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Utilization of Liquefied Natural Gas Re-gasification Cold Energy in Power Generation Cycles

الإستفادة من الطاقة الباردة لإعادة الغاز الطبيعي المسال في دورات توليد الطاقة

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الإستهلال

قَالَ تَعَالَىٰ:

﴿ وَمَا تَوْفِيقِيٓ إِلَّا بِٱللَّهِۚ عَلَيْهِ تَوَكَّلْتُ وَإِلَيْهِ أُنِيبُ ﴾

صدق الله العظيم

سورة هود ـ الأية (88)

Dedication

We dedicate this project to our parents for the love and support they have provided throughout our entire life, they have been there for every decision we have made and help our dreams become reality, to our friends and families for their help and encouragement. We also dedicate this project to our dear friends Eng. **Alrsheed Hamed & Eng. Momen Hassan.**

Acknowledgment

Thankfulness and appreciation for Allah as always before and after

Without the encouragement and support of some people this thesis would have not been feasible.

We would like to express our gratitude to our supervision Dr. Zeinab Abdullah for her ideal supervision, her sage advice in significant criticisms and patient encouragement aided the writing of this innumerable ways.

We are indebted to our colleges of Sudan University of science and technology.

Once again, we thank all those who have encouraged and helped us

Abstract

This project studies the comparison between the amount of energy generated from the three common cycles used for power generation, the three cycles used are Direct Expansion cycle, Rankine cycle, and Combined Rankine cycle. The comparison is done using ASPEN HYSYS simulation program to identify which cycle is more reliable. The feed properties for each cycle are identical and so are for all the equipments to make the comparison more realistic. According to this study, it is found that it is possible to make use of the liquefied natural gas cold energy in the power generation which was being wasted.

المستخلص

يدرس هذا المشروع المقارنة في كمية إنتاج الطاقة بين أكثر دورات توليد الطاقة شيوعا، وهذه الدورات هي دورة التوسع المباشر، دورة رانكين، ودورة رانكين المدمجة. المقارنة تمت بإستخدام برنامج المحاكاة ASPEN HYSYS، لتحديد أي من الدورات هو الأكثر إعتمادية. خصائص الغاز الطبيعي للثلاث دورات هي متطابقة و كذلك خصائص المعدات المستخدمة متطابقة لجعل عملية المحاكاة أكثر واقعية. حسب هذه الدراسة وجد أنه يمكن الإستفادة من الطاقة الباردة للغاز الطبيعي المسال في توليد الطاقة بدلا عن اهدارها.

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Chapter 1

Introduction and literature Review

1.1 Natural Gas:

Natural Gas (also called **fossil gas**) is a naturally occurring hydrocarbon gas mixture consisting primarily of methane, but commonly including varying amounts of other higher alkanes, and sometimes a small percentage of carbon dioxide, nitrogen, hydrogen sulfide, or helium. It is formed when layers of decomposing plant and animal matter are exposed to intense heat and pressure under the surface of the Earth over millions of years. The energy that the plants originally obtained from the sun is stored in the form of chemical bonds in the gas **[Moniz, E.J. (2011). "The Future of Natural Gas]**

Natural gas is a non-renewable hydrocarbon used as a source of energy for heating, cooking, and electricity generation. It is also used as a fuel for vehicles and as a chemical feedstock in the manufacture of plastics and other commercially important organic chemicals.["**Organic Origins of Petroleum". US Geological Survey. Archived from the original on 27 May 2010.**]

On the other hand it is a major cause of climate change, both in itself when leaked and also due to the carbon dioxide it produces when burnt.

Natural gas is found in deep underground rock formations or associated with other hydrocarbon reservoirs in coal beds . Petroleum is another resource and fossil fuel found in close proximity to and with natural gas. Most natural gas was created over time by two mechanisms: biogenic and thermogenic. Biogenic gas is created by methanogenic organisms in marshes, bogs, landfills, and shallow sediments. Deeper in the earth, at greater temperature and pressure, thermogenic gas is created from buried organic material.[**Adam Voiland and Joshua Stevens. "Methane Matters". NASA Earth Observatory. Retrieved 15 September 2015.]**

Natural gas is often informally referred to as simply as "gas", especially when compared to other energy sources such as oil or coal. However, it is not to be confused with gasoline, especially in North America, where the term gasoline is often shortened in colloquial usage to *gas*.

In the 19th century, natural gas was primarily obtained as a by-product of producing oil, since the small, light gas carbon chains came out of solution as the extracted fluids underwent pressure reduction from the reservoir to the surface.

Unwanted natural gas was a disposal problem in the active oil fields. If there was not a market for natural gas near the wellhead it was prohibitively expensive to pipe to the end user.

In the 19th century and early 20th century, unwanted gas was usually burned off at oil fields. Today, unwanted gas (or stranded gas without a market) associated with oil extraction often is returned to the reservoir with 'injection' wells while awaiting a possible future market or to re-pressurize the formation, which can enhance extraction rates from other wells. In regions with a high natural gas demand (such as the US), pipelines are constructed when it is economically feasible to transport gas from a well site to an end consumer **[History". NaturalGas.org. Retrieved 1 December 2016].**

Natural gas extracted from oil wells is called casing head gas (whether or not truly produced up the annulus and through a casing head outlet) or associated gas.

The natural gas industry is extracting an increasing quantity of gas from challenging resource types **[Extraction". Natural Gas.org. Archived from the original on 8 July 2013]:**

- Sour gas.
- Tight gas.
- Shale gas.

There is some disagreement on which country has the largest proven gas reserves. Sources that consider that Russia has by far the largest proven reserves include the US addition to transporting gas via pipelines for use in power generation.

other end uses for natural gas include export as liquefied natural gas (LNG) or conversion of natural gas into other liquid products via gas to liquids (GTL) technologies. GTL technologies can convert natural gas into liquids products such as gasoline, diesel or jet fuel. A variety of GTL technologies have been developed, including Fischer–Tropsch (F–T), methanol to gasoline (MTG) and syngas to gasoline plus(STG+).

F–T produces a synthetic crude that can be further refined into finished products, while MTG can produce synthetic gasoline from natural gas. STG+ can produce drop-in gasoline, diesel, jet fuel and aromatic chemicals directly from natural gas via a single-loop process.

In 2011, Royal Dutch Shell's IA (47 600 km^3), the US Energy Information Administration (47 800 km^3), and OPEC (48 700 km^3). However, BP credits Russia with only 32 900 km³, which would place it in second place, slightly behind Iran (33 100 to 33 800 km³, depending on the source).

With Gazprom, Russia is frequently the world's largest natural gas extractor.

Major proven resources (in cubic kilometers) are world 187 300 (2013), Iran 33 600 (2013), Russia 32 900 (2013), Qatar 25 100 (2013), Turkmenistan 17 500 (2013) and the United States 8500 (2013). (12,000 cu mi) of natural gas and 50 billion barrels (7.9 billion cubic meters) of natural gas condensates. **[Natural Gas – Proved Reserves". The World Factbook. Central Intelligence Agency. Retrieved 1 December 2013.]**

It is estimated that there are about 900 000 km³ of "unconventional" gas such as shale gas, of which 180 000 km³ may be recoverable.

In turn, many studies from MIT, Black & Veatch and the DOE predict that natural gas will account for a larger portion of electricity generation and heat in the future.

The world's largest gas field is the offshore South Pars / North Dome Gas-Condensate field, shared between Iran and Qatar **[First cargo of Pearl GTL products ship from Qatar". Shell Global. 13 June 2011. Retrieved 19 November 2017.].**

It is estimated to have 51,000 cubic kilometers (12,000 cu mi of natural gas and 50 billion barrels (7.9 billion cubic meters) of natural gas condensates. Because natural gas is not a pure product, as the reservoir pressure drops when non-associated gas is extracted from a field under supercritical (pressure/temperature) conditions, the higher molecular weight components may partially condense upon isothermic depressurizing—an effect called retrograde condensation. The liquid thus formed may get trapped as the pores of the gas reservoir get depleted. One method to deal with this problem is to re-inject dried gas free of condensate to maintain the underground pressure and to allow re-evaporation and extraction of condensates. More frequently, the liquid condenses at the surface, and one of the tasks of the gas plant is to collect this condensate. The resulting liquid is called natural gas liquid (NGL) and has commercial value.

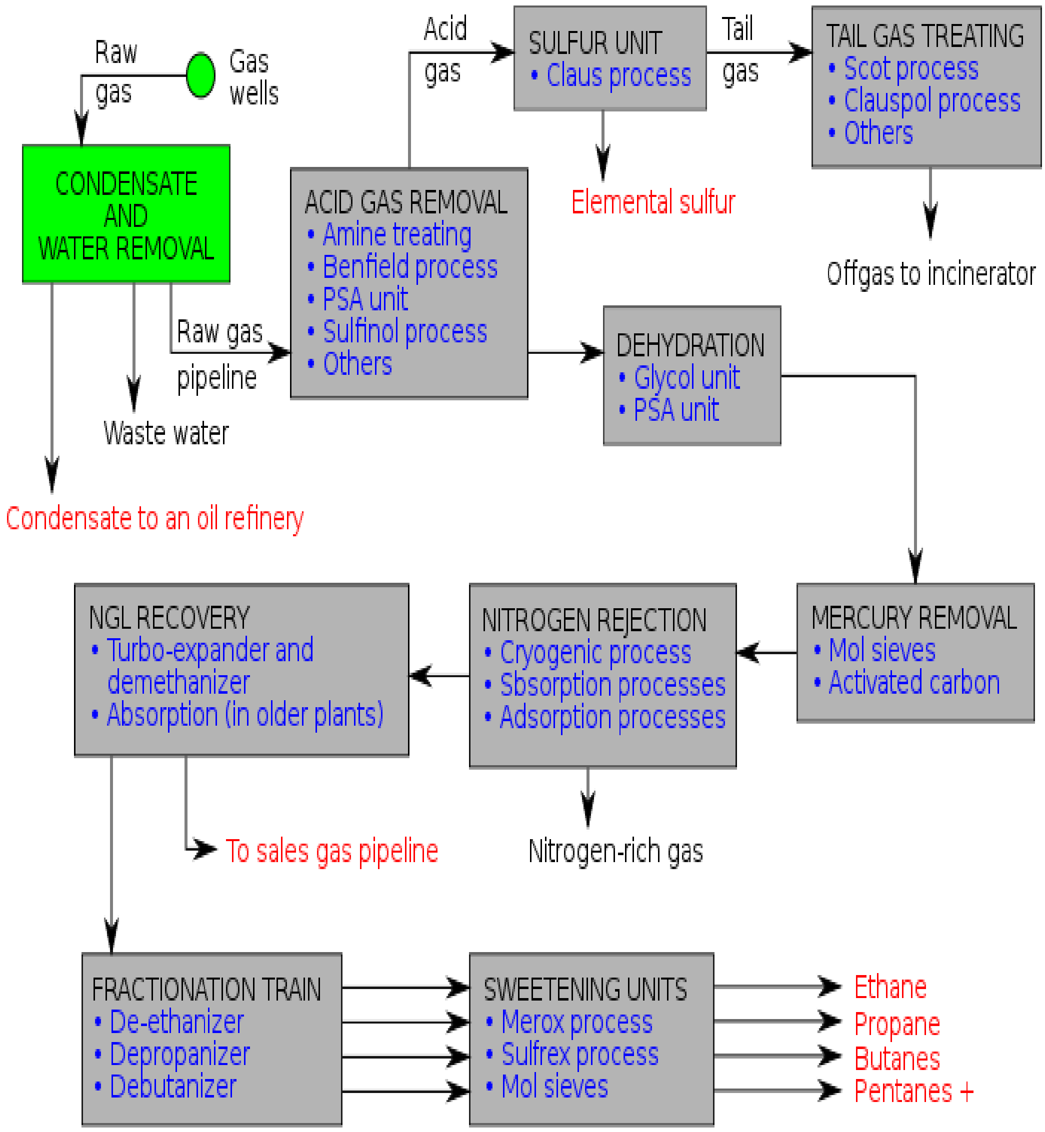
Natural gas was discovered accidentally in ancient China, as it resulted from the drilling for brines.

Natural gas was first used by the Chinese in about 500 BCE (possibly even 1000 BCE). They discovered a way to transport gas seeping from the ground in crude pipelines of bamboo to where it was used to boil salt water to extract the salt in the Ziliujing District of Sichuan.

The discovery and identification of natural gas in the Americas happened in 1626. In 1821, William Hart successfully dug the first natural gas well at Fredonia, New York, United States, which led to the formation of the Fredonia Gas Light Company. The city of Philadelphia created the first municipally owned natural gas distribution venture in 1836. By 2009, 66 000 km^3 (or 8%) had been used out of the total 850 000 km^3 of estimated remaining recoverable reserves of natural gas. Based on an estimated 2015 world consumption rate of about 3400 km^3 of gas per year, the total estimated remaining economically recoverable reserves of natural gas would last 250 years at current consumption rates. An annual increase in usage of 2–3% could result in currently recoverable reserves lasting significantly less, perhaps as few as 80 to 100 years. [**Michael Kanellos (9 June 2011). "In Natural Gas, U.S. Will Move From Abundance to Imports". Greentech Media.]**

1.2 Natural Gas Processing:

The block flow diagram below (Figure 1.1) shows how processing of the raw natural gas yields byproduct sulfur, byproduct ethane, and natural gas liquids (NGL) propane, butanes and natural gasoline **.[Natural Gas Processing: The Crucial Link Between Natural Gas Production and Its Transportation to Market]**



(Figure 1.1) : processing of raw natural gas

1.3 Liquefaction:

How is natural gas liquefied? Natural gas is converted into liquid in a liquefaction plant, or "train". An LNG train performs three main processes:

1. Pre-treatment dust and slug (water and condensate) is removed along with hydrogen sulfide (H_2S) and mercury (Hg). These pollutants can cause corrosion and freezing problems, especially in aluminum heat exchangers.

2. Acid Gas Removal and De-hydration Carbon dioxide (CO_2) is absorbed and removed from natural gas with an amine absorber (acid gas removal or AGR) and an adsorbent is used to remove water. These impure substances are removed so that ice will not form during the subsequent liquefaction process.

3. Heavy hydrocarbon separation and liquefaction of heavy hydrocarbons (C5+) are removed by fractionation before liquefaction. As shown in the liquefaction process schematic, natural gas is pre-cooled to about -31°F (-35°C) by propane. **[" Liquefied Petroleum Gas (LPG), Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG).]**

1.3.1 The Liquefaction Process:

After pre-cooling, natural gas moves through a tube circuit in the main cryogenic heat exchanger (MCHE) where it is liquefied and sub-cooled to between -238°F (-150°C) to -260°F (-162°C) by mixed refrigerant (MR). The MR is also pre-cooled and then separated in a high pressure separator. The vapor and liquid streams pass through separate tube circuits in the MCHE where they are further cooled, liquefied, and sub-cooled.

The two sub-cooled streams are let down in pressure, further reducing their temperatures. As the mixed refrigerant vaporizes and flows downward on the shell side of the MCHE, it provides refrigeration for liquefying and sub-cooling the natural gas. The LNG end flash at the outlet of the MCHE and in the receiving LNG storage tank generates flash gas and boil-off gas to make up the fuel gas needed mainly by the propane and MR gas turbine driven compression cycles.

1.3.2 How LNG is converted to gas?

LNG is reheated with at least one heat exchanger and converted to gas using one of two common methods. In one technique, a small amount of the LNG is burned in a submerged combustion vaporizer, which produces the heat needed to gasify the remaining LNG.

The second method uses open rack vaporizers to gasify LNG with heat from ambient water, such as seawater or river water. LNG enters from the lower part of the vaporizer heat exchanger and exits as gas from the upper part. The water is collected and eventually returned to its source.

This process release large amounts of cold energy “exergy”.

1.3.3 Cold energy utilization:

LNG cold energy can be utilized in all the processes where cooling is necessary. Some examples are given below:

- Carbon Dioxide liquefaction.
- Air Separation.
- NGL Fractionation.
- Cold storage.
- Power generation.
- Desalination of seawater.
- Dry Ice production

1.4 Literature Review:

The 2018 Outlook for Energy (ExxonMobil, 2018) forecasts liquefied natural gas (LNG) trade to meet one-third of the natural gas demand in the next three decades. LNG is preferred for long distance transportation because its volume is approximately 600 times less than its same mass in gaseous phase. Natural gas liquefaction requires cryogenic conditions (around 160 C), which results in a large amount of energy being consumed during the liquefaction process. Therefore, LNG is necessary to be re-gasified before it is transported to end users. However, re-gasification without energy recovery results in most of the cold energy of LNG being wasted. In general, the LNG cold energy is wasted to seawater during re-gasification, and it can be recovered by applying cold energy recovery processes. To address this issue, different approaches towards LNG cold energy recovery have been reported. Kanbur and others reviewed various processes that are used to recover LNG cold energy. They found that since its introduction, LNG cold energy has been utilized mainly for power generation. **[2018 Outlook for energy: a view to 2040. ExxonMobil; 2018]**

Thus, the major concern of LNG cold recovery is electricity production.

Electricity production is done by various cycles such as the direct expansion cycle, Rankine cycle and the Combined Rankine cycle.

1.4.1 Direct Expansion Cycle:

The direct expansion system has been growing rapidly due to its ability to get rid of most duct work and piping. The popularity of this system is because the installation work has been made easier reducing the cost of overall system.

Advantages of direct expansion cycle:

- Low installation cost.
- Ease to test, adjust and balance the system .
- Low energy consumption.
- Low maintenance cost.

1.4.2 Rankine cycle:

This process was developed in 1959 by Scottish engineer William J.M Rankine, and it is a thermodynamic cycle which converts heat into mechanical energy which usually gets transformed into electricity by electrical generation.

The efficiency of Rankine cycle is limited by heat of vaporization by the fluid.

1.4.3 Combined Rankine Cycle:

A combined Rankine cycle is a combination between direct expansion cycle and Rankine cycle. It consist of all of the equipments of the tow cycles .

Advantages of combined Rankine cycle:

- Generate more power than other cycles

Disadvantages of combined Rankine cycle:

- Needs more equipments.
- High capital cost.
- Difficulty of installation.
- Difficulty of maintenance.

1.4.4 Previous researches:

1. Choi and others attempted to recover LNG cold energy for Power generation by adopting five process configurations: direct Expander, Rankine cycle, direct expansion with Rankine cycle, two stage Cascade Rankine cycle, and three-stage cascade Rankine cycles. [**A review of cryogenic power generation cycles with liquefied natural gas cold energy utilization]**

The net power, and thermal and exergy efficiencies of each configuration's performance were evaluated. They concluded that the three-stage cascade Rankine cycle using propane as the working fluid exhibited the best performance.

2. Sun and others suggested an LNG re-gasification power plant with a Rankine cycle using a mixed composition working fluid. They reported that a decrease in exergy loss in the heat exchanger afforded the highest efficiency with a relatively simple process configuration.

3. Gomez and other proposed an LNG power plant by applying closed Brayton and Rankine cycles.
They performed case studies by applying different working fluids (helium or nitrogen) for the closed Brayton cycle and carbon dioxide, ammonia, ethanol, or water for the Rankine cycle.
They concluded that the best working fluid for the closed Brayton cycle was helium while carbon dioxide worked best for the Rankine cycle.
Additionally, in their subsequent work, Gomez and others performed a thermodynamic analysis of a combined system comprising a closed Brayton cycle with helium, Rankine cycle with carbon dioxide, and fuel combustion. They analyzed the effect of different variables, including LNG pressure, compressor and turbine inlet temperatures, and compression ratio.

4. Garcia and others proposed Rankine cycles in series as a heat sink to utilize the LNG cold energy. The proposed power plant used the following sequence : Rankine cycle with argon, Rankine cycle with methane, direct LNG expansion, and Rankine cycle with methane or R14.
This group also proposed a power generation process design based on two Cascaded Rankine cycles with a direct LNG expander. They performed a sensitivity analysis of the pinch-point temperature and natural gas outlet pressure.

5. Fazlollahiand others suggested a cryogenic carbon-capture system with energy storage. They proposed a design that stored energy using natural gas as the working fluid at off-peak times and captured carbon dioxide during on-peak times.

6. Bao and others proposed a two-stage condensation Rankine cycle system using propane as the working fluid. Ghaebi and others suggested an ammonia-water cooling and power generation system that used LNG as the heat sink. They performed energy, exergy, and economic analysis, and sensitivity analysis of key variables. Ferreira studied the optimal working fluids for Rankine cycles with LNG cold recovery using a
multi-objective optimization approach via genetic algorithm.

7. Leeand Mistos suggested using an optimization methodology for the selection of multi-component working fluids. The objective of optimization was to minimize the area between the hot and cold composite curves. Lee proposed a process design methodology of an organic Rankine cycle based on the LNG cold recovery process, using super structure optimization approach.

8. Dutta and others analyzed the economic feasibility of power generation processes coupled with LNG re-gasification.
They proposed a genetic algorithm based on the economic optimization of various power generation processes via a combination of LNG direct expansion and organic Rankine cycle.
Some studies have also focused on the air separation unit and oxy-fuel combustion power plant.

9. Aspelund and Gundersen proposed a liquefied energy chain that utilized LNG cold energy for the oxy-fuel power plant and carbon capture. In the onshore sector, LNG cold energy is utilized to separate air, and liquefy nitrogen and carbon dioxide. Here, natural gas is used as the fuel in oxy-fuel combustion, while nitrogen and carbon dioxide are produced during power generation. In the off-shore sector, the cold energy of liquid carbon dioxide and nitrogen is used to liquefy natural gas.

10. Mehrpooya and others introduced two-stage Rankine cycles integrated with LNG and solar energy.
In their work, the LNG cold energy reduced the condensate pressure of the system and produced extra power.

11. Mehrpooya and Sharifzadeh proposed an oxy-fuel power generation cycle using LNG as the heat sink and a solar cycle as the heat source. In a later study, Mehrpooya suggested a coal-gasification process combined with an air separation unit. In this system, LNG was used for the heat sink, air separation unit, and cryogenic carbon capture unit.

12. Mehrpooya and Zonouz performed exergy and sensitivity analysis for an LNG cold utilization power plant coupled with an air separation unit, oxy-fuel combustion, and carbon capture.
At the same time, several studies have performed on energy storage systems on energy storage systems over the last decade. Among these systems, the cryogenic energy storage (CES) is the most suitable for large-scale energy storage because of its unique characteristics, including low internal energy but high exergy. The interest in CES systems has been renewed because of amid growing environmental concerns surrounding power plants.

13. Park and others applied the CES system to a two-stage Rankine cycle with an LNG re-gasification process. In their process, the air recovers the cold energy of LNG off -peak, while liquid air generates power on-peak. They stated that their system was an economical way to recover LNG cold energy into the CES system.
However, because of the low capacity of the system, the utilize LNG cold energy recovery as an auxiliary energy source in the energy grid can be a better way than as the main energy source.
To address this issue, they developed a flexible energy storage and release process as an auxiliary to the energy grid from our previous work In the proposed system of the previous work, the direct expansion process is applied to the LNG re-gasification process, while air is continuously liquefied and stored using cold and work from the direct expansion LNG re-gasification process, as a successive work**.**

1.4.5 Working fluid:

There are two types of working fluids [**Wang T. The theoretical study of working fluid for Rankine cycle utilizing cold energy of LNG. Dissertation for the Master Degree. Shanghai: Shanghai Jiao Tong University, 2011.]**

1) Single working fluid:

The principles of the selection of the single working fluid in cryogenic Rankine cycle and the combined cycle are presented as follows:

(1) friendly to environment,
(2) large heat of vaporization,
(3) good chemical and thermal stability,
(4) high thermal conductivity,
(5) small kinetic viscosity,
(6) Nearly vertical liquid saturation line, and non-toxic, easy to produce and low cost, etc .

Moreover, the triple point of the working fluid should be lower than the lowest temperature of system operation, which ensures that the solidification and the jam of the working fluid will not happen at any place in the circulation.

Lu et al. **[“Introduction to STG+ Technology”. Primus Green Energy. February 2013. Retrieved 5 March 2013.]** have selected different working fluids to compare their performance in sub-critical Rankine cycle with LNG as its heat sink and seawater as its heat source.

The regularity appears similar when employing four working fluids of R152a (CH3CHF2), R290 (C3H8),R600 (C4H10) and R134a (CH2FCF3) in the investigated cycle, i.e., the total amount of electricity generated from circulation first increases and then decreases with t he evaporation temperature rising, which confirms that there exists an optimal evaporation temperature where the power output gets the maximum.

Meanwhile, R290 is proved to be with the comprehensively optimum properties in contrast to other working fluids in enthalpy drop within equal entropy, saturation pressure and other attributes.

Corresponding to a heat source temperature of 20°C, the best evaporation temperature of R290 maintains at 11.08°C.

Consequently, the optimum condensing and vaporizing temperature ought to be taken into account as part of the principles when selecting the single working fluid in Rankine cycle and the combined cycle.

2) Mixed working fluids:

Although Rankine cycle and the combined cycle employing propane as working fluid are the most feasible ways to recovery LNG cold exergy, isothermal phase change process of single medium in condenser makes a great LNG exergy loss which confines the cycle performance to a relatively low level. Considering the fact that the condensing temperature of mixed working fluid matches well with LNG vaporization temperature, due to the temperature-variation phase change of mixed media, the single working fluid is supposed to be substituted by the mixed one to enhance the overall cycle performance. The mixture of R22 and R142b (CH_3CClF_2) has been proved to perform better than any one of two pure refrigerated fluids in LNG cold energy power system, according to the study conducted by Kim and others.

However, the gradually severe environment issue constricts the use of Freon, and organic mixed fluids turn into commonly employed media.

1.4.6 Aspen Hysys:

ASPEN HYSIS [**Study Of Crygonic System With ASPEN - HYSIS Analysis By SOMADUTTA SAHOO.**] is a chemical process simulator used to mathematically model chemical processes, from the unit operations to full chemical plants and refineries , HYSYS is used extensively in industry and academia for steady-state and dynamic simulation, process design, performance modeling, and optimization. HYSYS also is a simulation environment designed to serve many processing industries especially Oil, Gas and Refining. With Aspen HYSYS one can create rigorous steady state and dynamic state models for plant design, performance monitoring, troubleshooting, operational improvement, business planning, and asset management. Through completely interactive Aspen Hysys interface, one can easily manipulate process variables and unit operation topology, as well as fully customize simulation using its customization and extensibility capabilities. The process simulation capabilities of Aspen Hysys enable engineers to predict the behavior of a process using basic engineering relationships such as mass and energy balance, phase and chemical equilibrium, and reaction kinetics. With reliable thermodynamic data, realistic operating conditions and the rigorous Aspen Hysys equipment models, they can simulate actual plant behavior. Some of the important Aspen Hysys features are listed below:

I have taken the contents of introduction to Aspen Hysys from Hysys tutorial.

(1) Windows Interoperability: Interface contains a process flow sheet view for graphical

layout, data browser view for entering data, the patented Next expert guidance system to
guide the user through a complete and consistent definition of the process flow sheet.

(2) Plot Wizard: Hysys enables the user to easily create plots of simulation results.
(3) Flowsheet Hierarchy and Templates: Collaborative engineering is supported through
hierarchy blocks that allow sub-flowsheets of greater detail to be encapsulated in a single
high-level block. These hierarchy blocks can be saved as flowsheet templates in libraries.

(4) Equation-Oriented Modeling: Advanced specification management for equation oriented model configuration and sensitivity analysis of the whole simulation or specific
parts of it. The unique combination of Sequential Modular and Equation Oriented solution technology allows the user to simulate highly nested processes encountered typically in the chemical industry.

(5) Thermo physical Properties: Physical property models and data are keys to generating accurate simulation results that can be used with confidence. Aspen Hysys uses the Extensive and proven physical property models, data and estimation methods available in Aspen Properties™, which covers a wide range of processes from simple ideal behavior To strongly non-ideal mixtures and electrolytes. The built-in database contains parameters for more than 8,500 components, covering organic, inorganic, aqueous, and salt species And more than 37,000 sets of binary interaction parameters for 4,000 binary mixtures.

(7) Convergence Analysis: to automatically analyze and suggest optimal tear streams, Flowsheet convergence method and solution sequence for even the largest flowsheets With multiple stream and information recycles.
Sensitivity Analysis: to conveniently generate tables and plots showing how process Performance varies with changes to selected equipment specifications and operating Conditions.

(8) Design Specification: capabilities to automatically calculate operating conditions or Equipment parameters to meet specified performance targets.

(9) Data-Fit: to fit process model to actual plant data and ensure an accurate, validated Representation of the actual plant.

(10) Determine Plant Operating Conditions that will maximize any objective function Specified, including process yields, energy usage, stream purities and process economics.

(11) Simulation Basic Manager: This feature available in Aspen Hysys for using Different fluids like nitrogen, air, acetylene as per requirement. Also several fluid Packages like BWRS, MWRS, and ASME are provided to calculate properties at different states.

1.4.7 Objectives:

This project aims to compare between direct expansion cycle and Rankine cycle and combined Rankine cycle to determine which is better in terms of power generation.

Chapter 2

Methodology

2.1 Process Description:

This chapter will describe the simulation steps for the three common cycles for power generation, the simulation process was carried out to identify the optimum cycle that generates more power. The three cycles are :

A: Direct expansion cycle.

B: Rankine cycle.

C: Combined cycle.

The simulation is carried out using ASPEN HYSYS.

2.1.1 Direct Expansion Cycle:

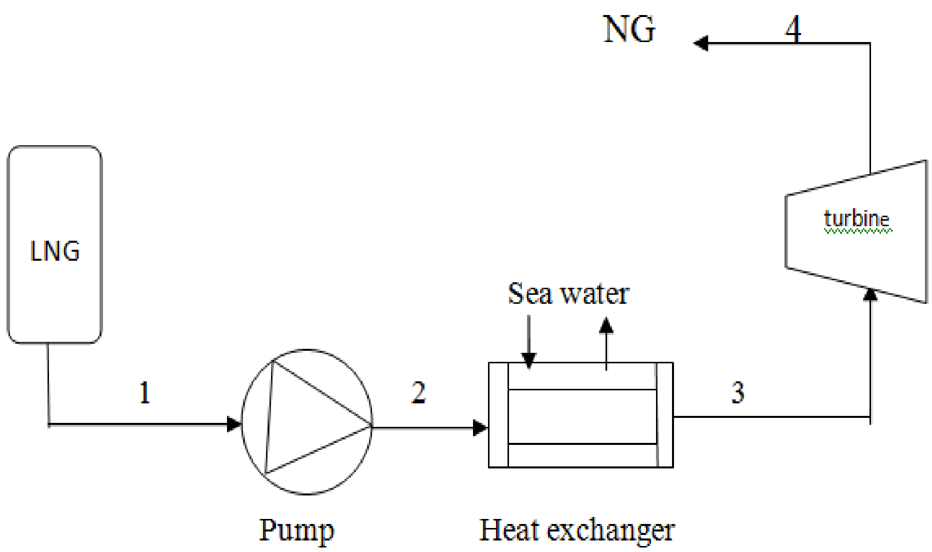


Figure (2-1): Direct Expansion Block Diagram

The power generation cycle utilizing LNG cold energy is varied from the simple direct expansion of LNG as shown in (figure 2-1) to very complex cycles, the direct expansion is an open cycle where LNG is pumped [1-2] and then evaporated by heat source [2-3], and the pressurized vapor sent to the turbine where power is generated [3-4], and finally NG is supplied to the users [4], despite the simplicity of this cycle but it does not utilize the cold energy of LNG, only using the LNG pressure energy, so its efficiency is low.

2.1.2 Rankine Cycle:

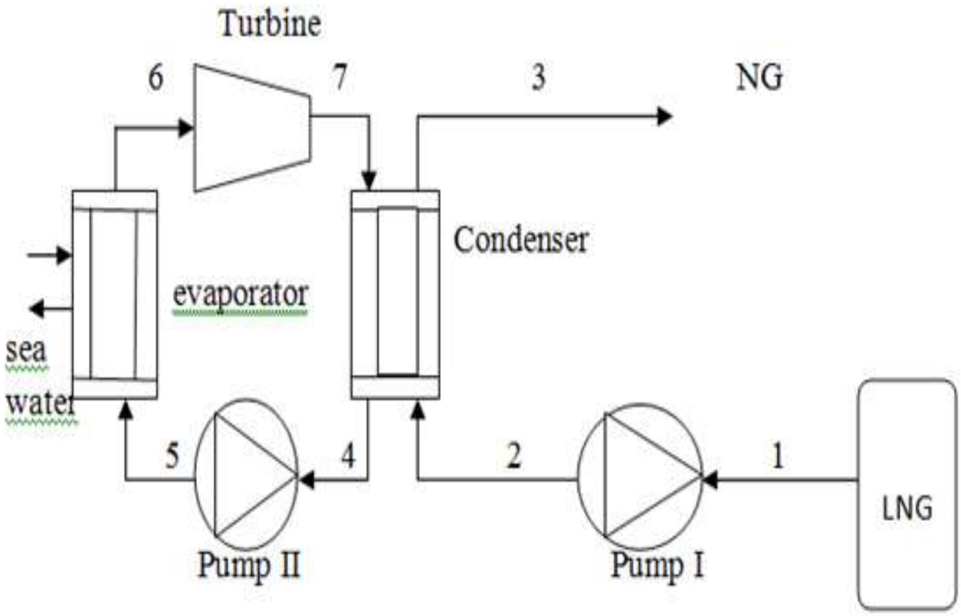


Figure (2-2): Rankine Cycle Block Diagram

In Rankine cycle which goes through four stages of condensation, compression, vaporization, and expansion to generate power where LNG is pumped [1-2] and then heated using a heat source [2-3]. A working fluid with low boiling temperature is usually used, this working fluid is evaporated by low quality heat source such as sea water, air, and industrial waste heat [5-6] , while LNG cold energy is used as a heat sink for the cycle [7-4] as shown in (figure 2-2). This Rankine cycle uses the cold energy of LNG and it has higher efficiency than the direct expansion cycle, but it does not utilize the pressure energy of the LNG. Also the large temperature difference between the working fluid and LNG in the condenser is not preferable from exergetic point of view .

2.1.3 Combined Cycle:

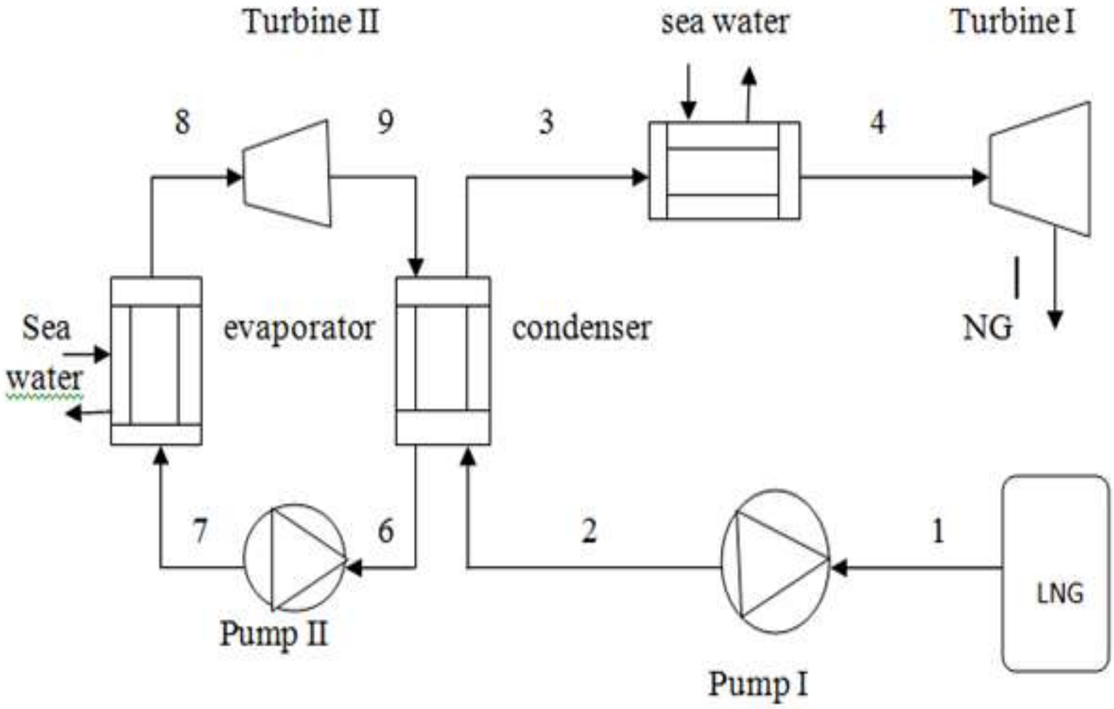


Figure (2-3): Combine Cycle Block Diagram

When direct expansion cycle integrated with Rankine cycle the resulting cycle called combined cycle as shown in (figure 2-3), LNG is pumped [1-2] and then evaporated [2-3], and the pressurized vapor sent to the turbine where power is generated [3-4], the combined cycle utilizes the cold and pressure energy of the LNG , the connection between the two sub-cycle is realized through the condenser where the working fluid (Propane) condenses by the cold energy released from LNG [9-6] and then pumped [6-7] into an evaporator [7-8], and then was introduced to the turbine. The combined cycle is the most commonly used one among cryogenic power generation cycles of LNG in practical power plant .

2.2 Simulation steps

2.2.1 Direct Expansion Cycle:

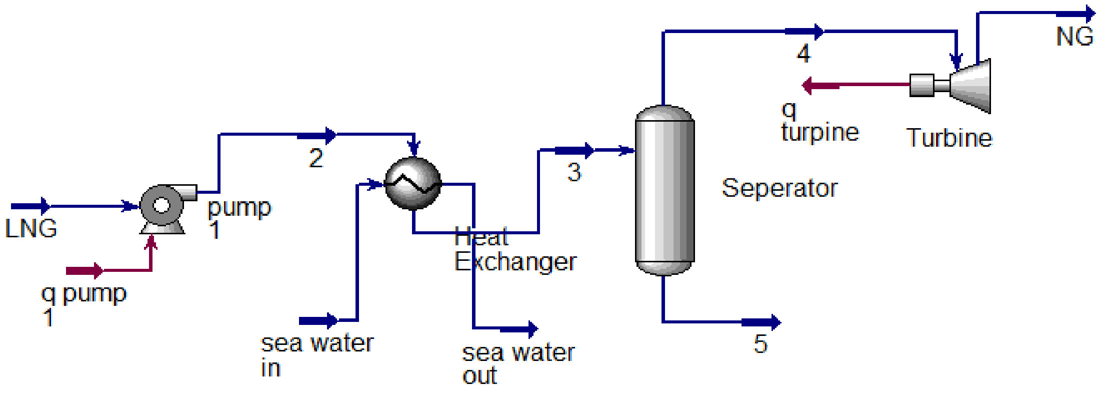


Figure (2.4): Direct Expansion Flow sheet

LNG is fed into a pump (-162.2 C, 101.325 KPA) to increase its pressure to 1000 KPA and the energy needed in the pump was (q 1 pump), the adiabatic efficiency of the pump was 90%, and then fed into a heat exchanger [2] , using sea water as a heat source with temperature and pressure being 25 C and 101.325 KPA respectively to reduce LNG temperature to -60.79 C .

The LNG was pumped into a heat exchanger to convert it into NG , and then fed into a separator [3], to separate the remaining liquid to obtain pure NG gas, and then the NG was fed to a turbine [4] having an adiabatic efficiency of 75%.

2.2.2 Rankine Cycle:

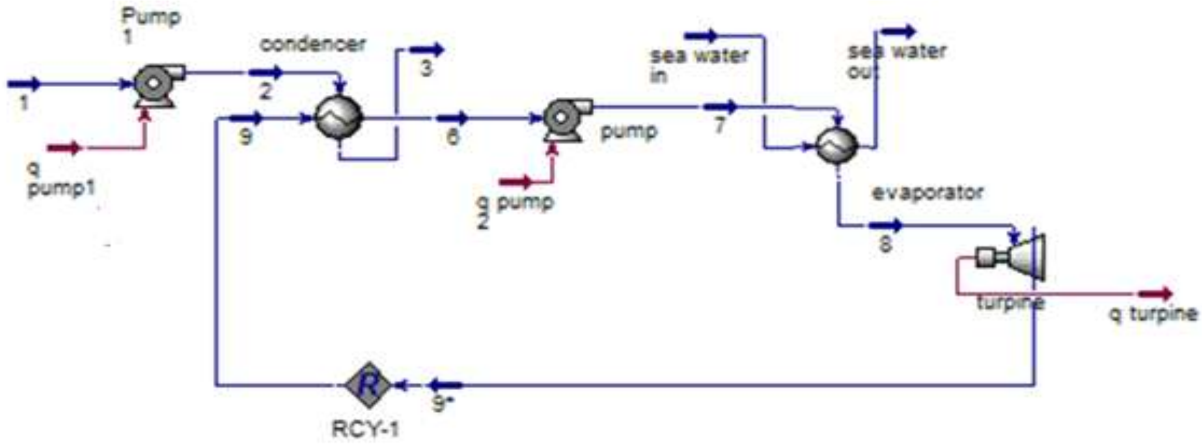


Figure (2.5): Rankine Cycle Flow sheet

LNG is feed to pump1 (-162C, 101.3KPA) to increase its pressure to 1000 KPA and the energy needed in the pump was (q pump1) and adiabatic efficiency of the pump was 90%, and then fed into condenser [2].

Recycled propane is introduced to the condenser tube side [6] and then stream [6] was fed to a pump 2 to increase liquid pressure to 1000 KPA, the outlet stream was then pumped into an evaporator to evaporate the pumped liquid and the evaporator outlet gas stream [8] was fed into a turbine having an adiabatic efficiency of 73.781% , the power generated from the turbine was 23.89 KW (q turbine). Then outlet stream [9] recycled to condenser in tube side inlet.

2.2.3 Combine Cycle:

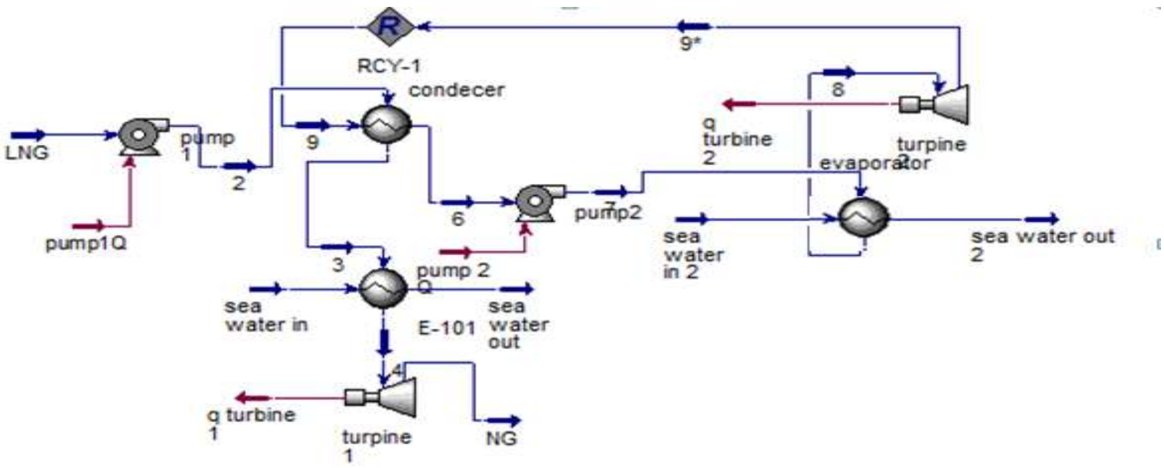


Figure (2-6): Combine Cycle Flow sheet

LNG is feed to pump1 (-162.2 C, 101.3KPA) to increase its pressure to 1000 KPA and the energy needed in the pump was (q pump1) and adiabatic efficiency of the pump was 90%, and then fed into condenser in shell side inlet [2],and shell side outlet [3] fed into heat exchanger, using sea water as heat source and out let stream [4] fed to turbine .

Recycled propane is fed to the condenser tube side [6], and then stream [6] was fed to a pump 2 to increase liquid pressure to 1000 KPA [7], then stream[7] was fed into an evaporator to evaporate the pumped liquid, using sea water 2 as heat source . The outlet stream [8] was fed to a turbine, and then outlet stream [9] was recycled back into tube side inlet.

2.3 Simulation Assumptions:

LNG feed is identical for the three cycles as shown in figure (2-7) and figure (2-8).

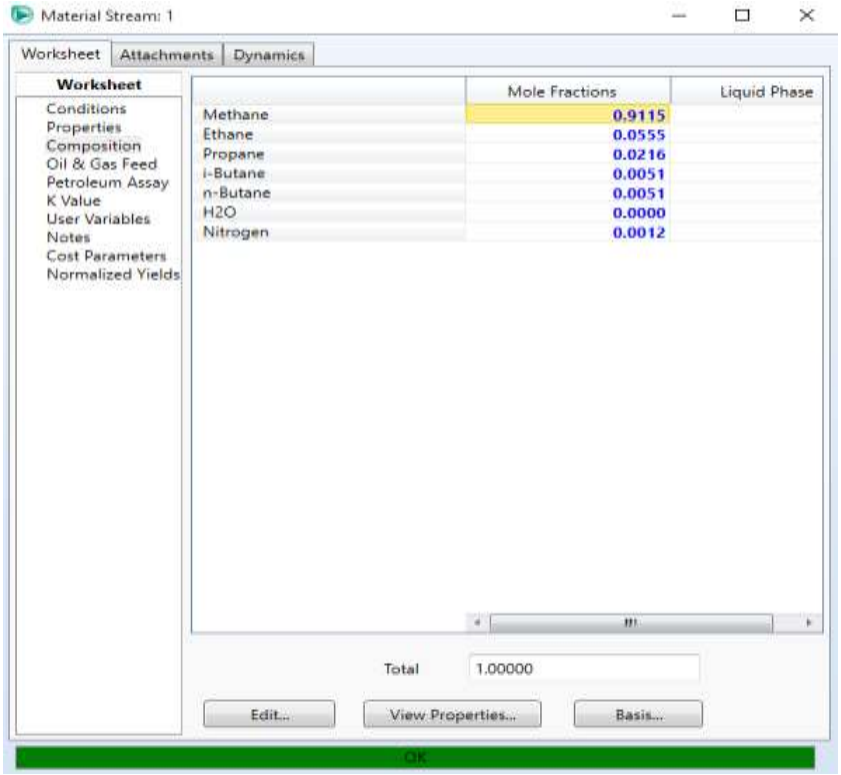


Figure (2-7): LNG feed composition.

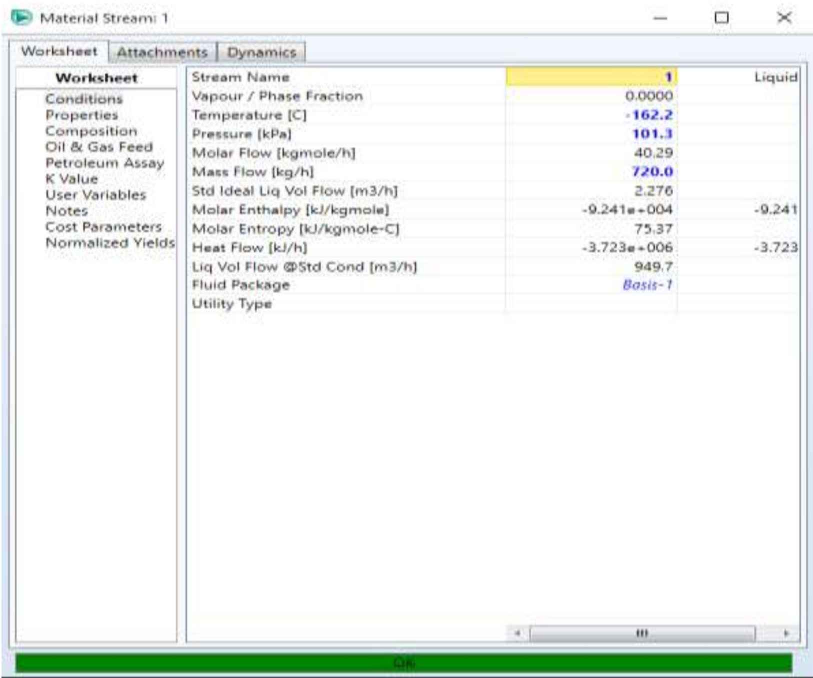


Figure (2-8): LNG feed conditions.

Pumps efficiencies are identical for the three cycles as shown in figure (2-8).

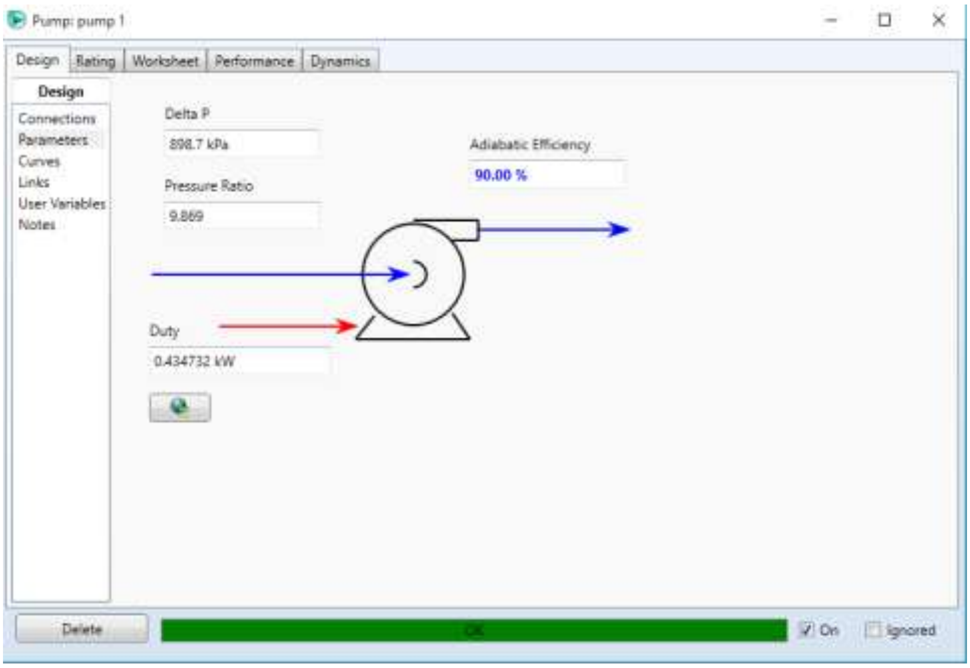


Figure (2-9): Pumps efficiencies

Turbine adiabatic efficiency is identical for the three cycles as shown in figure (2-9).

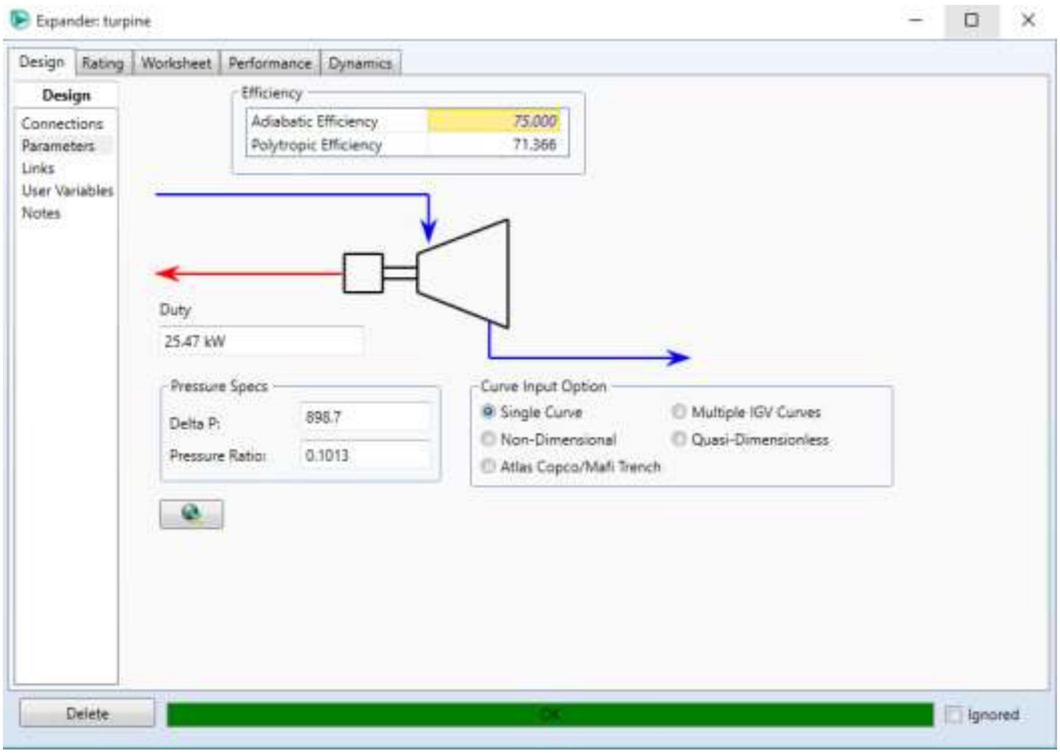


Figure (2-10): Adiabatic efficiency of the turbines.

Chapter 3

Results

3.1 Direct Expansion Cycle:

For direct expansion cycle all flow rates, pressure, temperature and enthalpy for all streams are shown in table (3-1).

Stream name and flow sheet of direct expansion cycle was clarified in figure (2-4)

Table (3-1): Direct expansion cycle streams conditions

Condition / Streams	Flow rate [kgmole/h]	Pressure [kpa]	Temperature [C]	Enthalpy [kj/kgmole]	Vapor fraction
LNG	40.29	101.325	-162.2	-9.241*10^4	0.0000
Stream 2	40.29	1000	-161.8	-9.237*10^4	0.0000
Stream 3	40.29	1000	-101.9	-8.323*10^4	0.8799
Stream 4	35.45	1000	-101.9	-7.992*10^4	1.0000
Stream 5	4.839	1000	-101.9	-1.075*10^5	0.0000
Sea water in	555.1	101.325	25	-2.862*10^5	0.0000
Sea water out	555.1	101.325	16.28	-2.875*10^5	0.0000
NG	35.45	101.325	-152.7	-8.165*10^4	0.9614

Also the amount of power consumed in pump 1 and amount of power generated in the turbine are shown in Table (3-2).

Table (3-2): Direct expansion power requirements.

Power / Equipment	Power required [kw]	Power generated [kw]
Pump 1	0.4347	0
Turbine	0	17.18

The amount of energy needed in pump 1 to increase LNG feed stream pressure from 101.325 kpa to 1000 kpa was 0.4347 kw.

3.2 Rankine Cycle:

Stream name and flow sheet of Rankine cycle was clarified in figure (2-5).

For Rankine cycle all flow rates, pressure, temperature and enthalpy for all streams are shown in table (3-2).

Table (3-3): Rankine cycle streams conditions.

Condition / Streams	Flow rate [kgmole/h]	Pressure [kpa]	Temperature [C]	Enthalpy [kj/kgmole]	Vapor fraction
1	40.29	101.325	-162.2	-9.241*10^4	0.0000
Stream 2	40.29	1000	-161.8	-9.237*10^4	0.0000
Stream 3	40.29	1000	-53.43	-7.996*10^4	0.9956
Stream 6	24.49	101.325	-48.15	-1.279*10^5	0.0000
Stream 7	24.49	1000	-47.73	-1.279*10^5	0.0000
Sea water in	555.1	101.325	25	-2.862*10^5	0.0000
Sea water out	555.1	101.325	11.33	-2.873*10^5	0.0000
Stream 8	24.49	1000	41.8	-8.187*10^4	1.0000
Stream 9*	24.49	101.325	-21.92	-1.073*10^5	1.0000
Stream 9	24.49	101.235	-21.05	-1.073*10^5	1.0000

Table (3-4): Rankine cycle power requirements.

Power / Equipment	Power required [kw]	Power generated [kw]
Pump 1	0.4347	0
Pump 2	0.5091	0
Turbine	0	24.28

The amount of energy needed in pump 1 to increase LNG feed stream pressure from 101.325 kpa to 1000 kpa was 0.4347 kw. We noticed that it is the same as Direct expansion cycle due to the fact that it has the same specifications and the inlet and outlet streams are the same. The amount of energy needed in pump 2 to increase stream 6 pressure from 101.325 kpa to 1000 kpa was 0.5091 kw.

3.3 Combined Rankine Cycle:

Stream name and flow sheet of Combined Rankine cycle was clarified in figure (2-6). For combined Rankine cycle all flow rates, pressure, temperature and enthalpy for all streams are shown in table (3-5).

Table (3-5): Combined Rankine cycle streams conditions.

Condition / Streams	Flow rate [kgmole/h]	Pressure [kpa]	Temperature [C]	Enthalpy [Kj/kgmole]	Vapor Fraction
1	40.29	101.325	-162.2	-9.241*10^4	0.0000
Stream2	40.29	1000	-161.8	-9.237*10^4	0.0000
Stream3	40.29	1000	-53.33	-7.992*10^4	0.9957
Stream4	40.29	1000	7.850	-7.748*10^4	1.0000
NG	40.29	101.325	-94.22	-8.12*10^4	0.9832
Sea water in	555.1	101.325	25	-2.862*10^5	0.0000
Sea water out	555.1	101.325	22.78	-2.864*10^5	0.0000
Stream 6	24.49	101.325	-48.15	-1.279*10^5	0.0000
Stream7	24.49	1000	-47.58	-1.278*10^5	0.0000
Stream8	24.49	1000	41.8	-1.038*10^5	1.0000
Sea water in 2	555.1	101.325	25	-2.862*10^5	0.0000
Sea water out 2	555.1	101.325	11.33	-2.873*10^5	0.0000
Stream 9*	24.49	101.325	-21.92	-1.073*10^5	1.0000
Stream9	24.49	101.325	-21.92	-1.073*10^5	1.0000

the amount of power consumed in pump 1, pump 2 and amount of power generated in the turbine 1, turbine 2 are shown in Table (3-6).

Table (3-6): combined Rankine cycle power requirements

power / Equipment	Power required [kw]	Power generated [kw]
Pump1	0.4347	0
Pump2	0.6109	0
Turbine1	0	41.82
Terbine2	0	24.28

The amount of energy needed in pump 1 to increase LNG feed stream pressure from 101.325 kpa to 1000 kpa was 0.4347 kw. We noticed that it is the same as Direct expansion cycle due to the fact that it has the same specifications and the inlet and outlet streams are the same. The amount of energy needed in pump 2 to increase stream 6 pressure from 101.325 kpa to 1000 kpa was 0.6209 kw.

3.4 Power Generation:

In order to calculate the total power generated in any cycle we should subtract the amount of power consumed in the pumps from the amount of power generated in the turbines .

Total power generation = power generated in the turbines – power consumed in the pumps.

Increase percentage = (Total power generated from a cycle – Total power generated from the direct expansion cycle) / total power generated from direct expansion cycle *100

Table (3-7) shows a comparison of the three cycles in the total power generated from the cycle.

Table (3-7): comparison in the total power generation

Power / Cycles	Power generated in turbines	Power consumed in pumps	Total power generation	Increase percentage
Direct expansion Cycle	17.18	0.4347	16.7453	---
Rankine cycle	24.28	0.4347+0.5091 =0.9438	23.3362	39.35
Combine cycle	41.82+24.28 =66.1	0.4347+0.6109 =1.0456	65.0544	288.49

We noticed there is an increase in the energy generated in Rankine cycle compared to Direct expansion cycle with a percentage of nearly 40%, this increase is due to the fact that in Rankine cycle we focused in using the LNG cold energy by adding a cycle of propane and adding power equipments and heat transfer equipments , but in direct expansion we only use LNG pressure energy.

Further improvement was noticed in combined Rankine cycle as there was a 288.28% increase percentage, it is due to the usage of both LNG cold energy and pressure energy by adding an additional heat exchanger and a turbine in Rankine cycle.

Chapter 4

Conclusion & Recommendation

4.1 Conclusion:

The designs have been performed using ASPEN HYSIS software; this gives benefits and useful results. From the simulation results observed we noticed that there is an increase in the power generated from the direct expansion cycle to Rankine cycle to combined Rankine cycle. This increase is due to the utilization of the design developed by Rankine, also in the combined Rankine cycle. This utilization is accomplished by adding new energy equipments (pumps and turbines), and new heat transfer equipments. Increasing in equipment number leads to more capital and operations costs. Also results show that increasing in power generated in the combined Rankine cycle is much more than the power generated in Rankine cycle, thus we prefer to use combined Rankine Cycle and not Rankine cycle, but cost analysis must be considered for better cycle selection.

4.2 Recommendations:

- We recommend not to waste the energy associated with re-gasification process of LNG..
- We also recommend to apply full economic analysis to make the right selection.

4.3 Referencing:

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