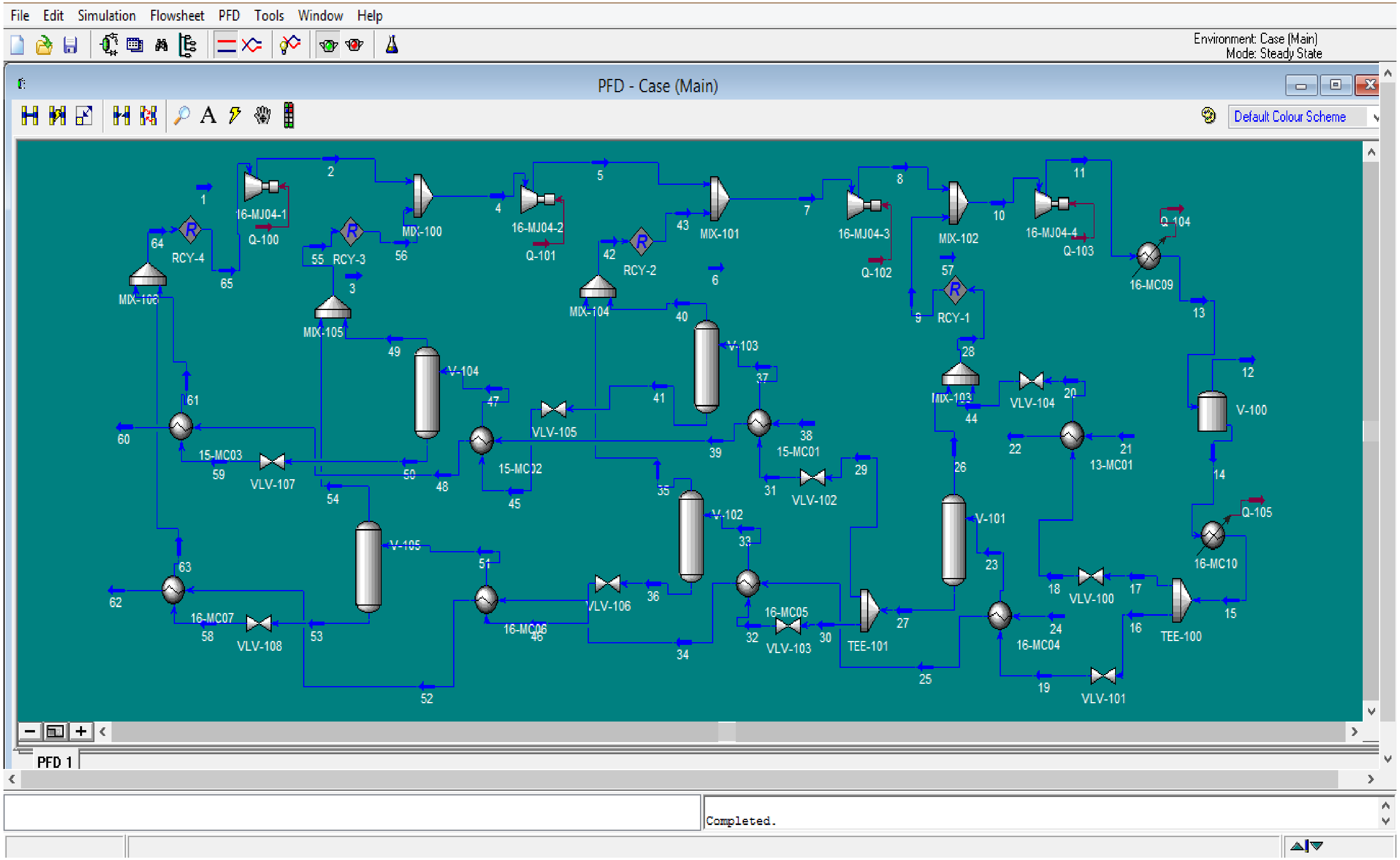

Figure 30: Propane Refrigeration Unit – Aspen Hysys Model

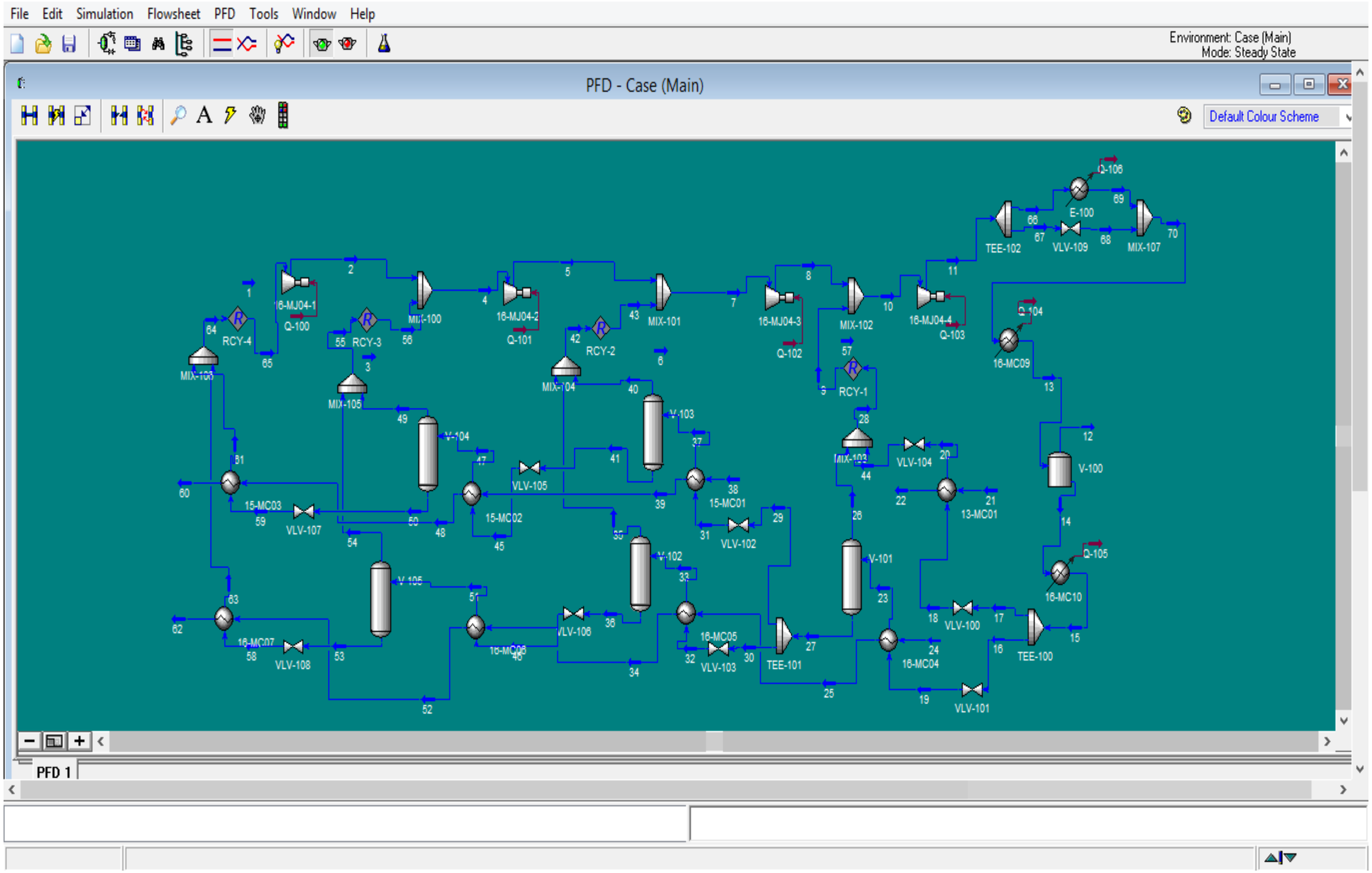

Figure 31: Propane Unit – Two Stages Condensing – Aspen Hysys