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THERMODYNAMIC ANALYSIS AND OPTIMIZATION OF CLAUDE LIQUEFACTION CYCLE

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Prof. Dr. Mehmet KANOĞLU

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Birnur ÖZTÜRKMEN

ABSTRACT

THERMODYNAMIC ANALYSIS AND OPTIMIZATION OF CLAUDE LIQUEFACTION CYCLE

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In this thesis, common gas liquefaction cycles are introduced and thermodynamic analysis and optimization of Claude liquefaction cycle is performed using common gases including air, oxygen, nitrogen, argon, methane, and fluorine. The cycle is simulated using EES software and operating data of the cycle is obtained under certain assumptions. In thermodynamic analysis of Claude cycle, liquid yield, net work input, COP, and second law efficiency are used as performance parameters. Parametric studies are done to investigate effects of gas inlet temperature, liquefaction temperature, compressor outlet pressure, effectiveness of heat exchangers, and expander flow ratio on the performance of Claude cycle. Optimum operating conditions that maximize system performance by minimizing the work consumption are determined. Thermodynamic analysis of this cycle indicates that the COP value is the highest for methane (0.386), second-law efficiency is the highest for nitrogen (57.5%), and work consumption is the lowest for argon (968 kJ/kg liq). Parametric studies show that a decrease in the inlet gas temperature, an increase in liquefaction temperature, and an increase in heat exchanger effectiveness provide higher values of liquid yield, COP, and second-law efficiency and lower values of work consumption. An optimum value is determined for the fraction of gas diverted to the expander, which turns out to be around 0.7. Also, the pressure for which the COP is maximum is determined to be a little over 5 MPa.

Keywords: Cryogenic, Liquefaction, Claude cycle, Thermodynamic analysis, Optimization

ÖZET

CLAUDE ÇEVRİMİNİN TERMODİNAMİK ANALİZİ VE OPTİMİZASYONU

ÖZTÜRKMEN, BİRNUR
Yüksek Lisans, Makine Mühendisligi Bölümü
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Bu tezde, gazların sıvılaştırılmasında yaygın kullanılan çevrimler tanıtılmış ve Claude sıvılaştırma çevriminin termodinamik analizi ve optimizasyonu, hava, oksijen, azot, argon, metan ve florin için gerçekleştirilmiştir. Çevrimin çalışma verileri belirli varsayımlar altında, EES yazılımı kullanılarak simüle elde edilmiştir. Claude çevriminin termodinamik analizinde, performans parametresi olarak sıvılaşan gaz oranı, net iş girişi, performans katsayısı ve ikinci kanun verimliliği kullanılmıştır. Parametrik çalışmalar, kompresör giriş sıcaklığı, sıvılaşma sıcaklığı, kompresör çıkış basıncı, ısı eşanjörlerinin etkinliği ve türbine gönderilen gaz oranının Claude çevriminin performansı üzerindeki etkilerini incelemek için yapılmıştır. İş tüketimini en aza indirgeyerek sistem performansını en üst düzeye çıkaran optimum çalışma koşulları belirlenmiştir. Bu sıvılaştırma çevriminin termodinamik analizi, performans katsayısı değerinin metan için en yüksek (0.386), azot için en yüksek ikinci kanun verimliliğinin (% 57.5) olduğunu ve iş tüketiminin argon için en düşük olduğunu (968 kJ / kg sıvı) göstermektedir. Parametrik çalışmalar, düşük kompresör giriş sıcaklığı, yüksek sıvılaşma sıcaklığı ve eşanjör etkinliğinde artışın daha yüksek sıvılaşan gaz oranı, performans katsayısı ve ikinci kanun verimliliği değerleri ve daha düşük iş tüketimi değerleri verdiğini göstermektedir. Optimum türbine gönderilen gaz miktarı 0.7 olarak hesaplanmıştır. Ayrıca COP'nin maksimum olduğu basınç değerinin 5 Mpa'ın biraz üzerinde olduğu tespit edilmiştir.

Anahtar kelimeler: Kriyojeni, Sıvılaşma, Claude çevrimi, Termodinamik analiz, Optimizasyon

To My Parents

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Mehmet Kanoğlu, who always shares his academic support and experiences with me. I thank Mechnanical Engineer Tuğberk Hakan Çetin for his valuable help in this thesis. From primary school to today, I want to thank my mother, father, and brothers for their endless support.

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ε	Expander flow ratio
h	Enthalpy (kj/kgK)
$\dot{m}$	Mass fow rate (kJ/kg)
$\dot{m}e$	Mass fow rate of expander (kJ/kg)
P	Pressure (Pa)
$\dot{Q}$	Rate of heat transfer (kj/kg)
r	Expander flow ratio
S	Entropy (kj/kgK)
T	Temperature (K)
y	Liquefaction yield
$\dot{w}$	Specific work (kj/kg)
η_{II}	Second law efficiency
COP	Coefficient of performance

CHAPTER 1

INTRODUCTION

Cryogenics is the science and technology that deals with temperatures less than about 120 K. Ones used the word “cryogenic” for the first time in 1894. Cryogenic cooling requires refrigeration technology different from conventional refrigeration. Achieving very low temperatures usually requires precooling of the gas by a lower temperature fluid as part of the process. The precooling gas is obtained by a separate refrigeration system. A modern refrigeration system that accomplish cryogenic temperatures involve precooling, heat exchangers, and Joule-Thompson (J-T) effect [1-3].

The liquefaction of gases is always considered as an important application for cryogenic technologies. During the gas liquefaction process, the gas temperature must be lowered below its crticial temperature. The phase change from gas to liquid state can be done at atmospheric pressure or a higher pressure.

Liquefaction of gases is the bringing of a gas into a liquid state by various methods. These methods can be used for scientific commercial or industrial purposes. Most gases can be made liquid under normal atmospheric pressure simply by cooling. For several gases such as carbon dioxide, additional pressurization must be applied. Liquefaction is mainly used for the storage of gases such as oxygen, nitrogen, and natural gas.

In 1895, two important devolopments in cryogenic technology happened. Carl von Linde who had established the Linde Eismaschinen AG in 1879, was given a basic patent on air liquefaction. He was the first one applied the ideas of gas liquefaction to the industrial applications. Again in 1895, Heike Kamerlingh Onnes was the founder of the Physical Laboratory at the University of Leiden. The helium was liquefied for the first time in 1908 in Onnes Laboratory.

The researchers studied the behavior of materials at low temparetures in the Leiden laboratory. Today, Leiden laboratory is one of the leading research centers in low temperatures physics.

The first liquefaction organization was formed by Claude and Delorme in 1902, named “Air Liquide”. The first air liquefaction installation was done in 1907 by Linde. George Claude improved simple Linde cycle by using reversed Brayton cycle with reciprocating expansion engine.

A cryogenic liquid typically has low boiling temperature. The most used cryogenic liquids in the freezing of food are "liquid nitrogen" and "liquid carbon dioxide" gas. The liquid nitrogen boils at -196°C and the carbon dioxide boils at -145°C.

The cryogenic freezing method is developed for certain food products. This method has some advantages such as being simple and cheap, space saving, and so on. However, the method is the most negative because cryogenic fluids are expensive. Liquid nitrogen is one of the most widely used cryogenic liquids. The air separation units produce both liquid nitrogen and liquid oxygen. The boiling point of oxygen is -183°C and that for nitrogen is -196°C. Nitrogen is commonly used in cryogenc freezing.

There are many examples of cryogenics engineering applications. Cryogenic technology is used in a wide variety of fields from industry to health. The oxygen and nitrogen liquids are commonly used to remove carbon from molten iron in the steel industry. Liquid nitrogen is the predominant cooling fluid in food freezing. Liquid propane in cylinders serves as a domestic fuel, liquid oxygen is carried in rockets, natural gas is liquefied for ocean transport and liquid nitrogen is used for low temperature refrigeration. Cryogenic recovery techniques used for recovery of scrap metals, rubber tires and other materials in car industry. Another major application is the production of liquid hydrogen, which is an energy carrier.

In this thesis, thermodynamic analysis of Claude gas liquefaction cycle is performed for air, nitrogen, oxygen, argon, methane, and fluorine. Performance of the cycle is assessed and the certain operating conditions are optimized to minimize work consumption.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

In this section, literature review has been carried out on the liquefaction of gases and liquefaction cycles. This chapter represent a brief literature research on the relevant literature related to this thesis.

2.2 Literature Survey

Nandi and Saragni [7] (1993) performed a thermodynamic evaluation of a liquefaction cycle for hydrogen. Certain operating conditions are used to analyze performance of the cycle. They compared the two cycles and determined that the second law efficiency for the precooled Linde Hampson cycle was lower than that for a standard precooled Claude cycle. They concluded that the cycle efficiency depends on the components and their efficiencies as well as certain operating parameters. The Claude cycle is a more efficient process for liquefaction of hydrogen compared to isenthalpic expansion.

Atrey [8] (1998) considered a Collins liquefaction cycle for helium. In this analysis, the fraction of the gas that is routed to expander is optimized. This was aimed to maximize liquid product. Also, effects of expander efficiency and heat changer effectiveness on the performance of the cycle were investigated.

Kanoglu et al. [9] (2007) studied geothermal energy use in hydrogen production and liquefaction. They considered some liquefaction alternatives. The geothermal source supplied heat to an absorption refrigeration cycle for precooling of the gas before liquefaction. In another alternative, a cogeneration scheme was considered. Geothermal power supplied electricity to a liquefactrion cycle and geothermal heat drove the absorption system.

Prasad [10] (2009) simulated the nitrogen liquefaction using Claude cycle.

Khalil and McIntosh [11] (1977) presented the analysis of Claude helium liquefier and performed optimization for inlet temperature and pressure of the turbine.

Thomas [12] (2012) studied liquefaction systems for helium gas. It was aimed to find optimum pressures, temperatures, and mass flow rates in the cycle in order to obtain maximum liquid yield.

Timmerhaus [13] (1989) studied a simple Linde Hampson cycle experimentally. The study indicated that using liquid nitrogen provides a higher effeiciency in comparison to simple system without nitrogen precooling.

Staats [14] (2011) analyzed hydrogen liquefaction cycle numerically. Considering some difficulties of commonly used industrial liquefaction cycles, some changes were proposed and helium-cooled hydrogen liquefaction was suggested. The Claude cycle is modified with two compressors, and called a “Dual Pressure” Claude cycle.

Syed [15] (1998) investigated a modified Collins cycle for hydrogen liquefaction. They compared performance of the cycle with helium and hydrogen systems.

Hubbel and Toscono [16] (1980) studied entropic optimization of Claude liquefaction cycle. The helium liquefaction cycle is selected for the minimization of entropy generation.

Chang [17] (2015) conducted a review for the cycles used in the liquefaction of gases. The main concept of this work was to provide a procedure for investigating different cycles and choosing a cycle to suit different design conditions.

Collins [18] (1946) tried to reduce irreversibilities in a refrigerator and liquefier.

Hilal [19] (1979) studied a cascade cycle and investigated the effect of expander number on the performance of the liquefier.

Hilal and Eyssa [20] (1980) studied a cycle in which the fraction of flow to turbine and turbine inlet temperature are optimized.

Sonani [21] (2016) investigated the effect of compressor inlet temperature on the performance of Claude liquefaction cycle. This study also includes thermodynamic modeling of Claude cycle by observing the humudity effect and inlet temperature of the air on the cycle performance.

Sayyaadi and Babaelahi [22] (2010) conducted an optimization study on a natural gas liquefaction process. The study was based on a thermoeconomic model which combined the first law and the second law using exergy as well as a cost model. A genetic algorithm is conducted to optimize the cycle to minimize the cost.

Bisht [23] (2014) studied Kapitza cycle for liquefying nitrogen. In this study, parametric studies were performed to investigate effects of varioous operating parameters such as expander flow fraction, isentropic efficiency of the expander on the second-law efficiency of the liquefaction cycle.

Fundamentals and thermodynamic analysis of gas liquefaction cycles were covered in several studies including Timmerhaus and Flynn [13] and Barron [24] (1985) Maytal [25] (2016) analyzed various gas liquefaction cycles including simple Linde-Hampson cycle.

Hilal [26] (1979) optimized Claude cycle for helium liquefiers.

Kanoglu et al. [27] (2002) considered a cascade cycle for natural gas liquefaction and expressed reversible work using some reversible refrigerators. It was determined that the reversible work was the exergy difference between the incoming gas stream and outgoing liquid stream.

Khalil et al. [28] (1977) studied heat exchangers for temperature levels in Claude cycles for helium liquefaction.

J.M. Moon et al. [29] (2007) performed experimental study on Kapitza and Claude liquefaction cycle and obtained that Kapitza cycle is more efficient than Claude cycle.

Sayyaadi et al. [30] (2010) investigated exergetic optimization of high pressure Claude cycle for LNG system and determined that optimizing compressor pressure ratio and fraction of mass diverted to expander would increase the second-law efficiency.

Matsubara et al. [31] (1980) optimized helium refrigeration cycles.

Tsatsaronis and Morosuk [32] (2010) investigated a three cascade system for liquefying natural gas using conventional and advanced exergy analysis. The study revealed the sites for increasing efficiency of the cycle and system components.

Kumar and Mishra [33] (2011) determined the second law of efficiencies of Helium liquefaction system and performed optimization studies.

2.3 Conclusions

In this chapter, the science of cryogenics is introduced and main areas of cryogenic gas technologies are described. The importance of liquefying gases is explained. A literature survey is provided to outline some notable studies on the subject of gas liquefaction cycles.

CHAPTER 3

GAS LIQUFEFACTION CYCLES

3.1 Introduction

Liquefaction of gases are used for scientific, industrial and commercial purposes. Liquefaction is used for analyzing the fundamental characteristics of gas molecules (intermolecular forces), storage of gases, superconductivity studies, and other refrigeration and air conditioning applications [10].

Many engineering processes are associated with the liquefaction of gases at cryogenic temperatures. Cryogenics is the science that addresses the production and effects of very low temperatures. The liquefaction of gases is considered as an important application for cryogenic technologies. At temperatures above the critical point value, a substance exists in the gas phase. The criticial temperatures of helium, hydrogen and nitrogen gases are −268°C, −240°C, and −147°C, respectively.

Therefore, these gases do not exist in liquid form at atmospheric conditions. Cryogenic temperatures cannot be obtained by conventional refrigeration techniques. Advanced refrigeration cycles called liquefaction cycles need to be used.

Liquefaction plants consist of numerous components interacted with each other. They consume a large amount of energy in the process. Therefore, it is essential to develop efficient liquefaction processes in order to improve the overall system performance and economic competitiveness.

In this chapter, we describe common gas liquefaction cycles. The cycles include Simple Linde Hampson Cycle, Precooled Linde Hampson Cycle, Kapitza Cycle, Collins Cycle, and Cascade cycle. Claude cycle is introduced in Chapter 4.

3.2 Simple Linde Hampson Cycle

Simple Linde Hampson cycle also known as the Joule-Thomson cycle is probably the simplest cycle in cryogenic technologies. It is simple but its efficiency is not high. Simple Linde-Hampson cycle liquefy most gases with the exception of helium and hydrogen. The simple throttling effect in this cycle cannot produce the low temperatures needed for helium and hydrogen.

Simple Linde Hampson cycle consists of a compressor, a heat exchanger, a Joule-Thompson valve, and a liquid reservoir. The schematic representation of the simple Linde-Hampson cycle and T-s diagram of the cycle are shown in Fig. 3.1. The simple Linde Hampson cycle is based on the throttling expansion for lowering temperature.

In this cycle at state 1, makeup gas mixes uncondensed portion of the gas and compressed by a compressor to a high pressure at state 2. The high pressure gas then passes through the heat exchanger where the gas is cooled by the uncondensed gas at state 3. Leaving the heat exchanger, the gas is throttled through a J-T valve and the temperature of the gas decreases. A portion of gas condenses providing a liqued yield. The resulting vapor-liquid mixture enters a phase separator where liquefied gas is removed as desired product and uncondensed gas is returned to the cycle to cool the high pressure gas [34].

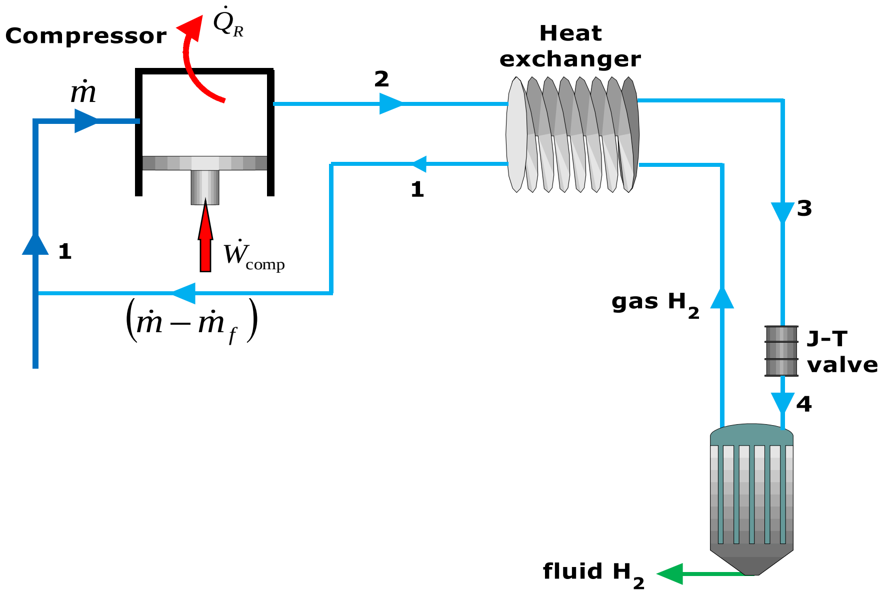


Figure 3.1 Schematic Representation of a Simple Linde-Hampson Cycle

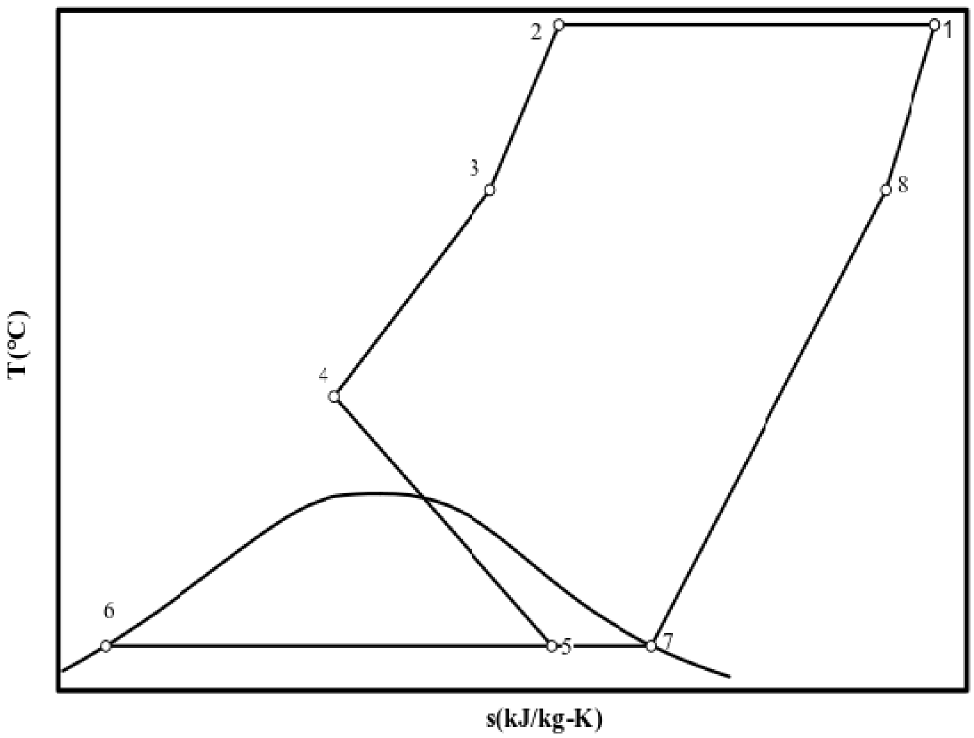


Figure 3.2 Temperature-Entropy (*T*-*S*) Diagram for a Simple Linde-Hampson Cycle

3.3 Precooled Linde-Hampson Cycle

The simple Linde-Hampson cycle is simple, it can liquefy many gases, but it is inefficient. The cycle requires high work input per unit liquid yield. Several cycles are proposed to improve the performance of the cycle. One such system is precooled Linde-Hampson cycle.

Inversion temperature is an important parameter for the liquefaction of precooled Linde Hampson cycle. Auxiliary refrigeration is required when the simple Linde cycle is used to liquefy gases if inversion temperature is below the ambient temperature. The inversion temperatures are 250, 205, and 45 K, for neon, hydrogen, and helium, respectively. Liquid nitrogen is the optimum refrigerant for hydrogen and neon liquefaction systems, while liquid hydrogen is the normal refrigerant on helium liquefaction systems [13].

Pre-cooled Linde Hampson cycle is used for the liquefaction of hydrogen and neon. Since the inversion temperature of hydrogen and neon is greater than the normal boiling point, nitrogen can be used as the precooling refrigerant for these fluids. The liquefaction of helium using the precooled Linde-Hampson liquefier requires the use of hydrogen as the precooling refrigerant. Practically, helium liquefiers avoid hydrogen usage as a precooling refrigerant by using expanders to provide the refrigeration that is reqiured to cool helium because of its lower inversion temperature [24].

Precooled Linde-Hampson cycle is an improvement over the simple Linde-Hampson cycle by decreasing temperature of the gas entering the main heat exchanger. The cycle includes a high pressure compressor, a set of heat exchangers, and Joule Thompson expansion valve [7]. A temperature much lower than the ambient is provided by the auxiliary refrigeration cycle using a fluid such as carbon dioxide, ammonia, or a freon compound used to cool the main gas stream [35]. Auxiliary refrigeration cycles are used with liquefaction systems in order to increase the liquid yield [36].

The schematic representation and *T-s* diagram of the Precooled Linde-Hampson cycle is shown in Figures 3.3 and 3.4, respectively. The gas enters at state 1 and compressed to state 2. The gas is cooled by the returning gas and more importantly by the auxiliary coolant to state 3. It is further cooled in a second heat exchanger. It is expanded in a J-T valve yielding a amixture of vapor and liquid. The liquid product is removed and the gas portion is returned to the second heat exchanger. As in other liquefaction cycle, the compressor operates close to isothermal conditions to minimize work requirement. This is achived by cooling of the gas as it is compressed.

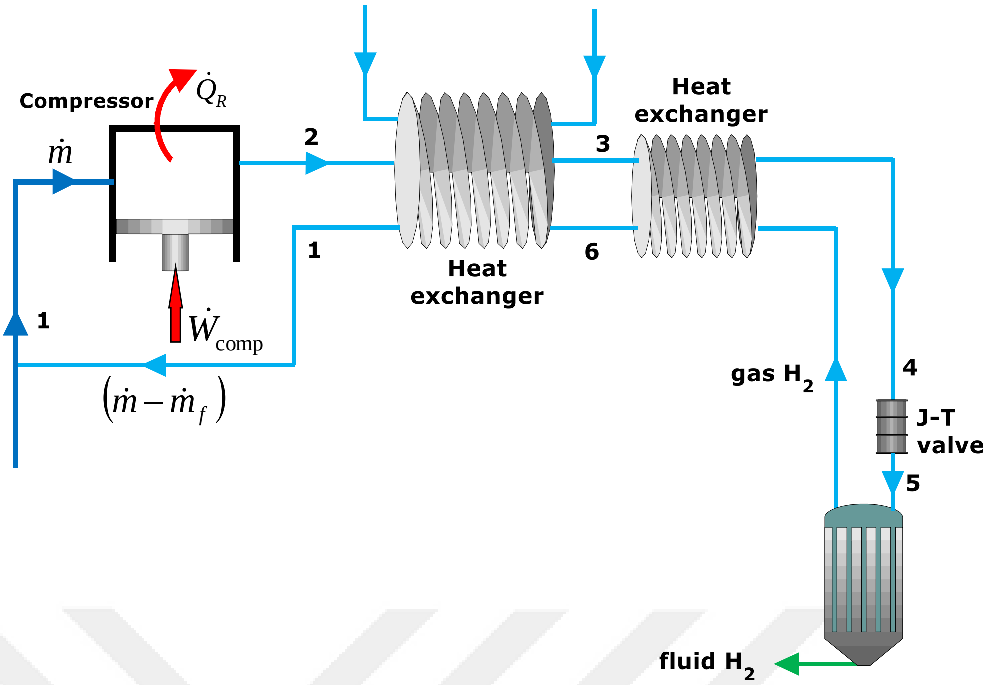


Figure 3.3 Schematic representation of a Precooled Linde-Hampson cycle

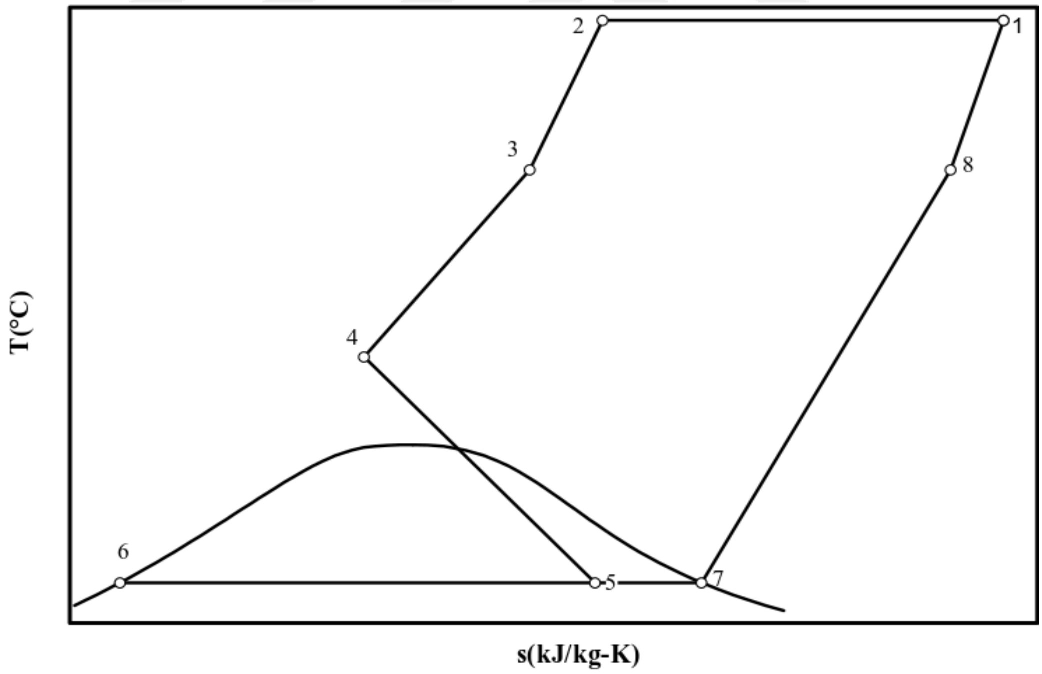


Figure 3.4 Temperature-entropy (*T-s*) diagram for a Precooled Linde-Hampson cycle

3.4 Kapitza Cycle

Kapitza cycle is modified from Claude cycle by removing coldest (third) heat exchanger from the system, as shown in Fig. 3.5. The T-s diagram of the cycle is given in Fig. 3.6. In reality, the first heat exchanger is a regenerator in which purification and precooling are done. Also, notable difference from Claude cycle is that the reciprocation expander is replaced with a rotary expander, which is more efficient. This type of expansion machine also permits the liquefaction of helium. Kapitza cycle work at relatively low pressures.

Kapitza cycle consist of a compressor, a regenerator, a heat exchanger, a J-T valve, an expander and a liquid reservoir. At state 1, the uncondensed portion of the gas and the makeup gas are mixed and compressed isothermally to a high pressure at the state 2. The high pressure gas is cooled in heat exchangers by uncondensed portion of the gas. Then the cool gas is throttled in J-T valve. The liquid portion is collected as desired product and the gas portion is send back to the cycle to cool high pressure gas and cycle is repeated.

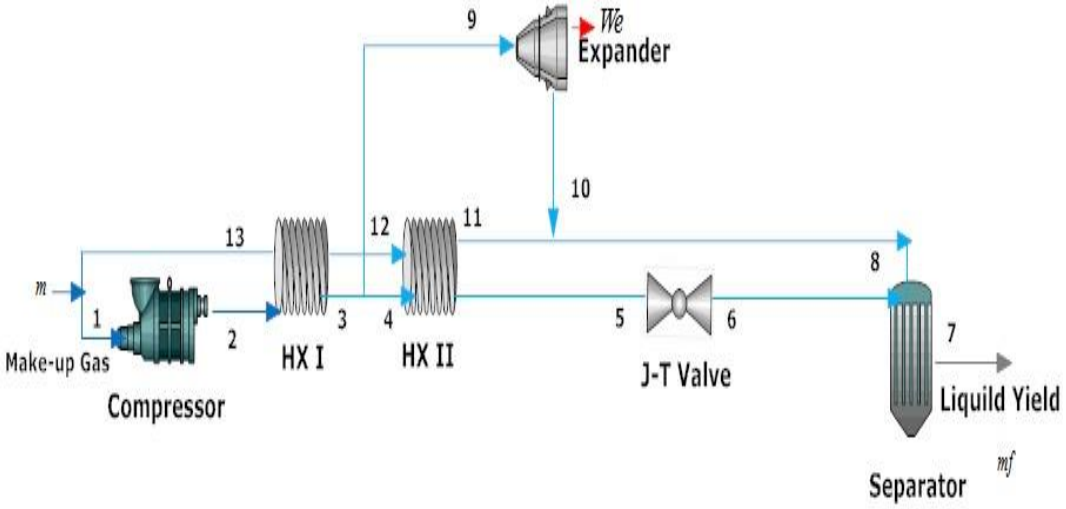


Figure 3.5 Schematic Representation of Kapitza cycle

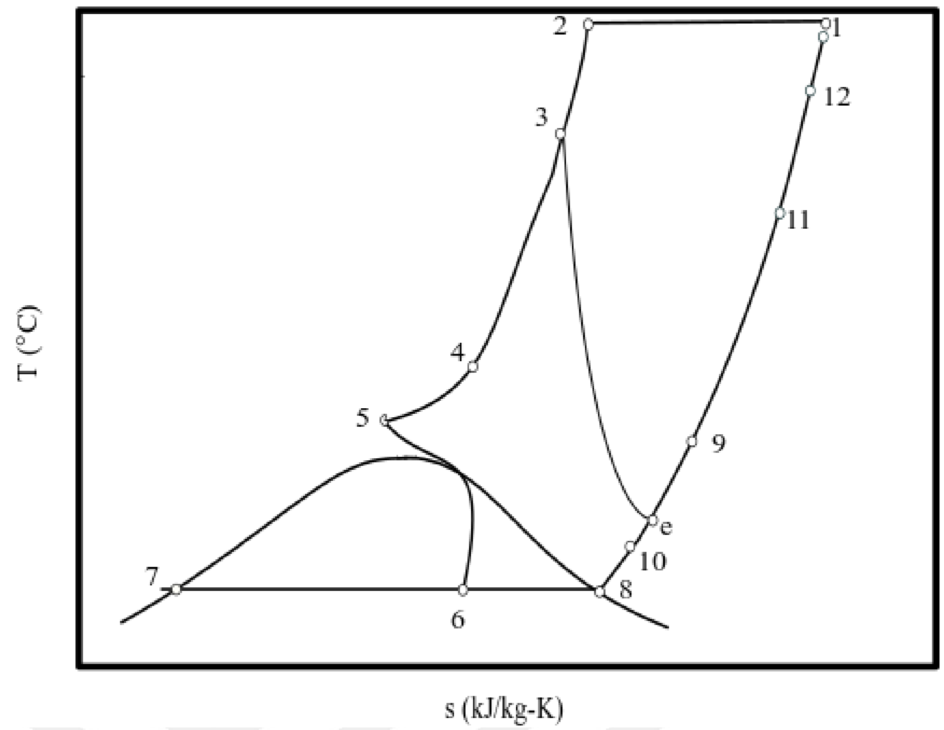


Figure 3.6 Temperature-entropy (*T-s*) diagram for a Kapitza cycle

3.5 Collins Cycle

The Collins cycle, which also known as Modified Claude cycle is one of the gas liquefaction cycles used for the liquefaction of helium. The design of helium liquefier based on the modefied Collins cycle would be possible when the design data at the temperatures across heat exchangers and expanders, effectiveness of heat exchangers and efficiencies of expanders, mass flow rate through compressor, expanders and J-T valve, etc., are made available.

Figure 3.7 gives a schematic diagram of Collins cycle and Figure 3.8 gives its process representation on *T-s* diagram. HX1, HX2, HX3, HX4, HX5, and HX6 are the nomenclature for the six heat exchangers used in this liquefaction system and EX1 and EX2 are the two reciprocating expanders. The design of the system is very important because of the thermophsical character of the helium. Different parameters like heat exchanger effectiveness, expander efficiencies, temperature of gas before expansion, total mass flow rate, mass flow fraction through expanders, affect the performance of the liquefier [8].

The system includes three parts of cooling for liquefaction of helium, two expansion engines of the reciprocating piston type followed by the J-T expansion valve. Pure helium gas is compressed to about 1.5 MPa pressure, precooled to 77 K and passes through the first heat exchanger. The gas expands in the first expander cooling the gas to about 60 K. This low pressure gas returns to compressor through the second and first heat exchangers, cooling the incoming high pressure gas. The gas continues through the third heat exchanger. A fraction of the gas expands in the second expander to about 20 K. This temperature is well below the inversion temperature of helium gas.

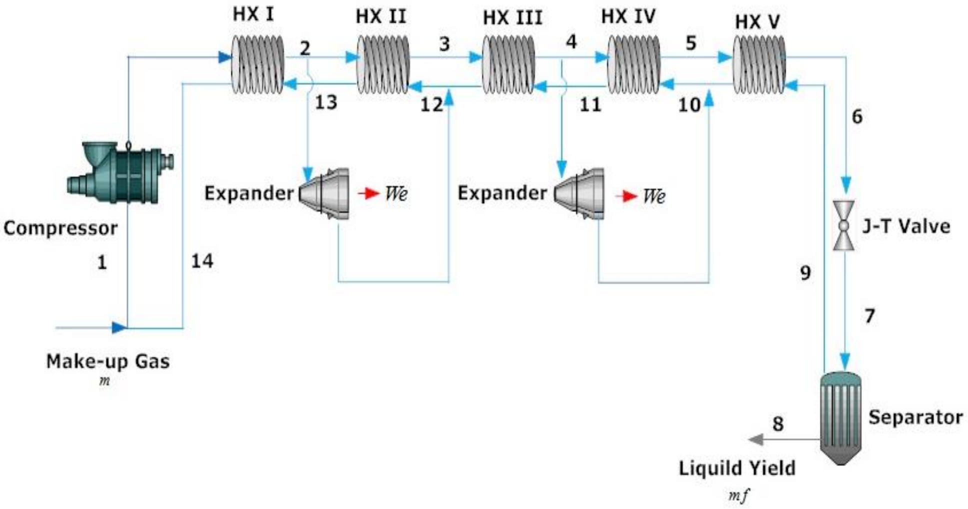


Figure 3.7 Schematic Representation of Collins Cycle

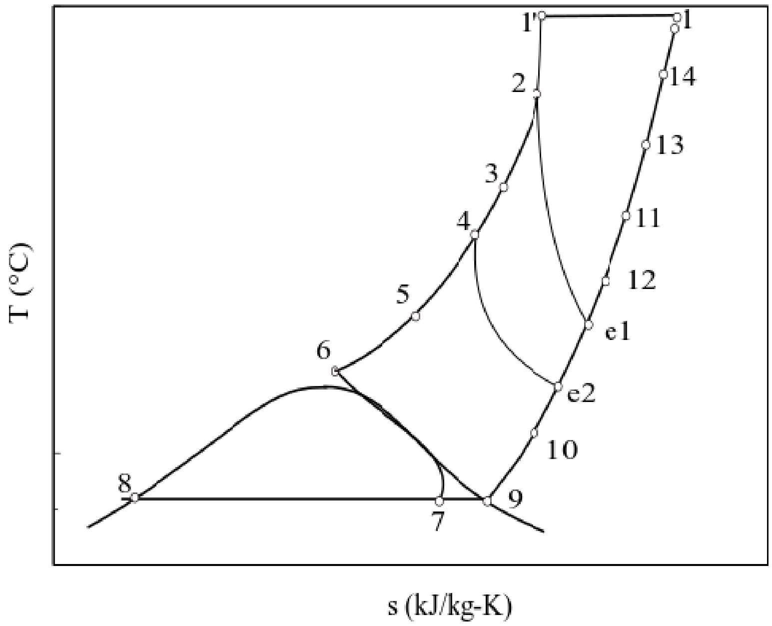


Figure 3.8 Temperature-entropy (*T-s*) diagram for a Collins Cycle

3.6 Cascade Cycle

For some industrial applications that require moderately low temperatures with a considerably large temperature and pressure difference, the single stage vapor-compression refrigeration cycles become impractical. One of the solutions for such cases is to perform the refrigeration in two or more stages which operate in series. These refrigeration cycles are called cascade refrigeration cycles. Therefore, cascade systems are employed to obtain high-temperature differentials between the heat source and heat sink. [44]

Cascade refrigeration cycle is used in various refrigeration processes in industrial applications. One such example is the supermarket refrigeration industry, where the evaporating temperature of frozen-food cabinets ranges from -40˚C to -80˚C. It is impossible to reach these temperatures with single-stage cooling systems. In two-stage systems, evaporator and condenser are filled with the same refrigerant. In cascade cooling applications, evaporator and condenser may be filled with different refrigerant couples.

Cascade refrigeration system uses more than one fluid as the refrigerant. In this system, each fluid has a progressively lower boiling temperature than the previous fluid used for precooling [36]. Each fluid runs as a separate closed circuit in one step or several steps in the appropriate temperature and pressure range [37]. As the fluid group, propane-ethylene-ethane, ammonia-ethylene-methane or freon22-freon13-methane refrigerant fluid groups can be selected. When the fluid group is selected, the other operating parameters are almost fixed [38].

Cascade method is often used because of its high efficiency. The cascade cyle was first used for liquefaction of air. In this system amonia is used to liquefy the ethylene in the first step and next step ethylene is used for natural gas.

The schematic of a cascade refrigeration system is shown in Figure 3.9. In the low temperature cycle, the refrigerant is isentropically compressed to state 2. It then passes through the cascade condenser where it gives heat to the refrigerant of the higher temperature cycle. In throttling device, it expands and two phase mixture results. Liquid yield is taken as product and the gas porton returns to heat exchanger. At the high temperature cycle, the refrigerant is compressed and then it rejects heat [38].

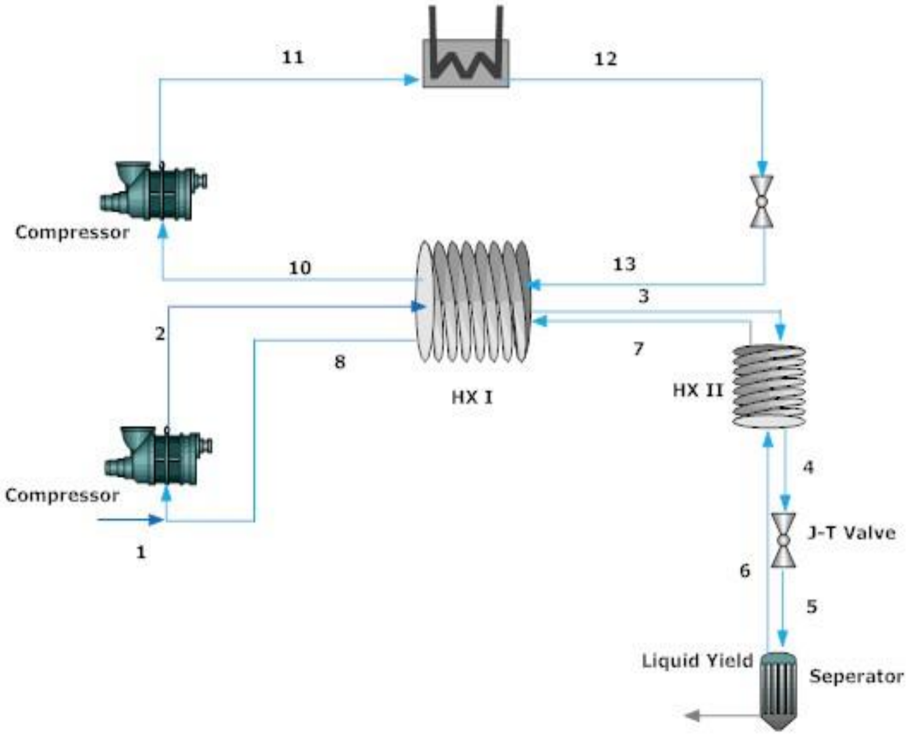


Figure 3.9 Schematic Representation of Cascade Cycle

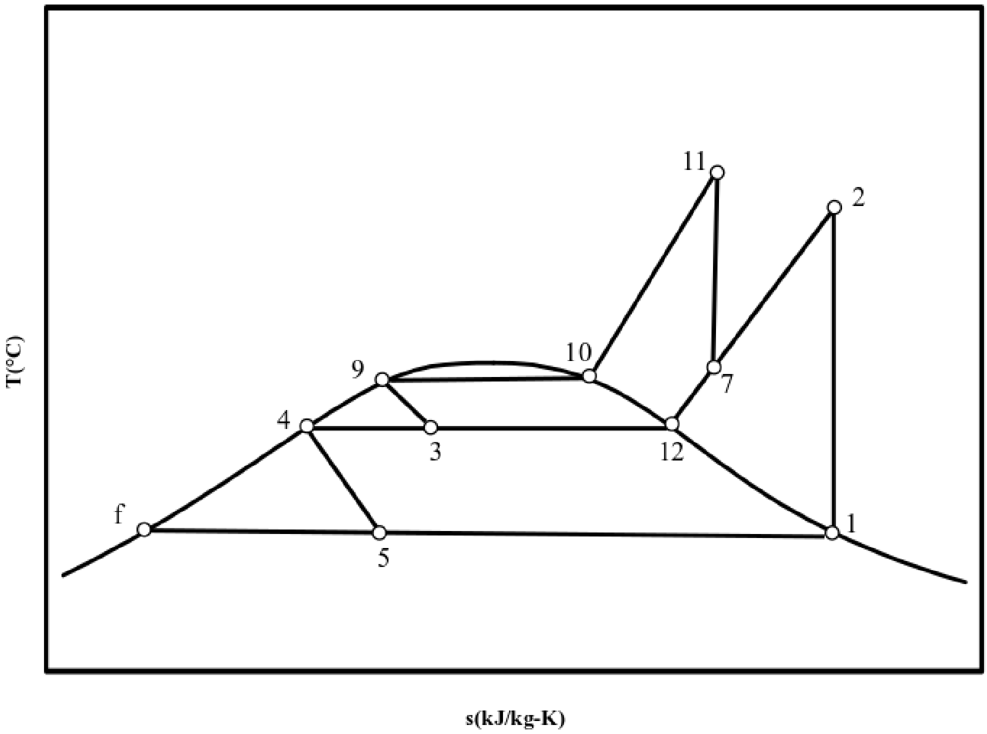


Figure 3.10 Temperature-entropy (*T-s*) diagram for a Cascade cycle

An important application of gas liquefaction is liquefaction of natural gas. The first cycle used (and still used) for natural gas liquefaction was the multistage cascade refrigeration cycle that uses three different refrigerants, namely propane, ethane (or ethylene), and methane in their individual refrigeration cycles.

3.7 Conclusions

In this chapter, several common gas liquefaction cycles are introduced. Main caharacteristics of the cycles are explained and their operations are described. Since gas liquefaction is an energy intensive process, it is important to understand characteristics of gas liquefaction cycles so that the most appropriate cycle for minimum work consumption can be identified for a given application.

CHAPTER 4

THERMODYNAMIC ANALYSIS OF CLAUDE LIQUEFACTION CYCLE

4.1 Introduction

Energy analysis is often the most significant part of an engineering system. Energy can be stored within a system in various macroscopic forms, it can be transformed from one form to another, and it can be transferred between systems. The total amount of energy is conserved in all transformations. Energy balances are widely used in the design and analysis of energy conversion systems [39, 40].

In this chapter, we provide thermodynamic analysis of Claude liquefaction cycle. Thermodynamic analysis is based on the first law of thermodynamics. The second law will be used in the supporting role as needed.The analysis of the cycle is performed using EES (Engineering Equation Solver) software with built-in thermophysical property functions such as enthaply, entropy, and specific heat for many substances.The software also allows parametric studies and optimization.

4.2 Thermodynamic Analysis of Claude Cycle

Claude cycle is a common cycle used to liquefy gases including helium and hydrogen. To liquefy a gas, temperature of the gas should be lowered to below critical temperature. Claude cycle uses isenthalpic expansion together with isentropic expansion.Claude cycle may be defined as the simple Linde-Hampson cycle precooled by the reversed Brayton refrigerator, and consists of three heat exchangers, one expander and a Joule-Thompson valve for final expansion stage. In Claude cycle, refrigeration effect is produced by the Joule-Thompson valve and the expander. Replacing the throttling valve by an expander increases the efficiency of the liquefaction process. Refrigeration effect produced by the expander depends on the flow of the gas diverted through the expander and the inlet temperature of the expander. J-T valve's liquefaction effect is related to the inlet temperature of the valve. Higher inlet temperature from the expander increase the refrigeration effect produced by the expander but increases the inlet temperature of the J-T valve. Therefore, the liquefaction effect produced by J-T valve is reduced. There must be an optimum value for the expander inlet temperature.

The schematic representation and the *T-s* diagram of the cycle are given in Figures 4.1 and 4.2 [1-4]. In Claude cycle, the high-pressure gas is separated from the main stream, expanded in an expander from which it exhausts as a saturated or slightly superheated vapor and mixes with the low-pressure return stream. The high-pressure stream to be liquefied is cooled down through the heat exchangers and is expanded through a Joule-Thompson (J-T) valve to a liquid reservoir. The gas portion mixes with the expander exhaust and returns to the cycle through the heat exchanger system. In compressor, the gas is compressed to a pressure of about 4 MPa and it passes through the first heat exchanger. About 70-80 percent of the gas is diverted from the stream and expanded through the turbo expander.

The expansion processes in J-T valve is common because of simplicity of the construction. However, from thermodynamic point of view, it is undesirable because it is a highly irreversible process. Thermodynamically, expansion valve can be replaced with a turbo expander.

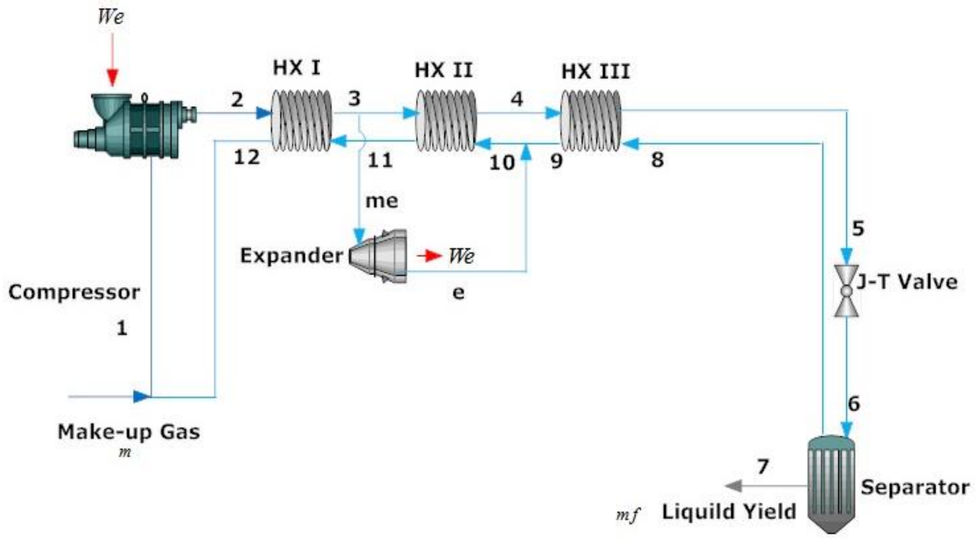


Figure 4.1 Schematic Representation of Claude Cycle. J-T: Joule Thompson, HX: Heat exchanger, *m* = mass flow rate of gas, m_f: mass flow rate of liquid.

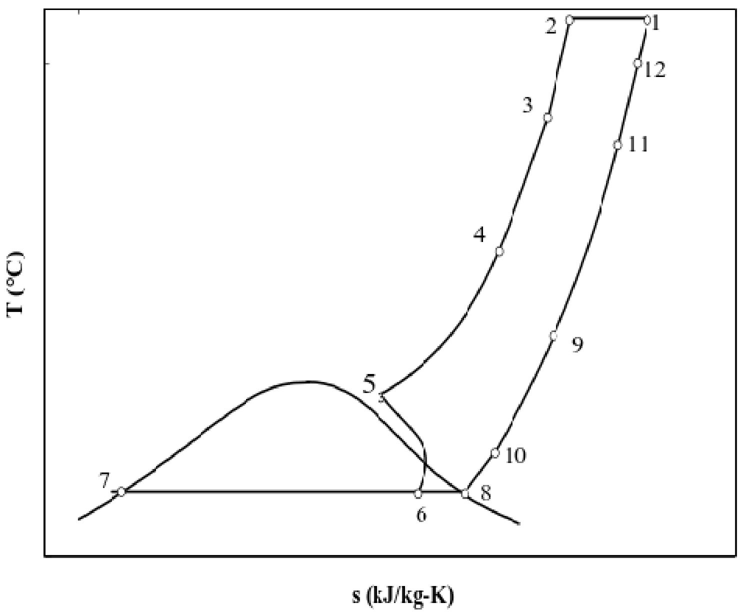


Figure 4.2 Temperature-entropy (*T*-*s*) Diagram of Claude Cycle

In this study, the following assumptions for thermodynamic analysis of the cycle are considered:

- System is at steady-state conditions.
- Changes in potential and kinetic energies are negligible.
- Compressor is isothermal.
- Expander is adiabatic and its isentropic efficiency is 100%.
- Effectiveness of heat exchangers is 100%.
- There is no pressure drop through piping and heat exchangers.

The first law of thermodynamic is applied to each of system components. The liquefaction process is basically a heat removal process between inlet state (1) and liquid state (7).The refrigeration effect per unit mass of liquefaction can be expressed as

$$q_L = h_1 - h_f \qquad \mathbf{(4.1)}$$

where h_f is the enthalpy of saturated liquid at stage (7). The refrigeration effect per unit mass of gas can be determined from

$$q_L = h_1 - h_2 + r(h_3 - h_e) \qquad \mathbf{(4.2)}$$

where r is the non-dimensionalized mass fraction ratio diverted through the expander:

$$r = \frac{\dot{m}_e}{\dot{m}} \tag{4.3}$$

In Claude cycle, the work produced by the expander is given as

$$w_e = r(h_3 - h_e) \tag{4.4}$$

Liquefied mass fraction of the inlet gas is expressed as

$$y = \frac{\dot{m}_f}{\dot{m}} \tag{4.5}$$

Energy balance for compressor gives the compressor work per unit mass of the gas:

$$w_c = h_2 - h_1 - T_1(s_2 - s_1) \tag{4.6}$$

Net work input to the cycle per unit mass of gas is given by

$$w_{net} = w_c - w_e = h_2 - h_1 - T_1(s_2 - s_1) - r(h_3 - h_e) \tag{4.7}$$

Net work per unit mass of liquefaction can be expressed as

$$w_{liq} = \frac{w_{net}}{y} \tag{4.8}$$

Energy balances for HX I,HX II and HX III can be written, respectively, as

$$h_2 - h_3 = (1 - y)(h_{12} - h_{11}) \tag{4.9}$$

$$(1 - r)(h_3 - h_4) = (1 - y)(h_{11} - h_{10}) \tag{4.10}$$

$$(1 - r)(h_5 - h_4) = (1 - y - r)(h_9 - h_8) \tag{4.11}$$

The coefficient of performance for Claude cycle can be expressed as

$$COP_{actual} = \frac{q_L}{w_{liq}} = \frac{h_1 - h_f}{h_2 - h_1 - T_1(s_2 - s_1) - r(h_3 - h_e)} \tag{4.12}$$

Reversible work for any gas liquefaction cycle can be written as

$$w_{rev} = h_f - h_1 - T_1\left(s_f - s_1\right) \tag{4.13}$$

Second law efficiency for any gas liquefaction cycle is

$$\eta_{II} = \frac{w_{rev}}{w_{lig}} = \frac{h_f - h_1 - T_1\left(s_f - s_1\right)}{h_2 - h_1 - T_1(s_2 - s_1) - r(h_3 - h_e)} \tag{4.14}$$

The second law efficiency may also be expressed using actual and reversible COPs of the system:

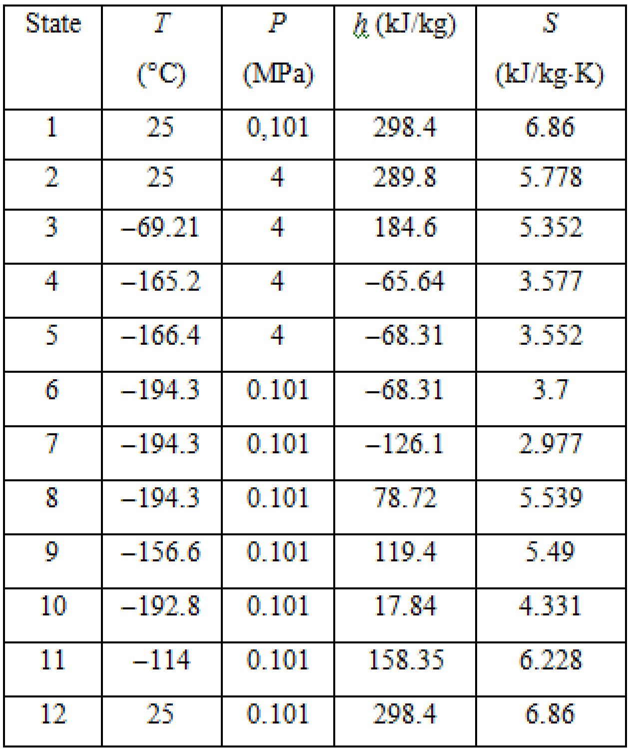
$$\eta_{II} = \frac{COP_{actual}}{COP_{reversible}} \qquad \mathbf{(4.15)}$$

and the reversible COP is

$$COP_{reversible} = \frac{q_L}{w_{rev}} = \frac{h_1 - h_f}{h_f - h_1 - T_1(s_2 - s_1) - r(h_3 - h_e)} \qquad \mathbf{(4.16)}$$

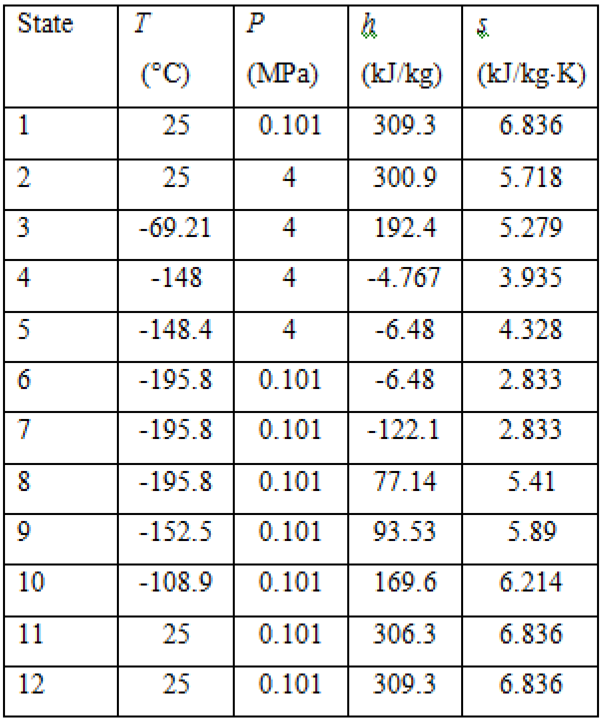
The cycle operation is simulated for various common gases including air, nitrogen, oxygen, argon, methane, and fluorine. The assumptions given earlier are used. The state data for the cycle operation are given in Table 4.1 through Table 4.6. In the calculations, the state of inlet gas is taken as 25°C and 1 atm and the compressor outlet pressure is taken as 4 MPa. Due to varying thermophysical properties, the data in the tables are different for various gases, and each gas has a different liquefaction temperature.

Table 4.1 Various Properties of Claude Cycle for Air. T_1 = 25°C, P_1 = 1 atm (0.101 MPa), and P_2= 4 MPa



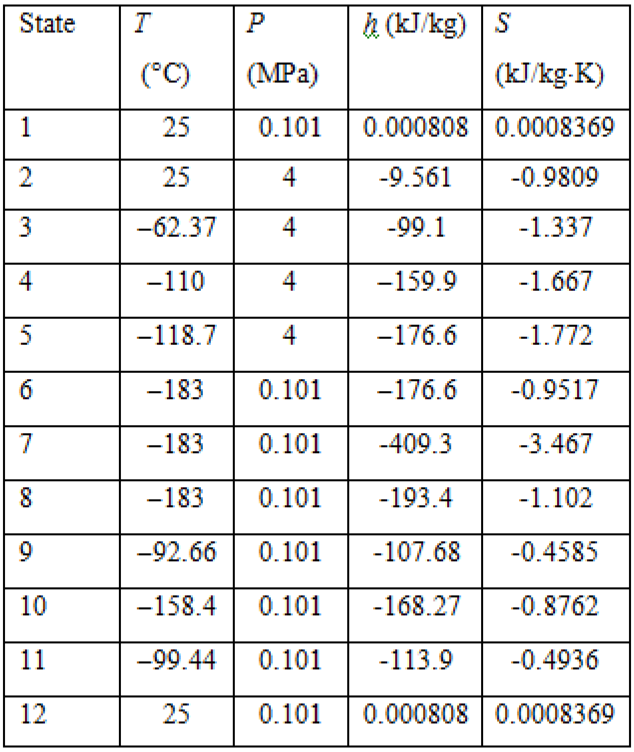
State	T (°C)	P (MPa)	h (kJ/kg)	S (kJ/kg·K)
1	25	0,101	298.4	6.86
2	25	4	289.8	5.778
3	−69.21	4	184.6	5.352
4	−165.2	4	−65.64	3.577
5	−166.4	4	−68.31	3.552
6	−194.3	0.101	−68.31	3.7
7	−194.3	0.101	−126.1	2.977
8	−194.3	0.101	78.72	5.539
9	−156.6	0.101	119.4	5.49
10	−192.8	0.101	17.84	4.331
11	−114	0.101	158.35	6.228
12	25	0.101	298.4	6.86

Table 4.2 Various properties of Claude cycle for nitrogen. T_1 = 25°C, P_1 = 1 atm (0.101 MPa), and P_2 = 4 MPa



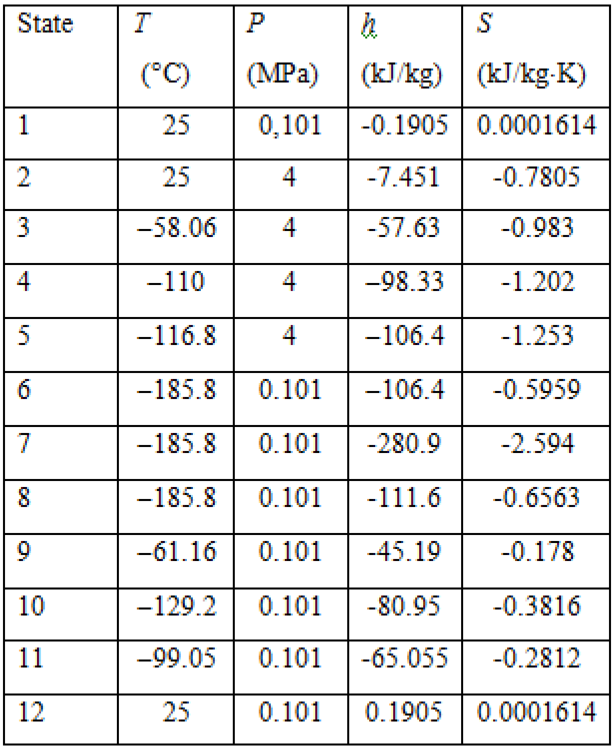
State	*T* (°C)	*P* (MPa)	*h* (kJ/kg)	*s* (kJ/kg·K)
1	25	0.101	309.3	6.836
2	25	4	300.9	5.718
3	-69.21	4	192.4	5.279
4	-148	4	-4.767	3.935
5	-148.4	4	-6.48	4.328
6	-195.8	0.101	-6.48	2.833
7	-195.8	0.101	-122.1	2.833
8	-195.8	0.101	77.14	5.41
9	-152.5	0.101	93.53	5.89
10	-108.9	0.101	169.6	6.214
11	25	0.101	306.3	6.836
12	25	0.101	309.3	6.836

Table 4.3 Various Properties of Claude Cycle for Oxygen. T_1 = 25°C, P_1 = 1 atm (0.101 MPa), and P_2 = 4 MPa



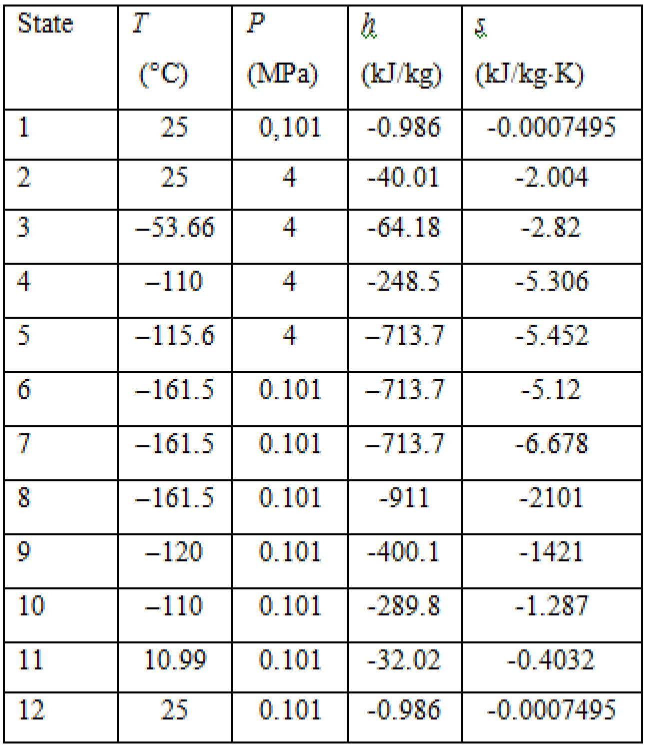
State	*T* (°C)	*P* (MPa)	*h* (kJ/kg)	*S* (kJ/kg·K)
1	25	0.101	0.000808	0.0008369
2	25	4	-9.561	-0.9809
3	−62.37	4	-99.1	-1.337
4	−110	4	−159.9	-1.667
5	−118.7	4	−176.6	-1.772
6	−183	0.101	−176.6	-0.9517
7	−183	0.101	-409.3	-3.467
8	−183	0.101	-193.4	-1.102
9	−92.66	0.101	-107.68	-0.4585
10	−158.4	0.101	-168.27	-0.8762
11	−99.44	0.101	-113.9	-0.4936
12	25	0.101	0.000808	0.0008369

Table 4.4 Various Properties of Claude cycle for Argon. T_1 = 25°C, P_1 = 1 atm (0.101 MPa), and P_2 = 4 MPa



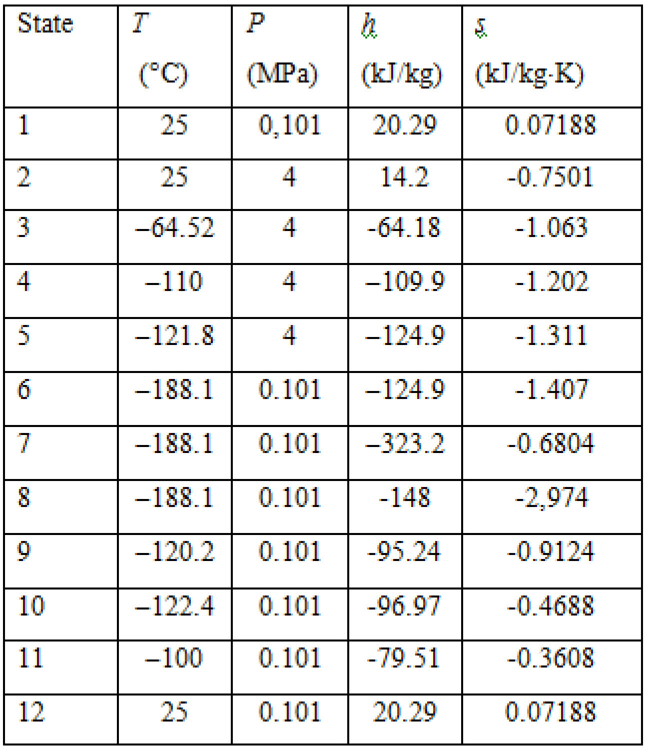
State	*T* (°C)	*P* (MPa)	*h* (kJ/kg)	*S* (kJ/kg·K)
1	25	0,101	-0.1905	0.0001614
2	25	4	-7.451	-0.7805
3	–58.06	4	-57.63	-0.983
4	–110	4	–98.33	-1.202
5	–116.8	4	–106.4	-1.253
6	–185.8	0.101	–106.4	-0.5959
7	–185.8	0.101	-280.9	-2.594
8	–185.8	0.101	-111.6	-0.6563
9	–61.16	0.101	-45.19	-0.178
10	–129.2	0.101	-80.95	-0.3816
11	–99.05	0.101	-65.055	-0.2812
12	25	0.101	0.1905	0.0001614

Table 4.5 Various Properties of Claude Cycle for Methane. T_1 = 25°C, P_1 = 1 atm (0.101 MPa), and P_2 = 4 MPa



State	*T* (°C)	*P* (MPa)	*h* (kJ/kg)	*s* (kJ/kg·K)
1	25	0,101	-0.986	-0.0007495
2	25	4	-40.01	-2.004
3	–53.66	4	-64.18	-2.82
4	–110	4	-248.5	-5.306
5	–115.6	4	–713.7	-5.452
6	–161.5	0.101	–713.7	-5.12
7	–161.5	0.101	–713.7	-6.678
8	–161.5	0.101	-911	-2101
9	–120	0.101	-400.1	-1421
10	–110	0.101	-289.8	-1.287
11	10.99	0.101	-32.02	-0.4032
12	25	0.101	-0.986	-0.0007495

Table 4.6 Various Properties of Claude Cycle for Fluorine. T_1 = 25°C, P_1 = 1 atm (0.101 MPa), and P_2 = 4 MPa



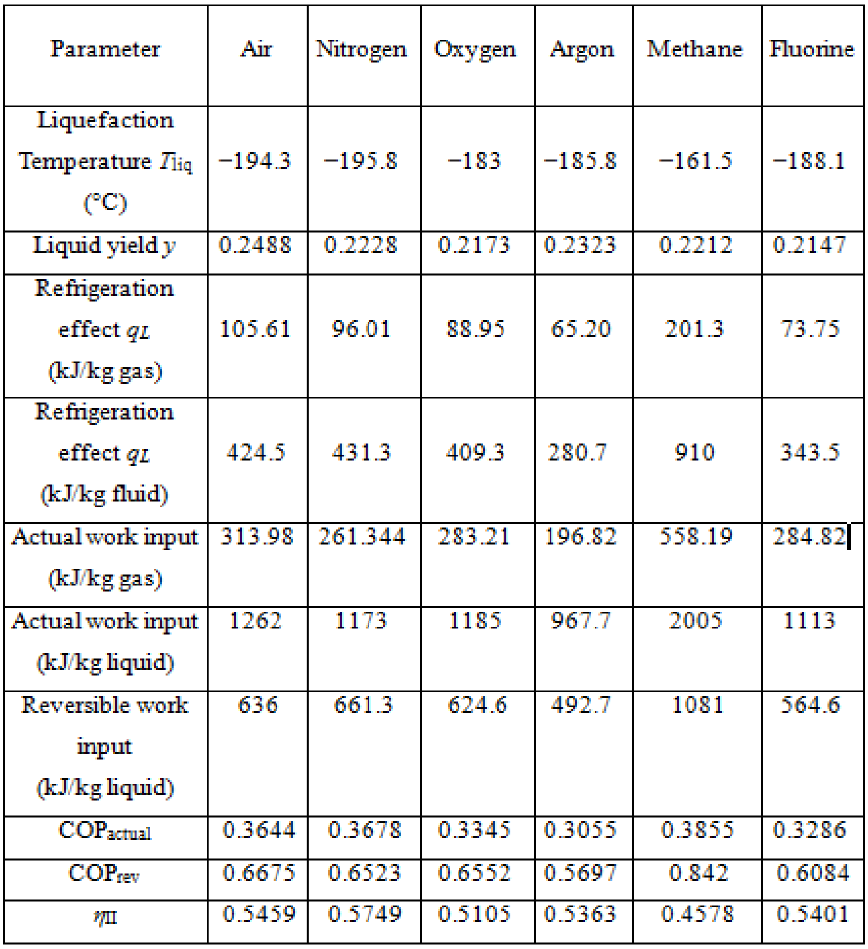
State	T (°C)	P (MPa)	h (kJ/kg)	s (kJ/kg-K)
1	25	0,101	20.29	0.07188
2	25	4	14.2	-0.7501
3	–64.52	4	-64.18	-1.063
4	–110	4	–109.9	-1.202
5	–121.8	4	–124.9	-1.311
6	–188.1	0.101	–124.9	-1.407
7	–188.1	0.101	–323.2	-0.6804
8	–188.1	0.101	-148	-2,974
9	–120.2	0.101	-95.24	-0.9124
10	–122.4	0.101	-96.97	-0.4688
11	–100	0.101	-79.51	-0.3608
12	25	0.101	20.29	0.07188

4.3 Performance Analysis of the Cycle

To investigate performance of Claude cycle for air, nitrogen, oxygen, argon, fluorine and methane, we use gas inlet state as 25°C and 0.101 MPa with a compressor outlet pressure of 4 MPa. Expander is assumed as isentropic. Compressor is taken as isothermal andthe effectiveness of the heat exchangers is assumed to be 100%. The mass fraction diverted to the expander is taken as 0.7.

Using thermodynamic relation in the previous section, the cycle is analyzed for the gases considered, and the results are given in Table 4.7. The performance parameters in Table 4.7 are taken as liquefaction temperature, liquefied mass fraction, refrigeration effect, actual and reversible work inputs, actual and reversible COPs and second-law efficiency. The results allow a comparison between the gases.

Table 4.7 Performance Parameters of Claude Cycle for the Liquefaction of Common Gases



Parameter	Air	Nitrogen	Oxygen	Argon	Methane	Fluorine
Liquefaction Temperature T_{liq} (°C)	−194.3	−195.8	−183	−185.8	−161.5	−188.1
Liquid yield y	0.2488	0.2228	0.2173	0.2323	0.2212	0.2147
Refrigeration effect q_L (kJ/kg gas)	105.61	96.01	88.95	65.20	201.3	73.75
Refrigeration effect q_L (kJ/kg fluid)	424.5	431.3	409.3	280.7	910	343.5
Actual work input (kJ/kg gas)	313.98	261.344	283.21	196.82	558.19	284.82
Actual work input (kJ/kg liquid)	1262	1173	1185	967.7	2005	1113
Reversible work input (kJ/kg liquid)	636	661.3	624.6	492.7	1081	564.6
COP_{actual}	0.3644	0.3678	0.3345	0.3055	0.3855	0.3286
COP_{rev}	0.6675	0.6523	0.6552	0.5697	0.842	0.6084
η_{II}	0.5459	0.5749	0.5105	0.5363	0.4578	0.5401

The liquefaction temperature is the highest for methane with −161.5°C and the lowest for nitrogen with −195.8°C. It is close to nitrogen for other gases. The minimum work requirement is 636 kJ/kg liq for air and 1081 kJ/kg for methane. The values are close to that of air for other gases. The same trend is also observed for the actual work input under assumed operating conditions.

The reversible and actual COP values are 0.668 and 0.364, respectively for air. For methane the corresponding values are 0.842 and 0.386, and for fluorine they are 0.608 and 0.329. The higher values, for methane is due to the fact that methane has a higher liquefaction temperature. The values for oxygen and nitrogen are close to that of air.

The analysis also includes the second-law efficiency. Recall that it is defined as the minimum work over the actual work. The second-law efficiencies are determined to be the highest for nitrogen with 57.5%, followed by 54.6% for air, 54.0% for fluorine, 53.6% for argon, 51.0% for oxygen, and 45.8% for methane.

The maximum amount of work is consumed (2005 kJ/kg liq) to liquefy one kg of methane. For other gases, the work values vary between 968 and 1262 kJ/kg liq. For this reason, Claude cycle is not preferred for natural gas liquefaction. Note that natural gas mainly consists of methane. Instead, mixed-refrigerant, cascade, and gas-expansion cycles are used. (Kanoglu, 2002). The mixed-refrigerant cycle is used most in large natural gas liquefaction plants. In this cycle, the natural gas stream is cooled by the consecutive vaporization of propane, ethylene, and methane.

Liquefaction is essentially a heat removal process from the gas between state 1 and 6. To liquefy gases, the temperature must be decraesed to very low temperatures. As a result, the COP values in liquefaction cycles are low. Table 4.7 shows that as the liquefaction temperature increases, the reversible COP increases.

A comparion of COP, second-law efficiency, and work consumption values are also shown using bar diagrams in Fig. 4.3, Fig. 4.4, and Fig. 4.5. These figures indicate that the COP value is the highest for methane (0.386), second-law efficiency is the highest (57.5%) for nitrogen, and work consumption is the lowest for argon (968 kJ/kg liq or 493 kJ/kg gas).

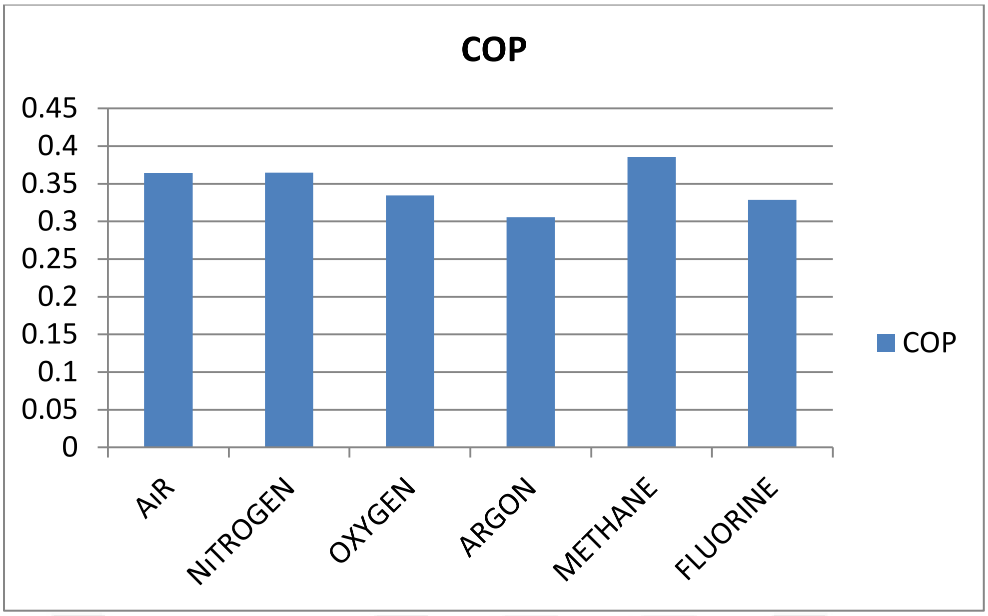


Figure 4.3 The COP of Various Gases in Claude Cycle

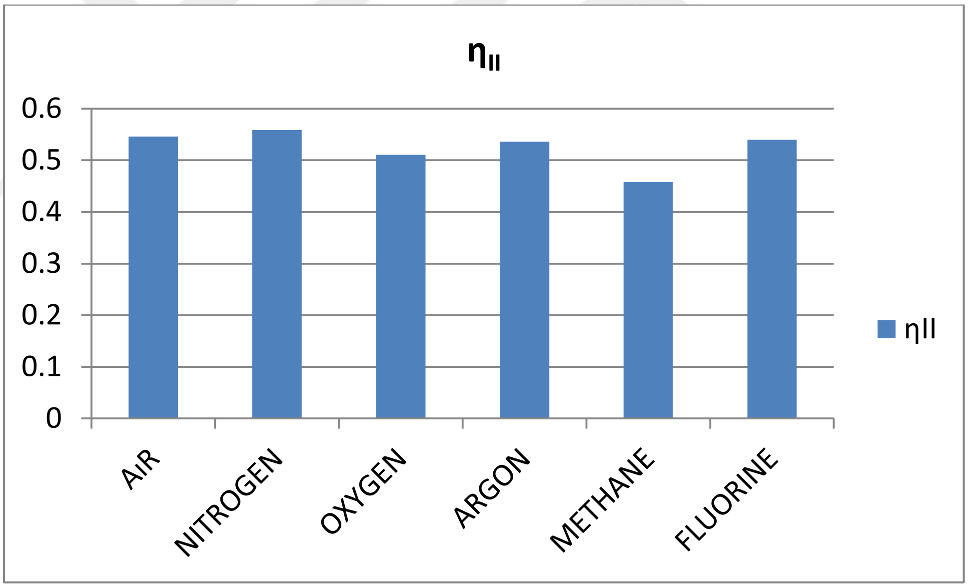


Figure 4.4 The Second-Law Efficiency of Various Gases in Claude Cycle

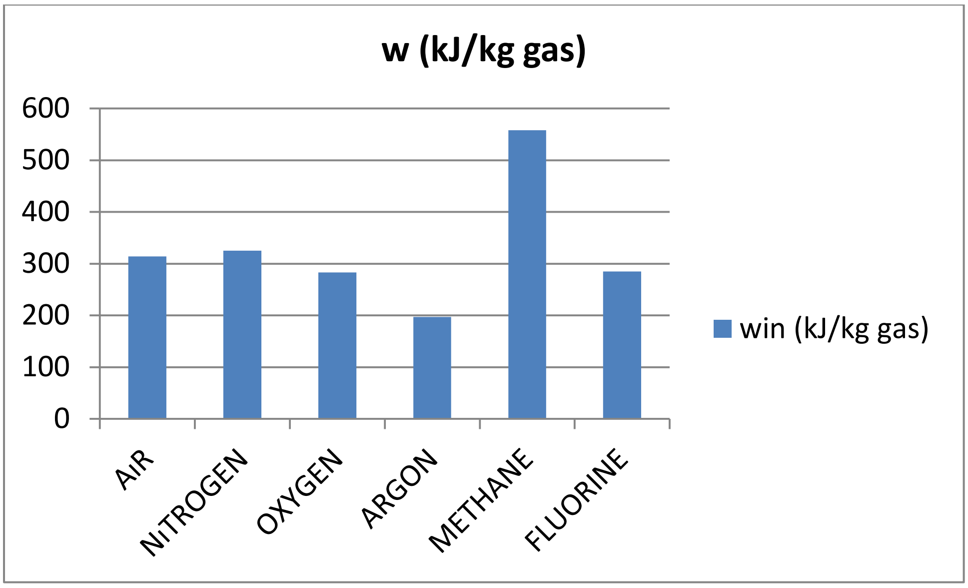


Figure 4.5 Actual Work Consumption of Various Gases in Claude Cycle

4.4 Conclusions

In this chapter, thermodynamic analysis of Claude liquefaction cycle is performed. The cycle is simulated under certain assumptions. Liquefaction temperatures, actual and reversible work consumptions, actual and reversible COP values, and second-law efficiencies are calculated considering the liquefaction of air, oxygen, nitroegn, argon, methane, and fluorine.

CHAPTER 5

PARAMETRIC ANALYSIS AND OPTIMIZATION

5.1 Introduction

In this chapter, parametric analysis and optimization of Claude liquefaction cycle is presented. The optimization studies were performed in order to achieve maximum system performance. For all enginering applications, optimization is necessary to minimize energy consumption, cost, and environmental impact. In gas liquefaction processes, the optimization problem is solved through the use of thermodynamic analysis.

Unit energy consumption is a major parameter for the evaluation of different liquefaction processes. Therefore it is usually taken as the objective function of the optimization process. The effect of some parameters such as turbine inlet temperature andcompresssor outlet pressure on the performance of the gas liquefaction cycle have been considered.The optimization of the cycles have been performed to minimize work consumption or maximize the efficiency of the cycles [40, 41, 42].

The performance of an actual liquefier can be compared to that of an ideal liquefier for different processes and working fluids. Optimization of liquid yield and specific work requirement have led to the optimization of operating conditions such as pressure levels, expander mass fractions, heat exchanger effectiveness, etc.

We present the results for the effects of various operating conditions on the system performance parameters. We also optimize the Claude liquefaction cycle for the liquefaction of various common gases.

5.2 Effect of Gas Inlet Temperature

The gas inlet temperature plays an important role on the performance of the liquefaction cycles. A methodology for performance of the first and second law analyses of gas liquefaction cycles is presented by Kanoglu et al. (2008).[34] A definition for the minimum work requirement is also provided. We follow this procedure to study and the the effect of gas inlet temperature on various cycle performance parameters.

The effect of gas inlet temperature on the net work input of the Claude cycle is investigated. Air, nitrogen, oxygen, methane, argon, and fluorine are considered. The gas temperature is varied from 0 to 25°C with an interval of 5°C. Figure 5.1 shows that net work increases linearly as the gas inlet temperature increases. The greatest work consumption is associated with methane while the lowest work is consumed for argon. At a gas temperature of 25°C, the work consumption is close 1800 kJ/kg for methane and about 650°C for argon.

The effect of gas inlet temperature on the second-law efficiency of the Claude cycle is given in Fig. 5.2. Recall that the second-law efficiency is defined as the minimum work over actual work for a liquefaction process. As the gas temperature increases, the efficiency decreases. The efficiency ranges between about 60 to 75 percent. Air has the highest efficiency values while methane has the lowest values. It is also observed that as the gas temperature changes from 0 to 25°C, the efficiency varies by less than 5 percent.

Fig. 5.3 gives the effect of gas inlet temperature on the actual COP of the Claude liquefaction cycle. As expected in a cooling cycle, the COP decreases with increasing gas temperature. Methane is associated with the highest COP values while nitrogen has the lowest COP values. COP values shown in the figure range between about 0.4 and 0.6. These low values are due to the fact that a liquefaction cycle requires the gas to be cooled to very low temperatures.

The effect of inlet gas temperature on the liquefed mass fraction of the gas (*y*) is investigated, and the results are shown in Figure 5.4. As the gas temperature increases, liquefied mass fraction decreases. Argon has the highest *y* values around 0.24 while nitrogen has the lowest values about 0.22.

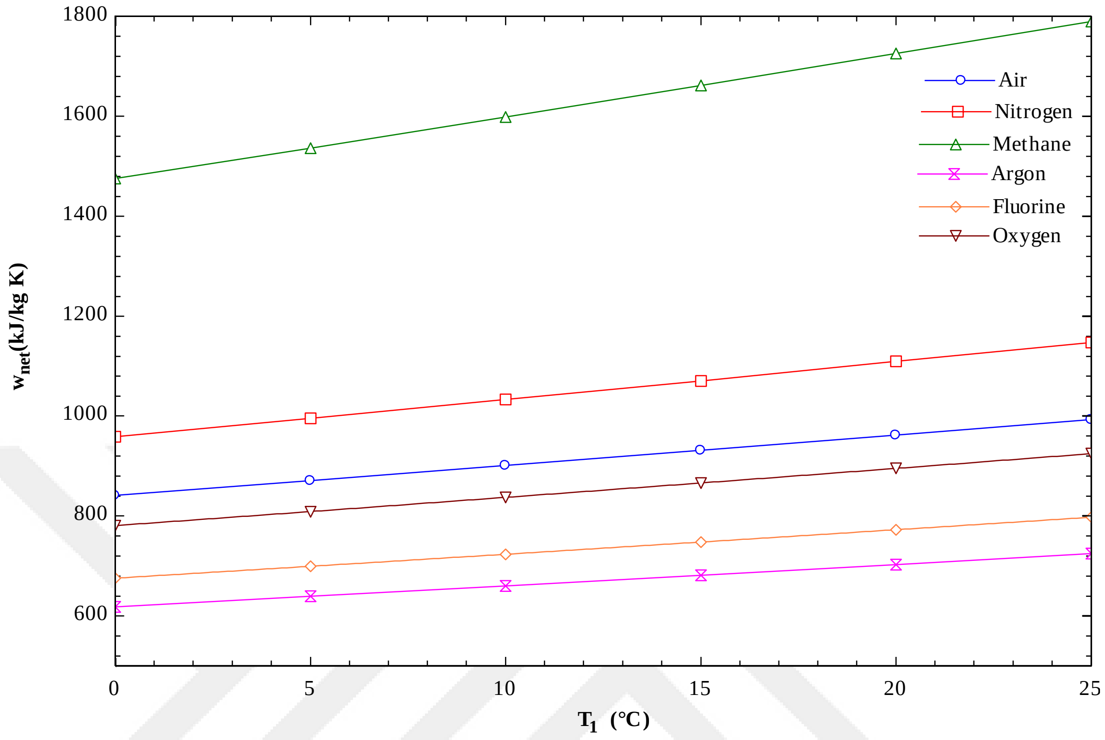


Figure 5.1 Effect of Gas Inlet Temperature on the Specific Work Consumption

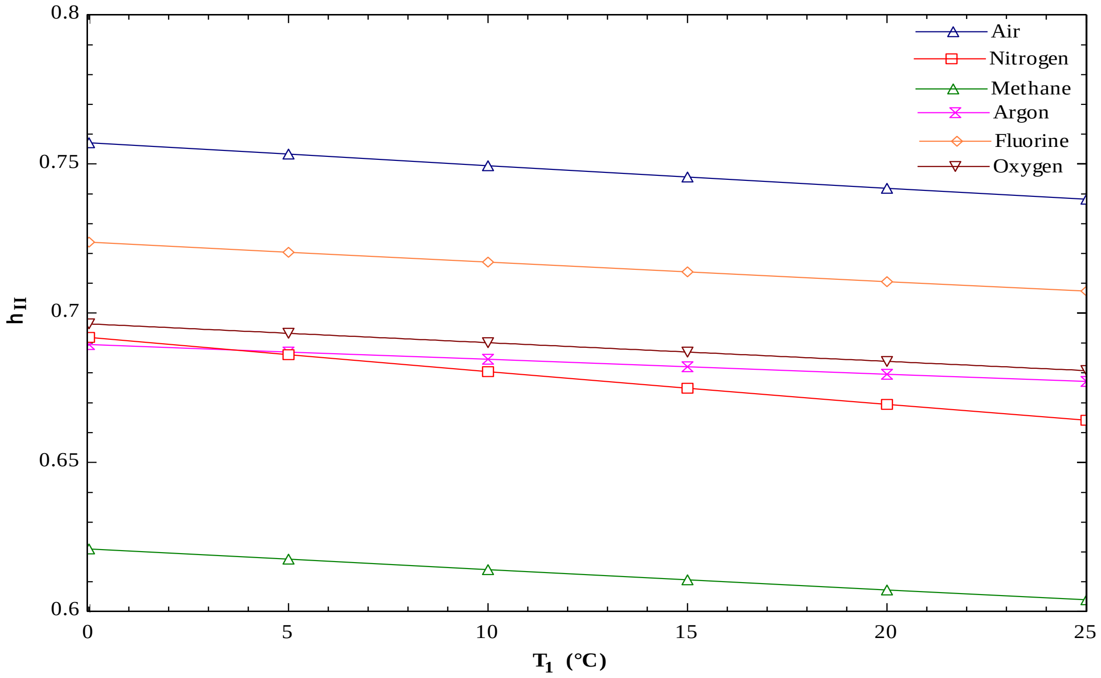


Figure 5.2 Effect of Gas Inlet Temperature on the Second-Law Efficiency

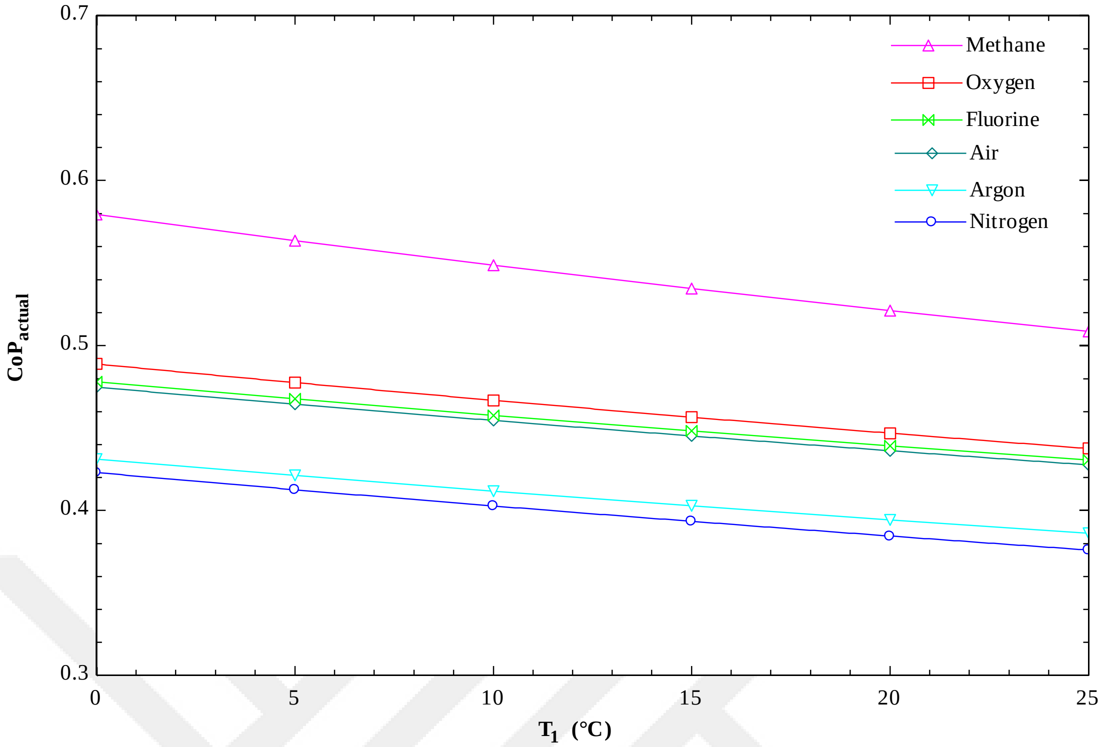


Figure 5.3 Effect of Gas Inlet Temperature on The Actual COP

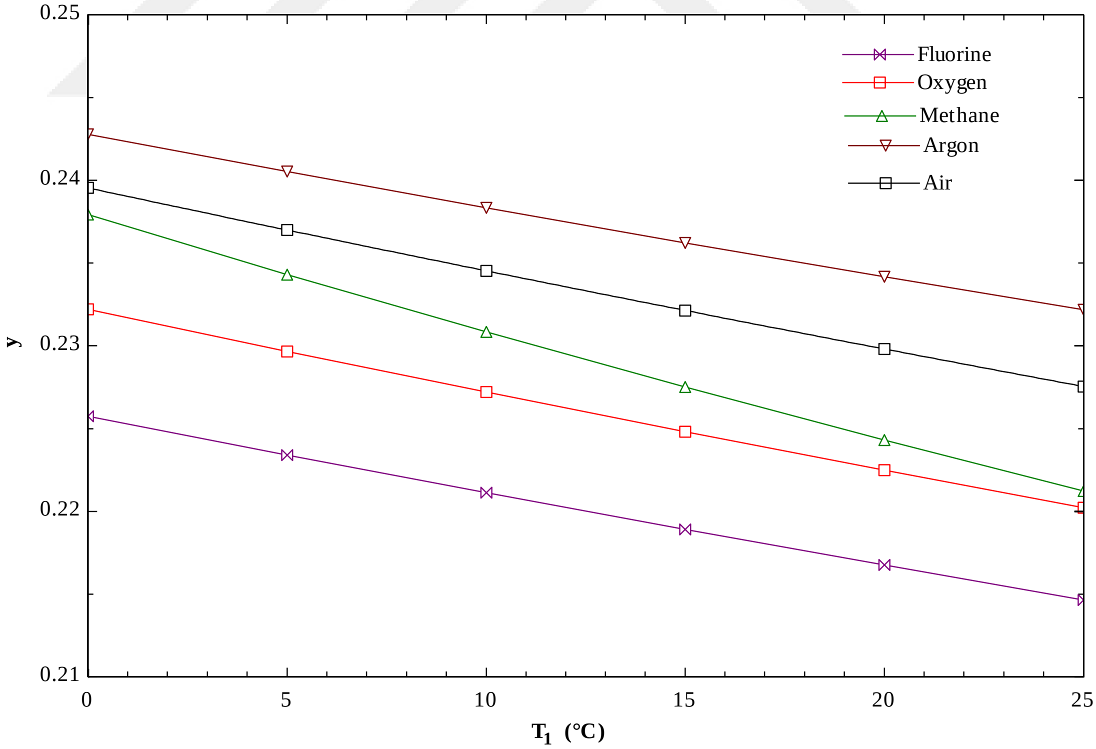


Figure 5.4 Effect of Gas Inlet Temperature on The Liquefied Mass Fraction of The Gas

5.3 Effect of Liquefaction Temperature

Very low temperatures should be achieved in order to liquefy a gas. Different gases have different liquefaction temperatures at atmospheric pressure. One can change liquefaction temperature by varying the pressure. For any cooling cycle, it is well-known that cooling a gas to a lower temperature require more work and is associated with a lower system performance. In this section, the effect of liquefaction temperature on main performance parameters of the Claude cycle is investigated.

Fig. 5.5 presents the effect of the liquefaction temperature of the gas on the second-law efficiency of the cycle. It appears that the second-law efficiency increases with increasing liquefaction temperature. The efficiency takes the highest values with air, followed by fluorine, argon, oxygen, and methane. The efficiency for air liquefaction varies between 74% and 90% when the liquefaction temperature changes from -195°C to -172°C. At a liquefaction temperature of -160°C for methane, the second-law efficiency is about 60%.

Fig. 5.6 gives the effect of liquefaction temperature on the net work requirement of the Claude cycle. As the liquefaction temperature increases, the net work decreases. The work values are the highest for methane and the lowest for argon. The values are ver close for air and oxygen. For methane, the net work consumption changes between 1600 and 1800 kJ/kg when liquefaction temperatures varies between -160 and -140°C. The values for air are between 800 and 1000 kJ/kg in the given range of liquefaction temperature.

The effect of liquefaction temperature on the liquefied mass fraction of the gas is shown in Fig. 5.7 for various gases. The liquefied mass fraction increases as the liquefaction temperature increases. Air is associated with the highest fractions while methane has the lowest values.

The effect of liquefaction temperature on the actual COP of the cycle is shown in Fig. 5.8 As the liquefaction temperature increases, the COP also increases. This trend is due to the fact that the refrigeration effect increases at a greater rate than the work input when the liquefaction temperature increases. The COP values are the highest for methane and the lowest for argon.

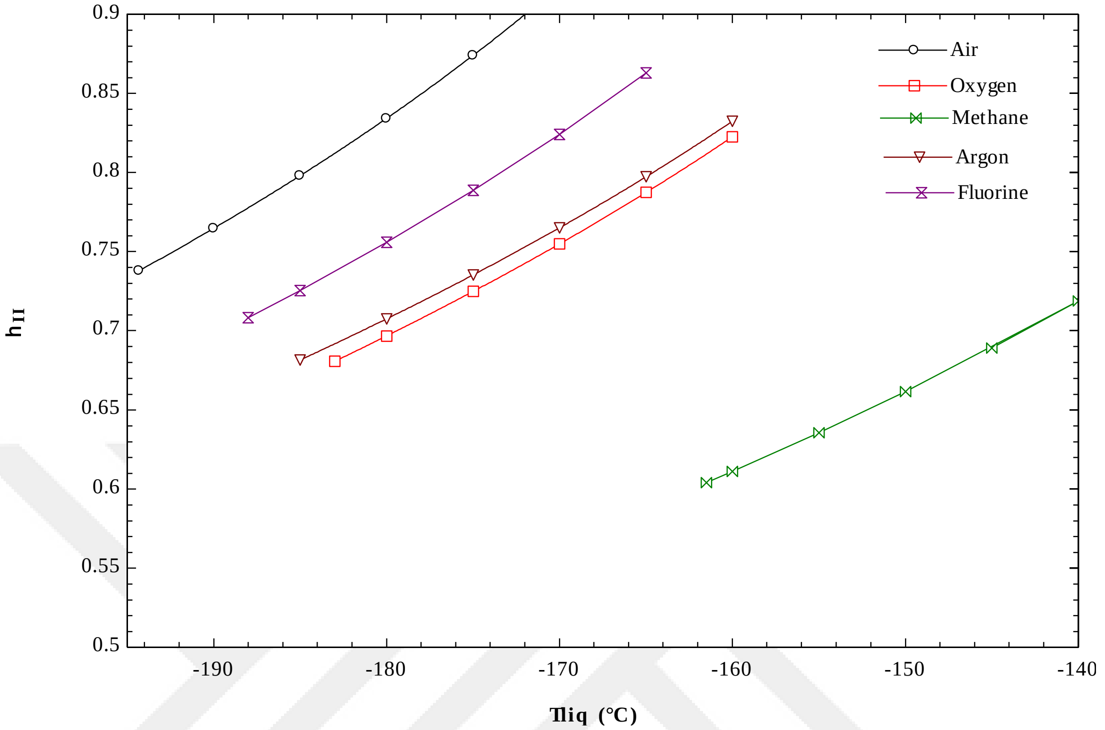


Figure 5.5 The Second Law Efficiency Versus Liquefaction Temperature for Various Gases

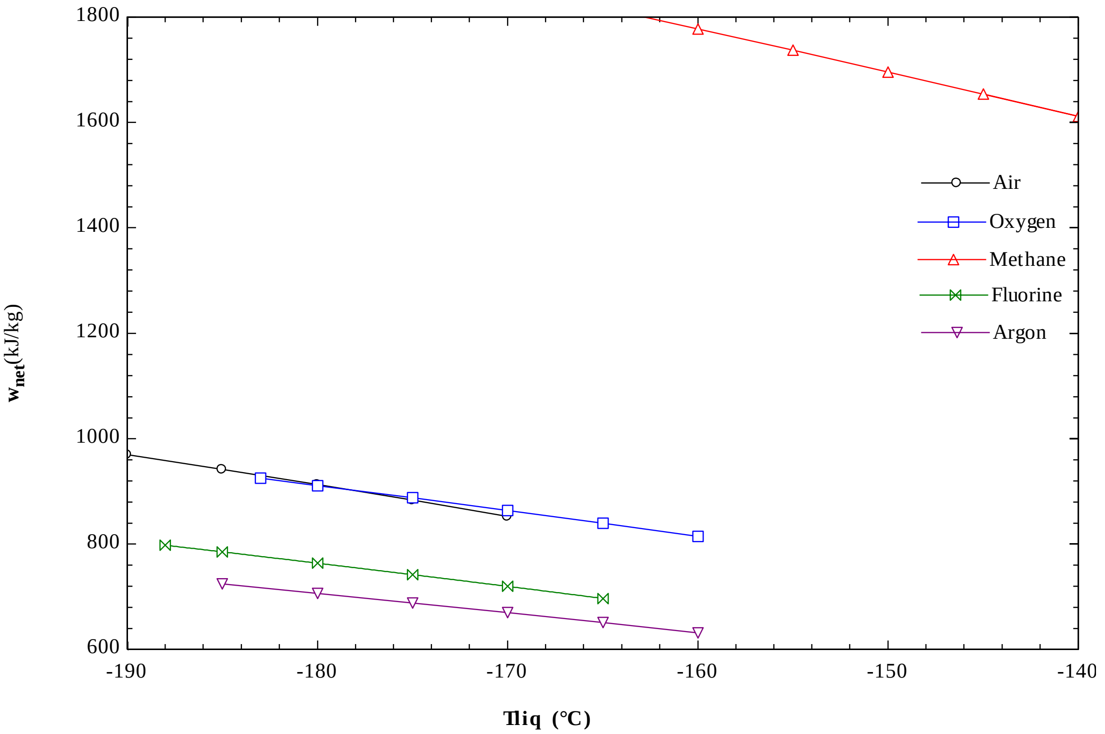


Figure 5.6 Work Consumption Versus Liquefaction Temperature for Various Gases

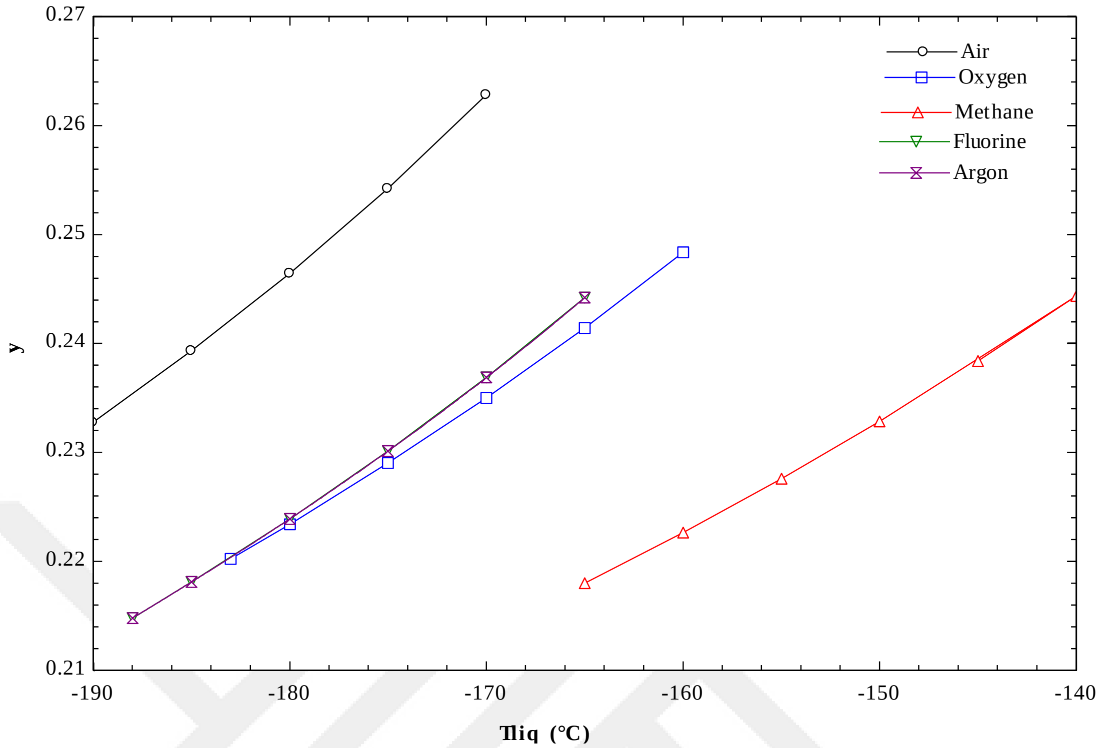


Figure 5.7 Liquefied Mass Fraction Versus Liquefaction Temperature for Various Gases

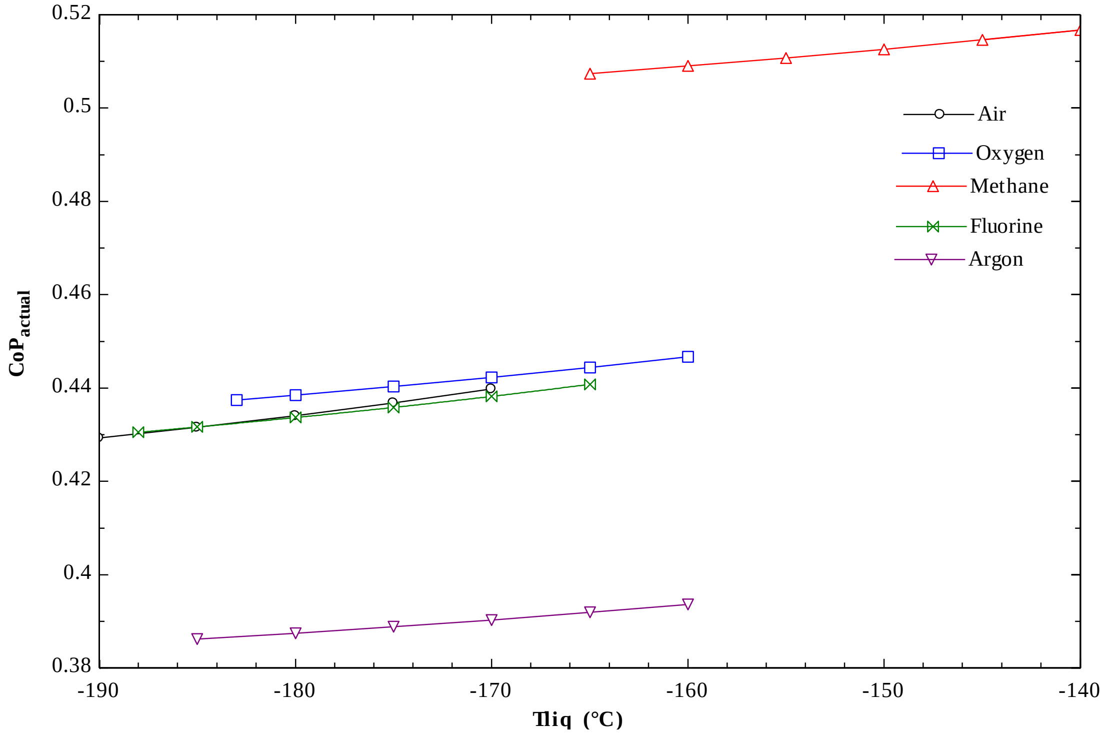


Figure 5.8 COP of The Cycle Versus Liquefaction Temperature for Various Gases

5.4 Effect of Compressor Outlet Pressure

Fig. 5.9 gives the effect of compressor outlet pressure on the second-law efficiency of the Claude cycle. It is observed that when the exit pressure of the compressor increases, the efficiency of the cycle increases, reaches a maximum, and then decreases. There is a further increase at much higher pressures, but these pressures are not practical. Therefore, we can ignore the last part of the trend.

A higher compressor outlet pressure means a higher expansion ration in the expander. This results in the production of higher liquefaction capacities. Therefore, it is possible to increase the amount of liquefied gas at higher pressures [40].However, there is a limit to this effect. At higher compressor outlet pressures, increased power consumption of the compressor starts to dominate the operation. Consequently, there is an optimum pressure giving the best performance for the cycle. In Fig. 5.9, the optimum pressure is observed to be a little over 5 MPa. This is in line with the current practices. This pressure is also achievable with current compressor technology. In Claude cycle, the optimum compressor outlet pressure is determined to be between 4 and 6 MPa.

Fig. 5.10 shows the effect of compressor outlet pressure on the liquefied mass fraction. It appears that as the pressure increases, the liquefied mass fraction increases. However, the work consumption also increases. Therefore, an optimum pressure, as shown in Figure 5.9 needs to be considered. Also, very high pressures are not practical with current compressor technology.

Fig. 5.11 shows the effect of compressor outlet pressure on the COP of the cycle. As the pressure increases, the COP first increases, reaches a maximum, and decreases. The pressure for which the COP is maximum is determined to be a little over 5 MPa.

Fig. 5.12 shows the effect of compressor outlet pressure on the net work input when the gas is supplied at 25°C. The trend in Fig. 5.12 is opposite to the trend in Fig. 5.11. That is, the work requirement first decreases, reaches a minimum, and increases. The same value of optimum pressure is observed.

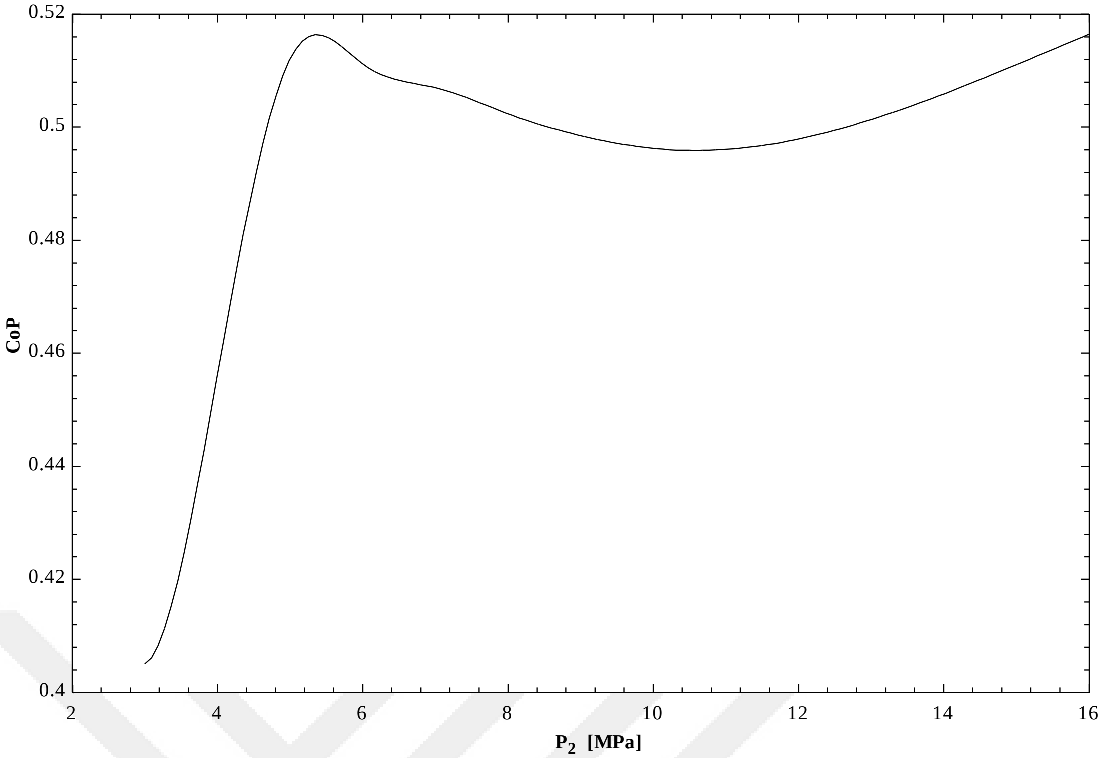


Figure 5.9 Effect of Compressor Outlet Pressure on the Second Law Efficiency of the Claude Cycle for Methane.

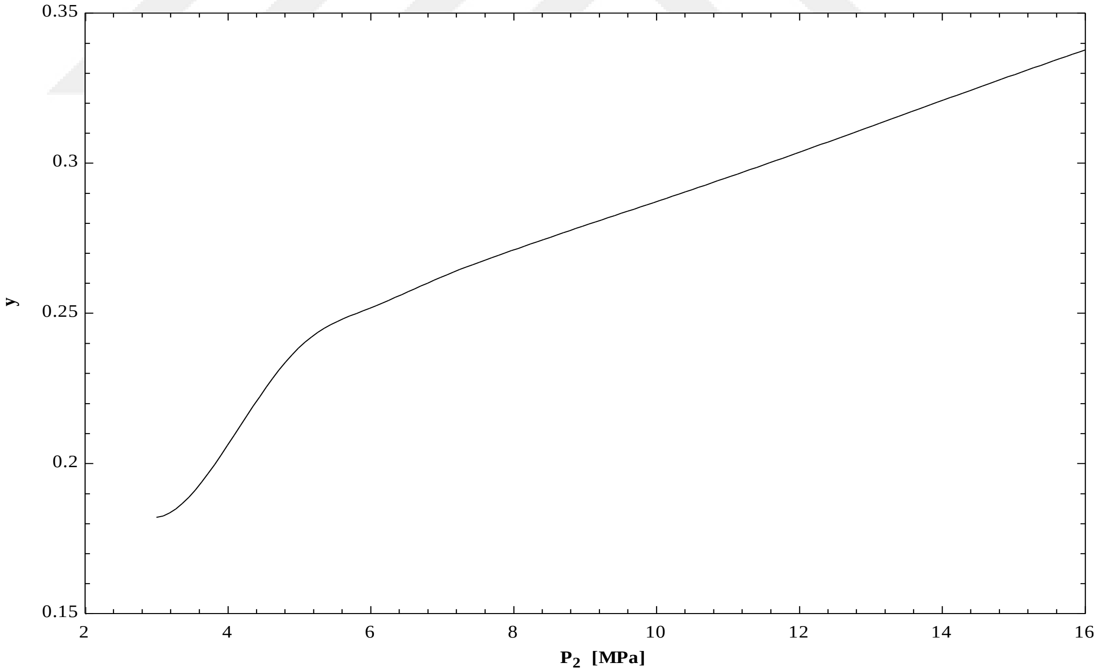


Figure 5.10 Effect of Compressor Outlet Pressure On the Liquefied Mass Fraction of the Claude Cycle for Methane

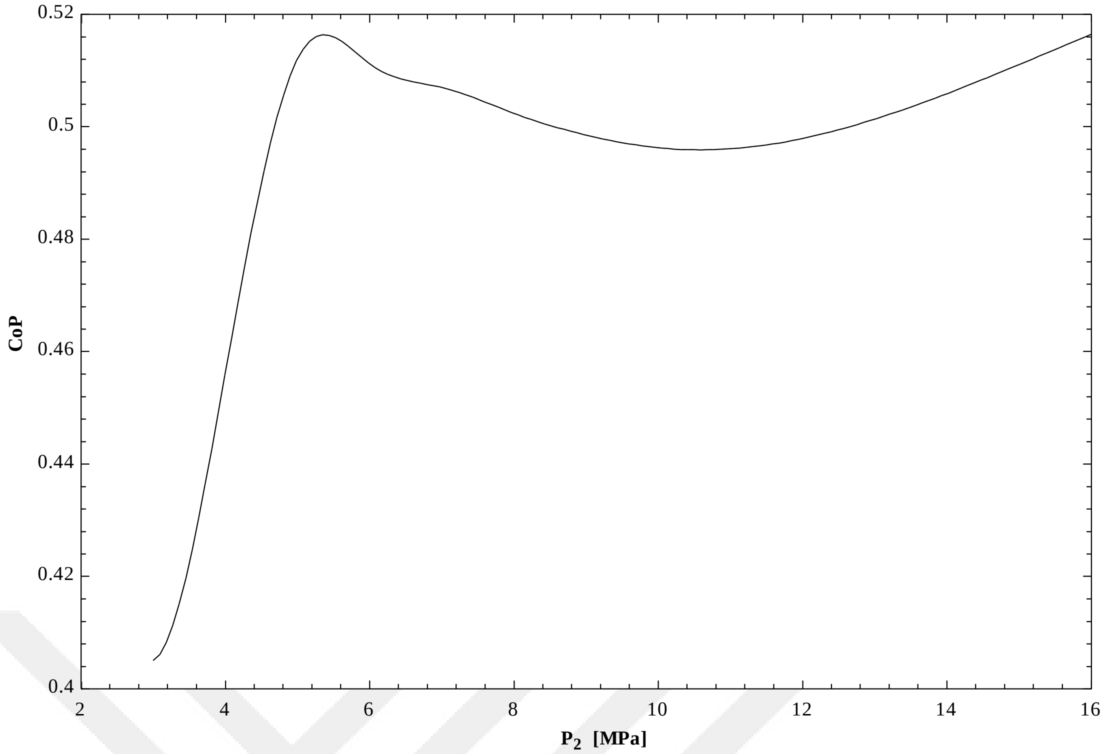


Figure 5.11 Effect of Compressor Outlet Pressure on the COP of the Claude cycle for Methane

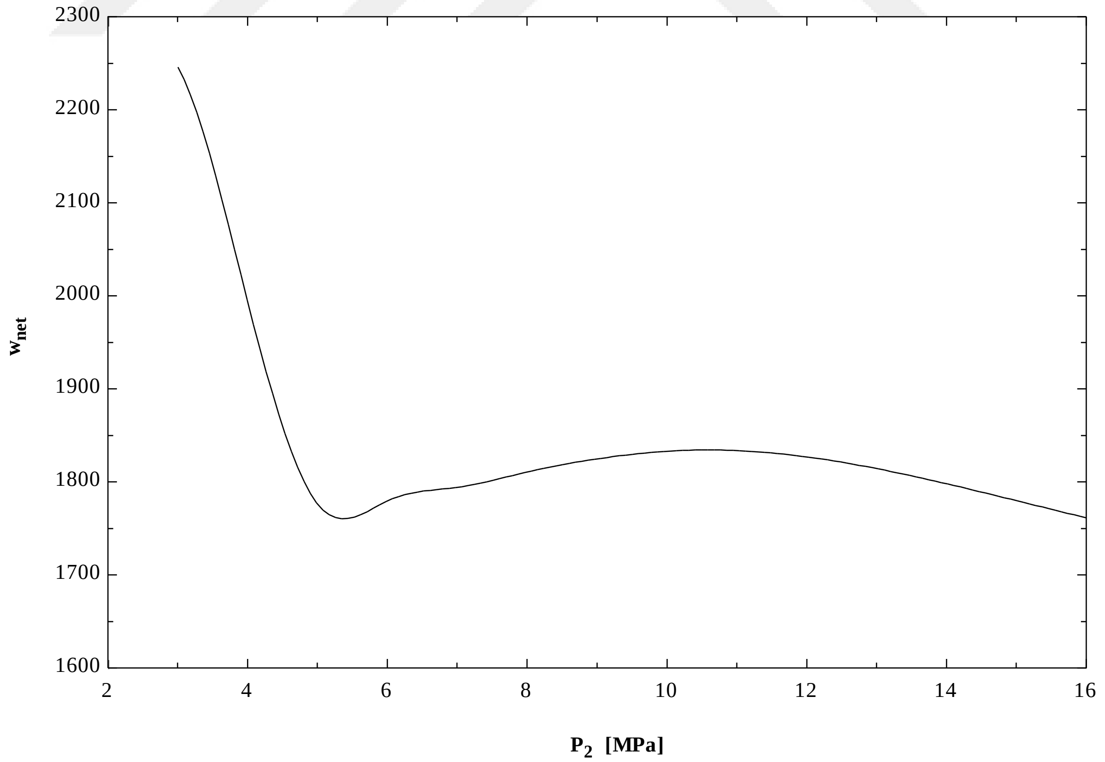


Figure 5.12 Effect of Compressor Outlet Pressure on the Net Work Input of the Claude Cycle for Methane

5.5 Effect of The Heat Exchanger Effectiveness

The performance of heat exchanger is one of the main parameter on the thermodynamic performance of the liquefaction cycle. The efficiency of the cycle greatly depend on the effectiveness of the heat exchanger. Claude cycle has three heat exchangers.

Table 5.1 shows the effect of heat exchanger effectiveness on the net work input and liquefied mass fraction. It is clear from the data in Table 5.1 that as the effectiveness increases, the work input decreases and the liquefied mass fraction increases. A higher effectiveness means a higher rat of heat removal from the gas. As the effectiveness changes from 95 to 100%, the liquefied mass fraction increases by about 6%, which is significant.

Table 5.1 Effects of heat exchanger effectiveness on the net work input and liquefied mass fractions.

ε	w_{net} (kJ/kg)	y
0.99	1181	0.2456
0.98	1198	0.2424
0.97	1215	0.2391
0.96	1233	0.2358
0.95	1252	0.2325
0.94	1271	0.2292
0.93	1291	0.2258
0.92	1312	0.2223
0.91	1334	0.2189
0.90	1357	0.2154

The effect of the effectiveness of the heat exchangers on the net work input of the cycle is given in Fig. 5.13. The figure gives the effects of each heat exchanger and all heat exchangers. The relative importance of a particular heat exchanger can be observed in the figure. Heat exchanger 3 appears to have the most effect on the work input as compared to heat exchangers 1 and 2.

Figure 5.14 shows the effect of heat exchanger effectiveness on the COP of the system. Again the effects of heat exchanger 1 and heat exchanger 2 are less than that of heat exchanger 3. As the effectiveness of all heat exchangers increase from 90% to 99%,the COP increases from 0.31 to 0.36. The effect of heat exchanger effectiveness on the second-law efficiency is given in Fig.5.15 and its effect on the liquefied mass fraction is given in Fig.5.16. The trends in these two figures are similar. The figures show that there is a significant change in the performance of the liquefier if the effectivenes of all the heat exchangers are increased simultaneously as compared to an increase in the effectiveness of an individual heat exchanger.

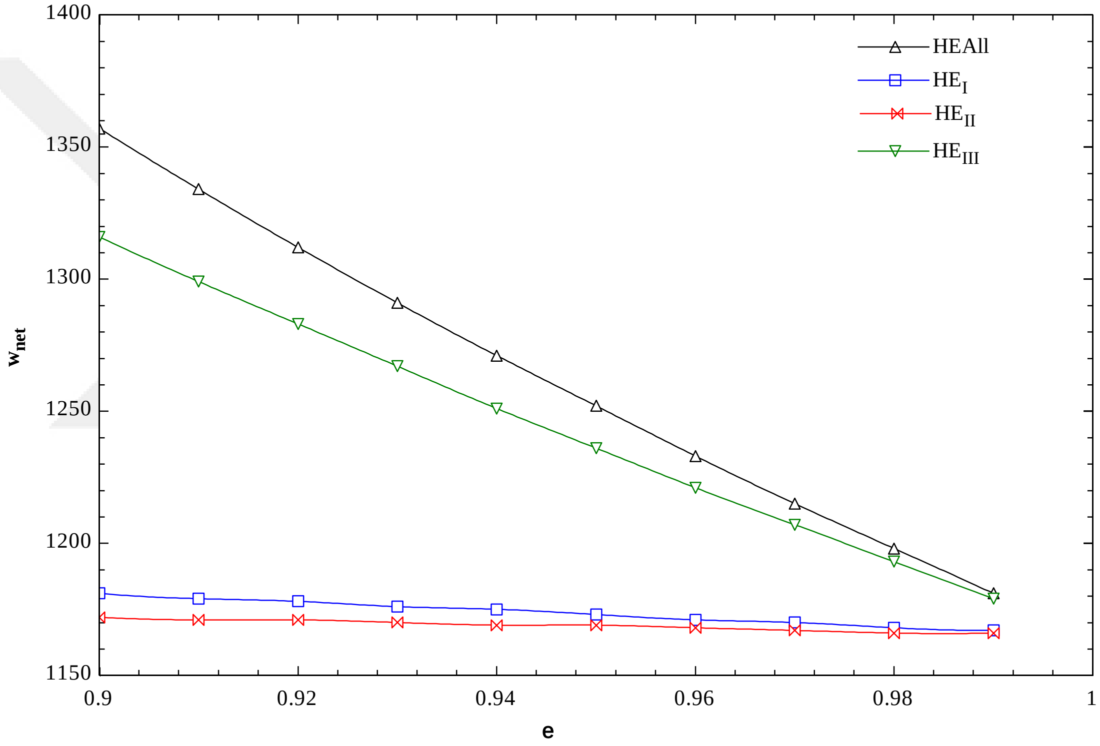


Figure 5.13 Effect of Heat Exchanger Effectiveness on the Work Consumption

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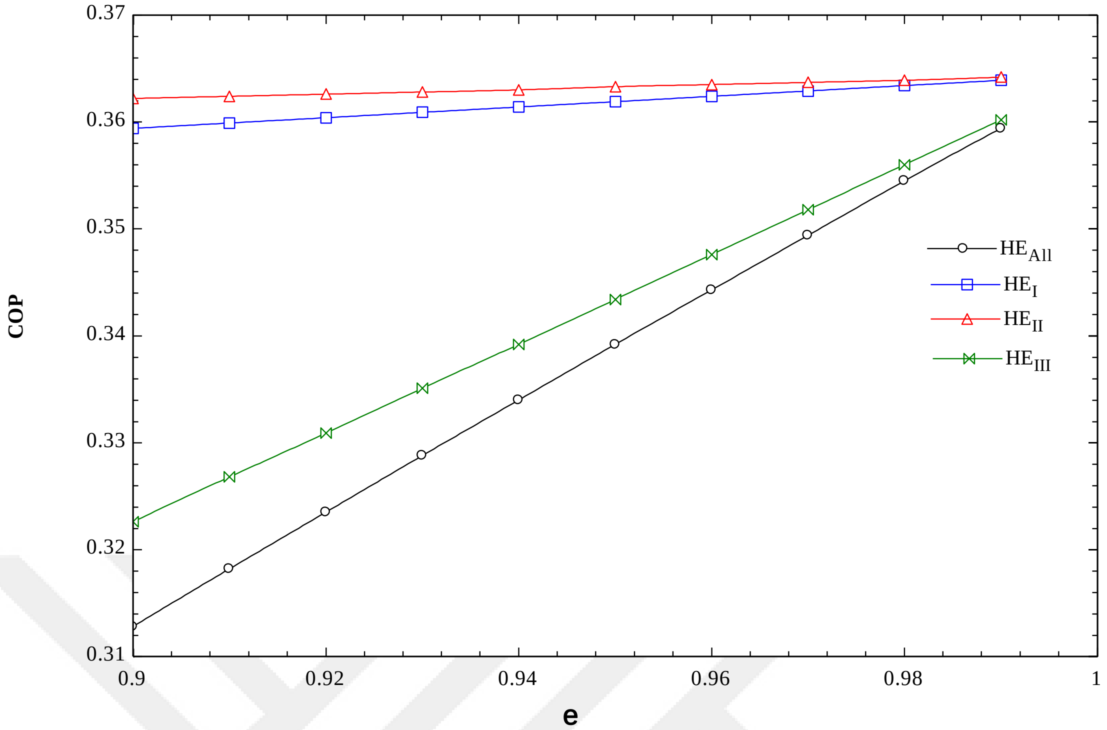

Figure 5.14 Effect of Heat Exchanger Effectiveness on the Coefficient of Performance

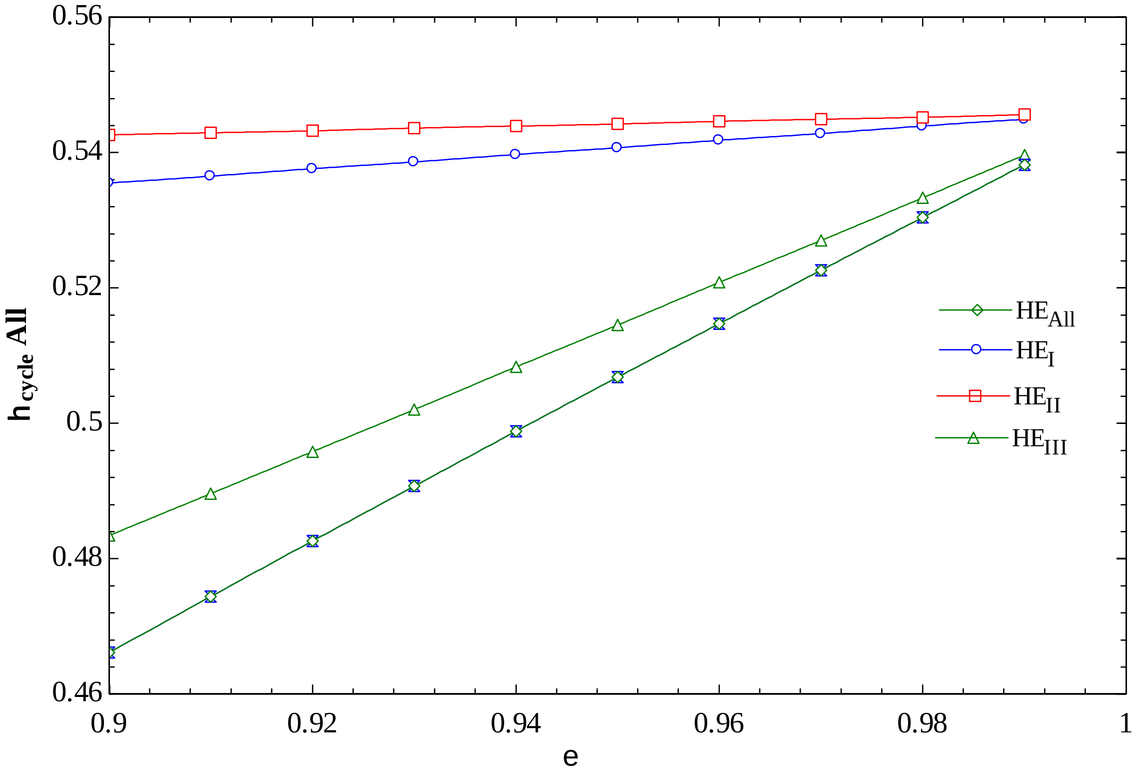

Figure 5.15 Effect of Heat Exchanger Effectiveness on the Second Law Efficiency

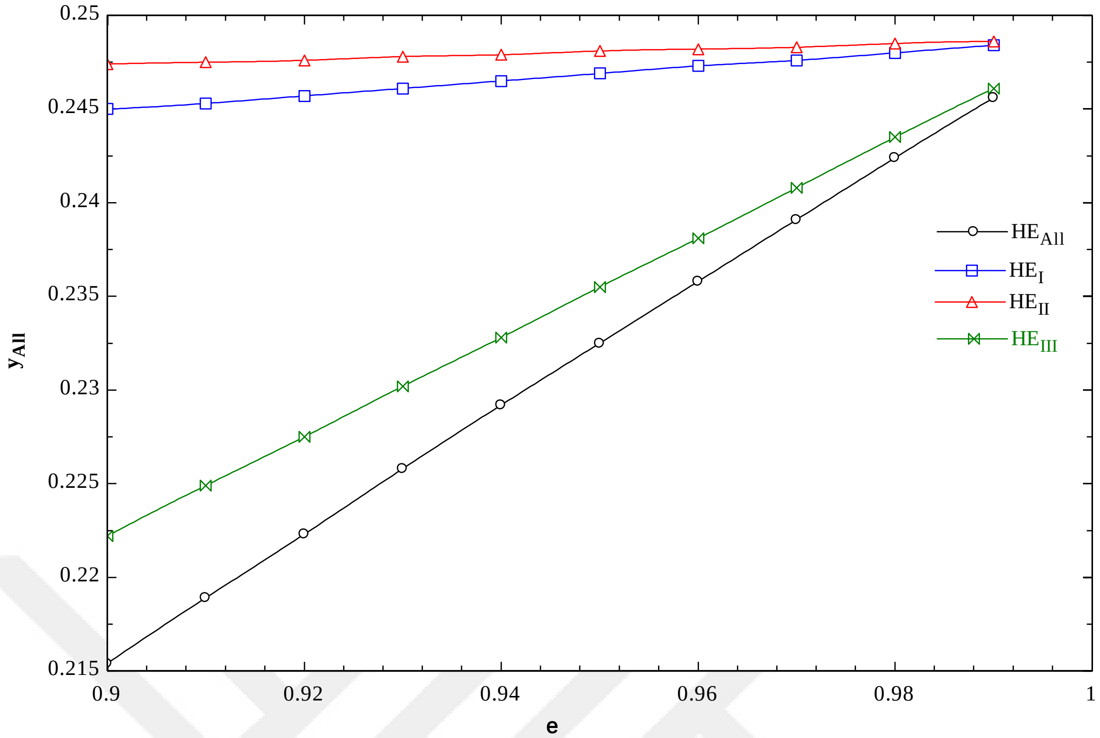

Figure 5.16 Effect of Heat Exchanger Effectiveness on the Liquild Yield

5.6 Effect of Expander Flow Ratio

In liquefaction cycles, the expander flow ratio is an important parameter affecting the performance of the cycle. Mass fraction diverted to the expander is proportional to the refrigeration effect produced by the expander. By increasing mass fraction diverted to the expander, more cooling can be achieved and more liquid yield can be obtained. However, this decreases the amount of returning gas and the associated precooling effect in heat exchangers. This is why the fraction of gas diverted to the expander should be optimized for maximum system performance.

The effect of expander flow ratio on the second-law efficiency of the Claude cycle is given in Fig. 5.17. The efficiency increases with the expander flow ratio, reaches a maximum, and decreases. Therefore, there is an optimum flow ratio that mazimizes the system performance. It is observed to be 0.76 for air (Fig. 5.17). It also appears that the second-law efficiency varies greatly as the expander flow ratio changes between 0.1 and 0.9. Fig. 5.18 gives the effect of expander flow ratio on the COP of the cycle. Fig. 5.19 gives the effect of expander flow ratio on the liquefied mass fraction. The trends in Figures 5.18 and 5.19 are very similar to that in Fig. 5.17, and the same optimum point is observed.

Figure 5.20 shows the effect of expander flow ratio on the the net work input. The analysis is done at 4, 10, and 20-MPa pressures. It is observed that a different optimum flow ratio is obtained at three different pressures. When the expander flow ratio increases, the liquefaction effect produced by the expander increase, and more liquid yield is obtained. On the other hand, this decreases the precooling of the gas in the heat exchangers. The optimum values of expander flow ratio are around 0.7. Note that the trend is for air but is similar for other gases.

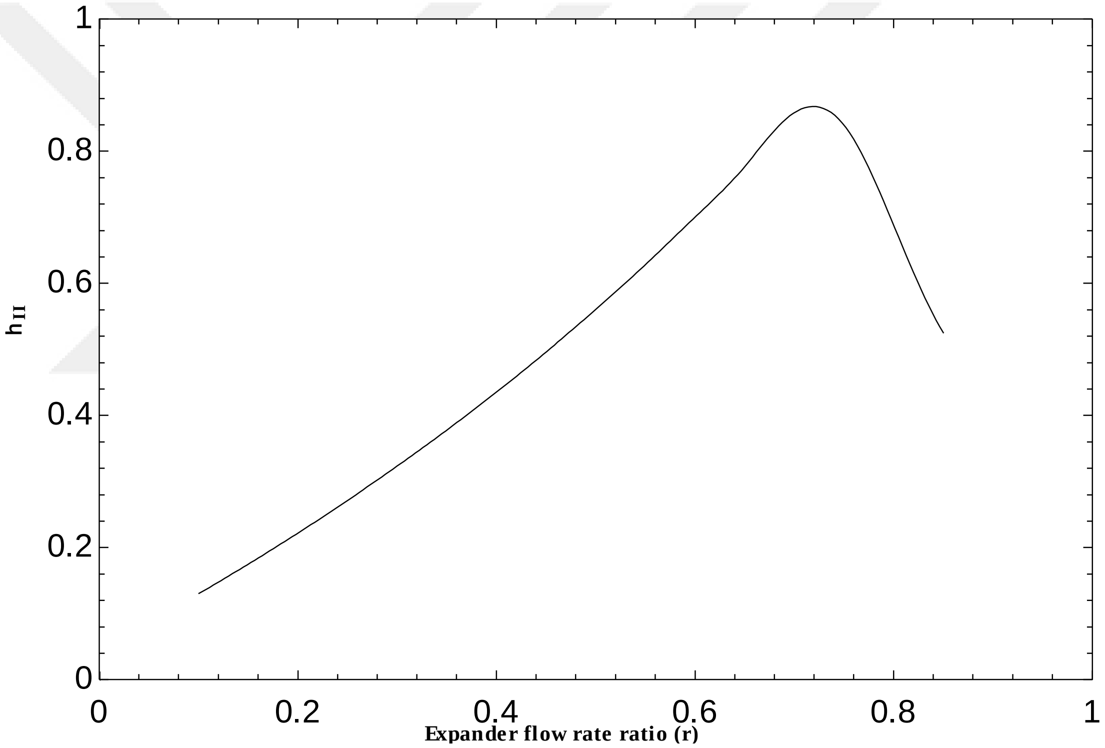

Figure 5.17 Effect of Expander Flow Rate Ratio on the Second Law Efficiency

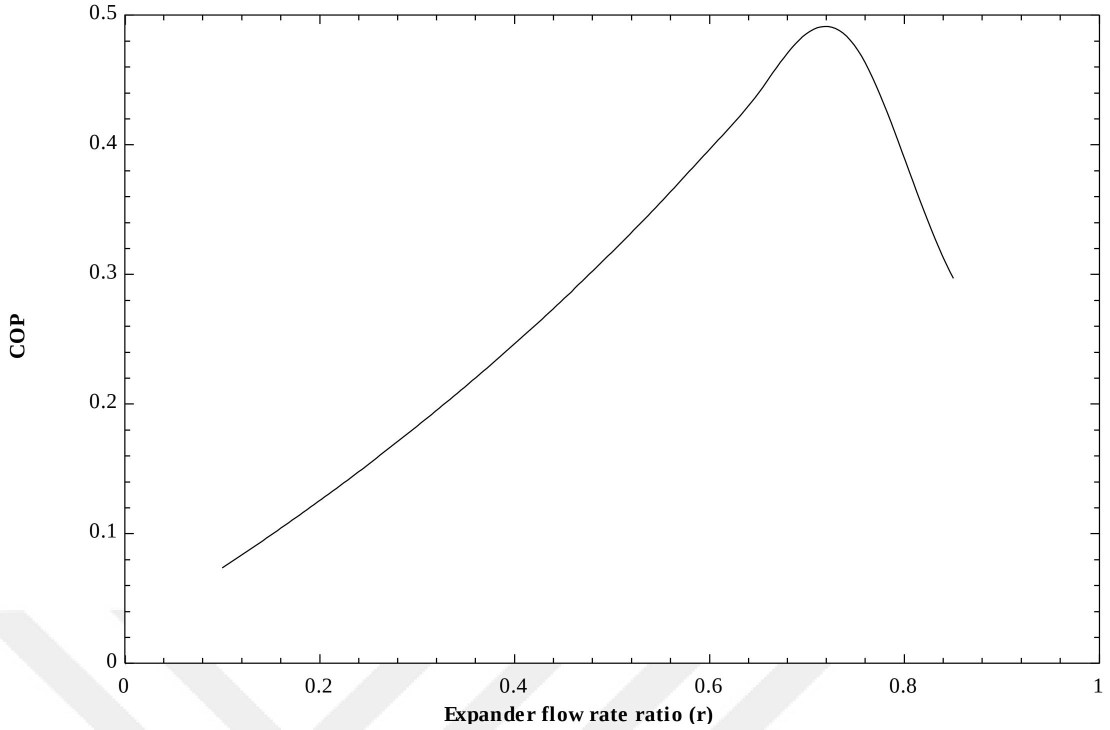

Figure 5.18 Effect of Gas Expander Flow Ratio on the Coefficient of the Performance (COP)

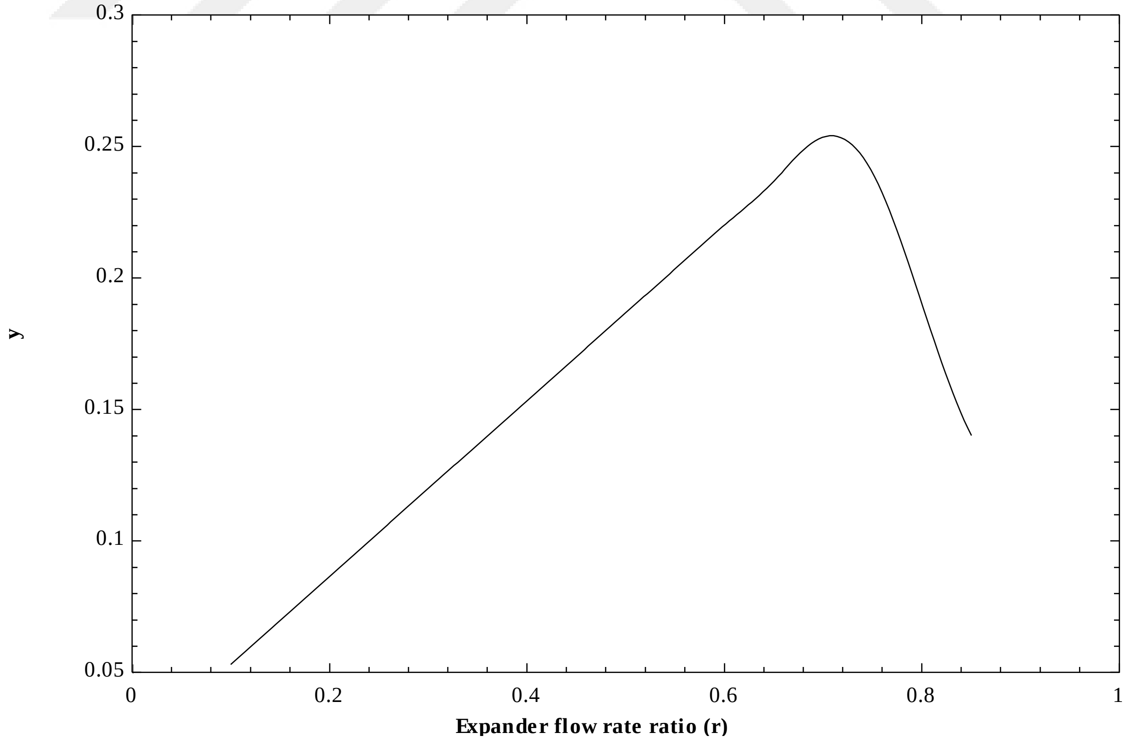

Figure 5.19 Effect of Gas Expander Flow Ratio on the Liquefied Mass Fraction

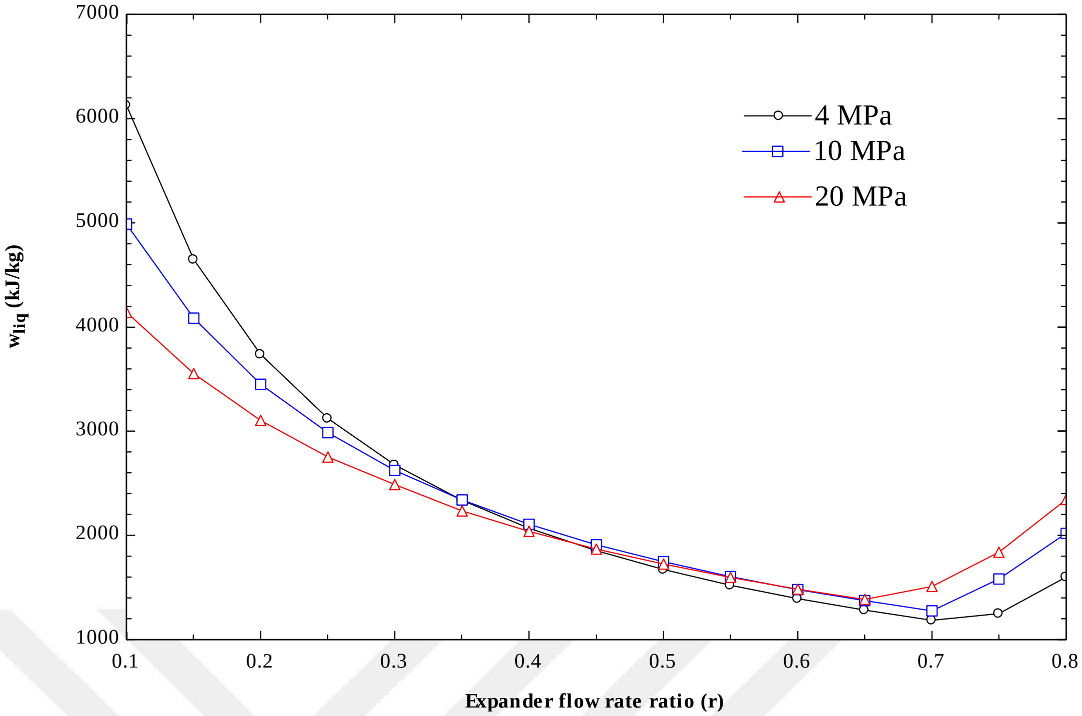

Figure 5.20 Effect of Gas Expander Flow Ratio on the Second Law Efficiency for Air

5.7 Conclusions

In this chapter, the effect of some main operating parameters on the performance of the Claude gas liquefaction cycle is studied. These operating parameters include gas inlet temperature, liquefaction temperature, compressor outlet pressure, expander flow ratio, and heat exchanger effectiveness. The effects of these parameters on the net work input, liquefied mass fraction, COP, and second-law efficiency are investigated. The analysis yields some optimum points for the compressor outlet pressure (around 5 MPa) and expander flow ratio (around 0.7).

CHAPTER 6

CONCLUSIONS

Cryogenics is used in a wide range of fields, from industrial to medical applications. Liquid oxygen and liquid nitrogen are used in the steel industry to remove carbon from molten iron. Liquid nitrogen is commonly used for food freezing. Cryogenic recovery techniques are used for recovery of scrap metals, rubber tires and other materials in car industry. On the other hand, cryogenic applications are used in transportation of natural gas, storage of energy as hydrogen, and superconducting magnets for energy storage. Liquefaction of gases is a major area of cryogenics and it is associated with great amounts of energy consumption. Therefore, minimizing energy use is the main objective in the analysis and optimization of liquefaction cycles.

In this thesis, common gas liquefaction cycles are introduced and thermodynamic analysis and optimization of Claude liquefaction cycle is performed. Claude liquefaction cycle works under relatively low pressures compared to the other gas liquefaction cycles. The analysis is done in computer environment using EES program. Parametric studies are done to investigate effects of certain operating parameters on the performance of Claude cycle. Optimum operating conditions that maximize system performance by minimizing the work consumption are determined. Common gases including air, oxygen, nitrogen, argon, methane, and fluorine are considered. In parametric studies, gas inlet temperature, liquefaction temperature, compressor outlet pressure, effectiveness of heat exchangengers, and expander flow ratio are varied. In thermodynamic analysis of Claude cycle, liquid yield, net work input, COP, and second law efficiency are used as performance parameters. The performance of the actual cycle is obtained under assumed operating conditions and compared to that of an ideal liquefier. Parametric calculations of liquid yield, specific work requirement, COP, and second-law efficiency have led to the optimization of compressor outlet pressure and expander flow ratio.

We summarize main findings of the study as follows:

1. Thermodynamic analysis of Claude liquefaction cycle indicates that the COP value is the highest for methane (0.386), second-law efficiency is the highest (57.5%) for nitrogen, and work consumption is the lowest for argon (968 kJ/kg liq or 493 kJ/kg gas).

2. The results show that heat exchanger effectiveness has a significant effect on the performance of the cycle. Higher effectiveness values are obtainable using more heat transfer surface areas. However, there is a limit to this due to cost considerations. It is no surprise that the heat exchangers used in liquefaction cycles usually have effectiveness values higher than 90%.

3. Gas liquefaction cycles should be operated at the highest liquefaction temperature possible. This is because as the liquefaction temperature increases the work consumption for a given liqued yield decreases.

4. The use of an expander in Claude cycle improves the system efficiency by decreasing the total work consumption in the cycle. At the same time, the liquefaction produced in the cycle is directly proportional to the mass flow rate directed to the expander. By increasing the mass diverted to the expander, more cooling can be achieved, and more liquid yield can be obtained. However, this also decreases the amount of returning gas, and consequently precooling effect in heat exchangers is reduced. There is an optimum value for the fraction of gas diverted to the expander. This value is determined to be between 0.6 and 0.8. Another advantage of an expander over a Joule-Thompson (J-T) valve is that the temperature of the gas is lower at expander outlet in comparison to the outlet of a J-T valve [54].

5. Claude cycle works under relatively low pressures compared to the other gas liquefaction cycles. A study of optimum compressor outlet pressure indicates that the value varies between 4 and 8 MPa. In this study, the value for methane and air are obtained to be around 5 MPa.

6. Expander inlet temperature is another important parameter for optimum operation of Claude cycle. At higher temperatures,liquefaction effect and work producedby the expander increase, but the liquefaction effect produced by the valve

decreases. In this study,the optimum operating conditions are determined for air as: $P_2 = 4.25$ MPa (compressor outlet pressure), $T_3 = -29.6$°C (expander inlet temperature) and $r = 0.6$ (expander flow ratio).

7. As the inlet gas temperature increases the work consumption increases, the liquid yield decreases, the COP decreases, and the second-law efficiency decreases. Therefore, the gas should enter the cycle at the lowest temperature possible.

8. This study can be be useful in better understanding of the liquefaction cycle and the design of more efficient liquefaction processes.

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