ENERGY AND EXERGY ANALYSIS FOR CRYOGENIC PROCESS DESIGN/RETROFIT

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ABSTRACT

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Keywords: Energy analysis/ Exergy analysis/ Cryogenic process/ Optimization/ Process design

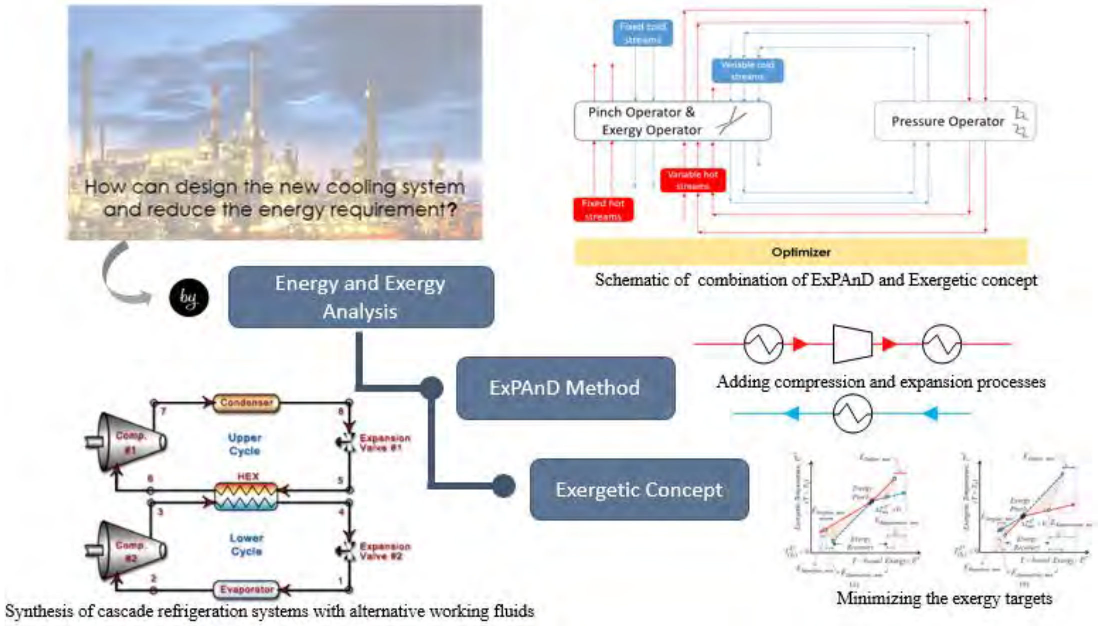
Energy and Exergy analysis are one of alternative techniques to analyze chemical processes in term of energy quality parameters such as enthalpy, entropy and exergetic temperature. The exergetic temperature can conduct Exergy Composite Curves diagram (ECCs) (Marmolejo-Correa, 2012) which represents exergy targets: exergy requirement, exergy rejection and exergy destruction etc. In addition, these targets can be used for improving processes. The strength points of these analysis are to design the new process and to improve the utility performance. Therefore, these analysis methods have been applied to low-temperature process that requires a large amount of energy consumption. In this work, there are two approaches of energy minimization. First model, a combination with ECCs diagram and mathematical programing (Wechsung, 2011) can synthesize a better design of process to reduce utility usage. Second model, a synthesis of cascade refrigeration systems (Colmenares, 1989) can indicate a configuration of refrigeration systems with alternative working fluids for minimizing the energy used by condenser and compressor. Besides that, these models were applied to a liquefied natural gas (LNG) production as a case study which comes from the Pro/II's tutorial (commercial engineering software). The results show that the Exergy and Energy analysis have an ability and potential to design new synthesis for cooling systems for sub-ambient processes and a combination of heat exchanger with compression and expansion processes.

บทคัดย่อ

ณัฐวัฒน์ ธีระชาญณรงค์ : การวิเคราะห์พลังงานและเอ็กเซอร์จีสำหรับการออกแบบและการปรับปรุงของกระบวนการที่มีการดำเนินการที่อุณหภูมิต่ำ (Energy and Exergy Analysis for Cryogenic Process Design/Retrofit) อ. ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ กิตติพัฒน์ สีมานนท์ 138 หน้า

การวิเคราะห์กระบวนการอุตสาหกรรมเคมีโดยการใช้ พลังงาน และเอ็กเซอร์จี เป็นหนึ่งในวิธีการวิเคราะห์พลังงานโดยอาศัยคุณภาพพลังงาน เช่น เอนทาลปี, เอนโทรปีและ เอ็กเซอร์เจติกเทมเพอเรเจอร์ โดย เอ็กเซอร์เจติกเทมเพอเรเจอร์ สามารถนำมาสร้างกราฟเอ็กเซอร์จีคอมโพสิทเคฟ (ECCs) (Marmolejo-Correa, 2012) ซึ่งกราฟนี้สามารถบ่งชี้ เอ็กเซอร์จี้ทารเก็ตหรือเป้าหมายที่สามารถนำมาประยุกต์ใช้ในการปรับปรุงกระบวนการให้มีประสิทธิภาพมากขึ้น เช่น exergy requirement, exergy rejection และ exergy destruction เป็นต้น โดยที่ข้อดีของการวิเคราะห์นี้คือสามารถนำมาใช้ในการออกแบบกระบวนการและใช้ในการปรับปรุงคุณภาพของพลังงานในกระบวนการให้ดียิ่งขึ้น ดังนั้นการวิจัยนี้ จึงนำการวิเคราะห์ในรูปของพลังงานและเอ็กเซอร์จีมาประยุกต์ใช้ในกระบวนการที่มีการดำเนินการที่อุณหภูมิต่ำ แต่มีการใช้พลังงานจำนวนมาก โดยงานวิจัยนี้มีการศึกษาวิธีการลดการใช้พลังงาน 2วิธี ดังนี้ วิธีแรก คือ การนำ กราฟECCs มาประยุกต์ร่วมกับโมเดลการคำนวณทางคณิตศาสตร์ (Wechsung, 2011) ซึ่งสามารถนำมาใช้ในการออกแบบกระบวนการใหม่ที่มีการใช้พลังงานในกระบวนการที่ลดลง วิธีที่สอง คือ การออกแบบวัฏจักรทำความเย็นแบบหลั่นร่วมกับสารทำความเย็นประเภทต่างๆที่เหมาะสม (Colmenares, 1989) เพื่อลดการใช้พลังงานโดยเครื่องควบแน่น (condenser) และเครื่องอัดไอ (compressor) โดยงานวิจัยจะนำ การวิธีการลดพลังงานทั้ง2วิธี มาประยุกต์ใช้กับ กระบวนการเปลี่ยนแก๊สธรรมชาติให้อยู่ในสถานะของเหลวโดยถูกนำมาจากกรณีศึกษาของโปรแกรมออกแบบกระบวนการผลิต (Pro/II V9.4) ผลการวิจัยพบว่าการวิเคราะห์กระบวนการอุตสาหกรรมในรูปของพลังงานและเอ็กเซอร์จี สามารถนำมาประยุกต์ใช้ในการออกแบบระบบทำความเย็นสำหรับกระบวนการที่มีการดำเนินการที่อุณหภูมิต่ำ และการออกแบบเครื่องแลกเปลี่ยนความร้อนร่วมกับกระบวนการเพิ่มความดันและลดความดัน

GRAPHICAL ABSTRACT



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CHAPTER I
INTRODUCTION

Most of sub-ambient chemical industries have used cryogenic process to keep process below ambient temperature according to boiling point of refrigerant. Normally, cryogenic process has used expansion process or refrigeration system as cooling system to decrease below room temperature to operating temperature. It meant cryogenic process had a high energy consumption on cool utility and also high utility cost on both of hot and cold utilities. Many industries have tried to solve these mentioning problems with heat recovery systems by reducing cold utility consumption or changing thermodynamic properties; such as temperature and pressure. Therefore, there are many developed methods for sub-ambient processes such as Heuristic Rules, Pinch Analysis, Exergy Analysis, Synthesis of Cascade refrigeration systems and Deterministic Optimization method etc.

A number of synthesis methods have been developed for reducing the consumption of external energies (heating, cooling and power) since the 1970s. Pinch analysis (PA) (Linhoff and Hindmarsh, 1983) is a usual method that used for identifying pinch temperature designing heat exchanger network (HEN) by heat integration; as known in arrangement of heat exchanger that can improve energy efficiency in process; to minimize both utility consumption and areas of HEN. However, PA is not suitable to use in sub-ambient processes, this method has only temperature as a design variable and pressure are not considered.

In sub-ambient process, pressure is more important because pressure can reduce work from compressor and expansion for phase changes. Another method is an Exergy Analysis (EA) for measuring the minimum exergy required or excessed by the heat recovery system. Especially, Pressure, temperature and composition are the main variable utilized for exergy calculation of streams. Consequently, the combination of PA and EA (Linnhoff and Dhole, 1992) used for optimization of heat recovery and work in sub-ambient process by using the Exergy Composite Curves (ECCs) that used enthalpy as x-axis and Carnot factor as y-axis to measure exergy loss from area between hot streams and cold streams due to heat transfer. In order to manipulate a condition of pressure, Extended Pinch Analysis and Design (ExPAnD) (Aspelund et al., 2007) is a new methodology with 10 Heuristic Rules used for an integration of compressor and expansion into HEN to utilize heating and cooling generated for sub-ambient process. Furthermore, exergetic temperature (Marmolejo-Correa, 2012) is proposed as a new energy parameter for conducting new energy diagram which represents exergy targets: exergy requirement, exergy rejection and exergy destruction. These targets can be used for optimization to utilize external energy. Moreover, Mathematical Programing has been combined with PA and EA to improve energy efficiency. Although, a combination with energy and exergy analysis can reduce energy consumption, synthesis of Cascade refrigeration systems (Colmenares, 1989) which is one of energy analysis is also useful method to reduce the energy used by compression and cooling process.

In this research, the main objective is to study methods for sub-ambient process and to optimize or reduce energy consumption by heat duty and shaft work in this process, which tries to increase annual profits and reduce annual expenses. Concerning heat recovery system with compression and expansion process, Exergy analysis (exergetic concept) is applied to energy analysis (pinch method) to improve energy performance in sub-ambient process likes Gas separation plant and Liquefied natural gas (LNG) production which they needs the cooling system.

CHAPTER II
LITERATURE REVIEW

Many products from petrochemical industry such as plastic and resin are produced from natural gas in Gas separation plant or upstream process. The main energy consumption for producing in cryogenic process is cooling system to separate product gases for sales. Actually, refrigeration system is a usual process to cool hot stream by heat pump. Hence shaft-work and heat duty used by compressor and condenser, respectively, in this heat pump are concerning to be optimized by many methods.

2.1 Refrigeration System

Refrigeration system has been defined as the process of extracting heat from a lower-temperature heat source and transferring it to a higher-temperature heat sink. A refrigeration system is a combination of equipment and cooling-fluid (refrigerant) that consists mainly 2 parts which are evaporator (low pressure part) and condenser (high pressure part) that shown in Figure 2.1.

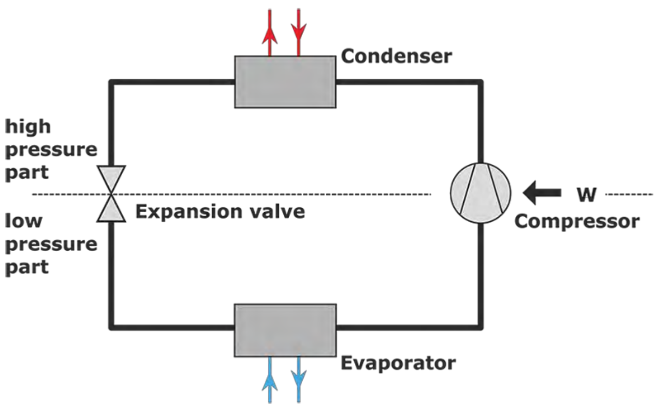

Figure 2.1 Refrigeration system.

In Figure 2.1, compressors obtains work and compress refrigerant to a higher pressure and temperature as a gas phase. The compressed refrigerant transfers to condense by condenser unit that taking energy out from fluid and changing to liquid form. Then liquid refrigerant passes through expansion valve or throttling valve to decrease pressure and temperature as well. The expanded fluid evaporates by evaporator unit. After that, refrigerant has flowed again in this cycles to cool process.

2.1.1 Configuration of Refrigeration

2.1.1.1 Carnot Refrigeration Cycle

The Carnot refrigeration cycle is defined as a reverse engine cycle that is an ideal case or simple system. Consequently, a Carnot refrigeration cycle is composed of 4 reversible processes as shown in Figure 2.2 (a) and 2.2 (b) and followed:

1. An isothermal process 4-1 which evaporated at constant temperature

2. An isentropic compression process 1-2 to increase pressure at constant entropy as a saturated gas

3. An isothermal process 2-3 which removed heat at constant temperature as a saturated liquid

4. An isentropic expansion process 3-4 at constant entropy

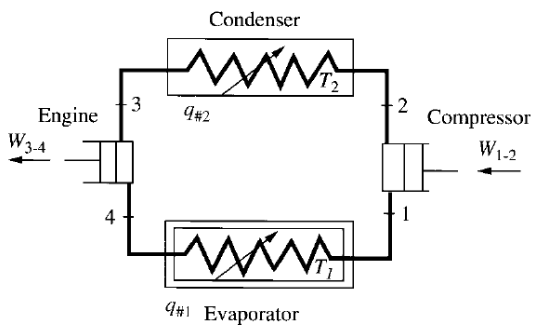

Figure 2.2 (a) Schematic diagram of carnot refrigeration cycle (Wang,2000).

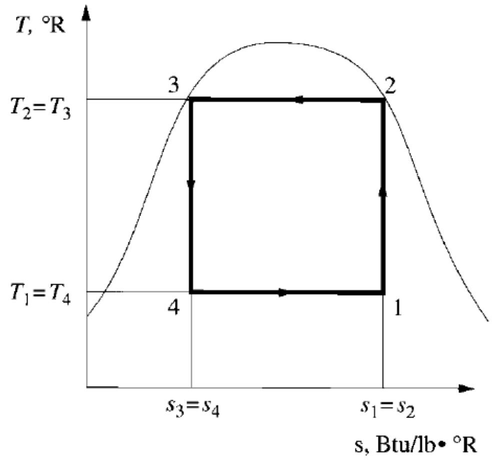

Figure 2.2 (b) T-S diagram of carnot refrigeration cycle (Wang,2000).

2.1.1.2 Single-Stage Ideal Vapor Compression Cycle

Single-stage means "this system have only one stage of compression in refrigeration system" that shown in Figure 2.3. Single-stage ideal vapor compressor cycle is used instead of Carnot cycle due to that method operate as superheated steam during compression to avoid compressor slugging damage. It has only one stage of compression, so it also has lower initial investment cost.

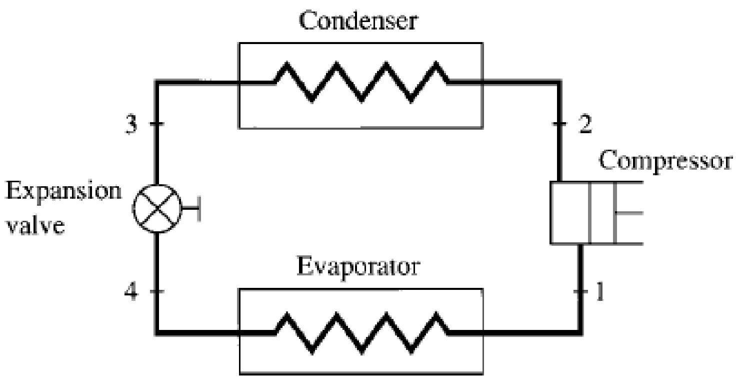

Figure 2.3 (a) Schematic diagram of single-stage ideal vapor compression cycle (Wang,2000).

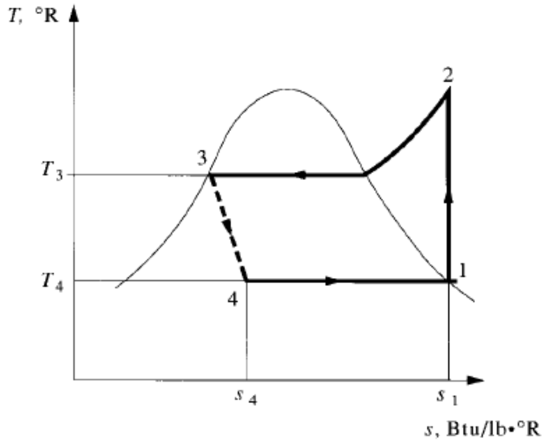

Figure 2.3 (b) T-S diagram of single-stage ideal vapor compression cycle (Wang,2000).

2.1.1.3 Multistage Vapor Compression Systems

When a refrigeration system is combined compressor more than one stage of compression like several compressor connected in series and system that has two separate refrigerant system or has a two which are a high-stage compressor and a low-stage compressor, it is called Multistage Vapor Compression Systems that shown in Figure 2.4.

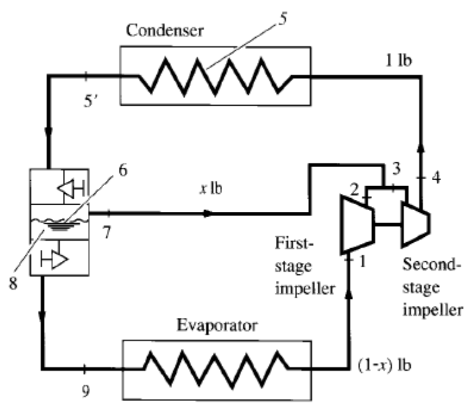

Figure 2.4 (a) Schematic diagram of multistage vapor compression systems (Wang,2000).

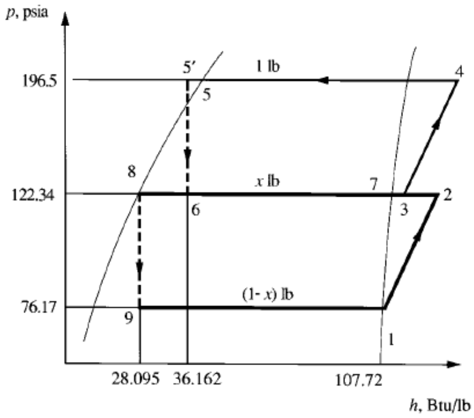

Figure 2.4 (b) T-S diagram of multistage vapor compression systems (Wang,2000).

It is used instead of single-stage system because the compression ratio between the ratio of the pressure of discharge and pressure of suction at compressor of each stage ($\frac{P_{dis}}{P_{suc}}$) is smaller than a single-stage system. Hence it can increase compressor efficiency. A combination of compressors has some advantage because it can obtain more efficiency and flexible operation than single-stage system. In addition, this method is feasible to reduce shaft-work at compressor. Nevertheless Multistage Vapor Compression Systems has higher capital investment and more complicated operating than single-stage.

2.1.1.4 Cascade Systems

A cascade system composes two separate single-stage refrigeration systems as a lower system and a higher system. These two systems are connected by a cascade condenser. A lower system's condenser becomes the evaporator of the higher system that means evaporator of higher system can obtain heat release from a lower system as shown in Figure 2.5.

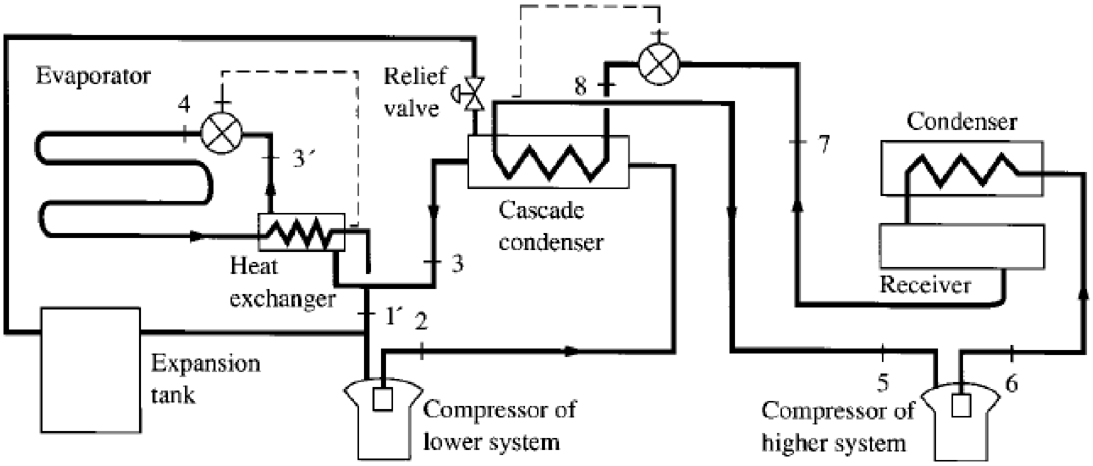

Figure 2.5 (a) Schematic diagram of cascade systems (Wang,2000).

The main advantage of cascade system is it has two separate refrigerant cycle, so it can manage or design suitably a different refrigerants or equipment in two sections. This is especially flexible when process need to apply with ultra-low-temperature operation but cascade still has some drawback which is more complicated than multi system due to the overlap of the condensing temperature of lower system and the evaporating temperature of the higher system.

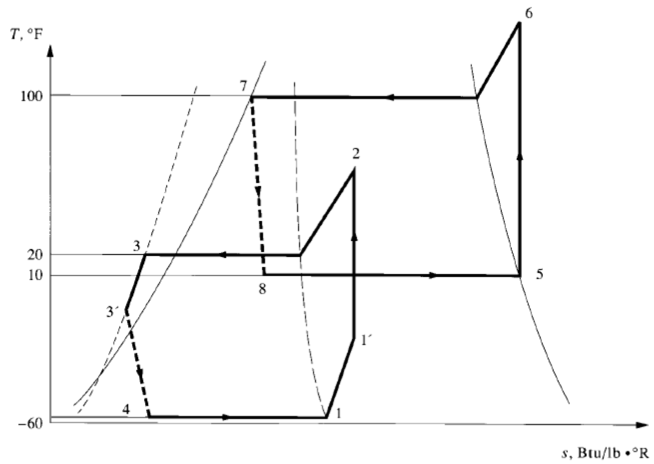

Figure 2.5 (b) T-S diagram of cascade systems (Wang,2000).

2.2 Fundamental Principle

2.2.1 Thermodynamic for Refrigeration System

2.2.1.1 First Law of Thermodynamic

The first law of thermodynamics is called the law of conservation of energy that means the net heat supplied to the system is equal to the net work done. In refrigeration system, it can simplify as follow:

Simplify first law: $W = Q_h - Q_c$ (2.1)

Q_h = heat injected in system

Q_c = heat rejected from system

W = net work done

2.2.1.2 Second Law of Thermodynamic

The second laws of thermodynamic can be explained in several ways. First, it is impossible to construct a heat engine which is 100% efficient. Hence a heat engine must be exhausted as heat loss. Another way is the entropy of an isolated system never decreases. It can only stay constant or increase.

Second law: $$\dot{S} = \sum_k \frac{\dot{Q}_k}{T_k} + \sum_k S^*{}_k + \sum_k \dot{S}_{ik} \quad (2.2)$$

Simplify second law: $$\frac{Q_h}{T_h} + \frac{Q_c}{T_c} = 0 \quad (2.3)$$

2.2.1.3 Refrigerator

A refrigerator is one of consequence with first law and second law of thermodynamics. The refrigerator is a cyclic machine similar to heat engine. This engine has main target to maintain the refrigerated space at a low temperature as shown in Figure 2.6.

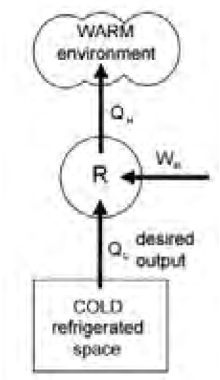

Figure 2.6 Schematic diagram of refrigerator (Bahrami, 2015).

Substitution Eq. (2.3) into Eq. (2.1), work of refrigeration can be obtained as following:

$$W = Qh\,\eta_{mech}\left(\frac{T_h - T_c}{T_h}\right) \tag{2.4}$$

η_{mech} is defined as a mechanical efficiency of the system

In this case, all of refrigerators operating are reversible process. Therefore, η_{mech} is equal to 1. Furthermore, Carnot efficiency indicates the maximum possible conversion of heat to work that can be calculated by:

$$\eta_c = \frac{T_h - T_c}{T_h} \tag{2.5}$$

T_h is defined as a temperature while fluid enters the engine

T_c is defined as a temperature while fluid leaves the engine

2.2.1.4 Coefficient of Performance of Refrigeration System

The coefficient of performance is defined as an index of performance of a thermodynamic cycle or a thermal system. COP is used instead of thermal efficiency because the COP value is possible to value more than 1.

The coefficient of performance (COP) is defined as the ratio:

$$\mathrm{COP} = \frac{Q_c}{W} \tag{2.6}$$

The Carnot efficiency of refrigerators is defined as the maximum ratio of COP following as:

$$\eta = \frac{T_c}{T_h - T_c} \tag{2.7}$$

2.2.2 Pinch Analysis

Pinch Analysis (PA) (Linhoff and Hindmarsh, 1983) is one usual method for design of chemical process by using heat integration to maximize heat recovery between hot and cold steams and also minimize utility loads. Hence it can identify energy cost and design heat exchanger network (HEN). Pinch Analysis provides a target for the minimum energy consumption. Therefore, Composite curves (CCS) is demonstrated as a tool to determine the energy targets. Composite curves is a graphical representations with temperature and enthalpy that shown in Figure 2.7.

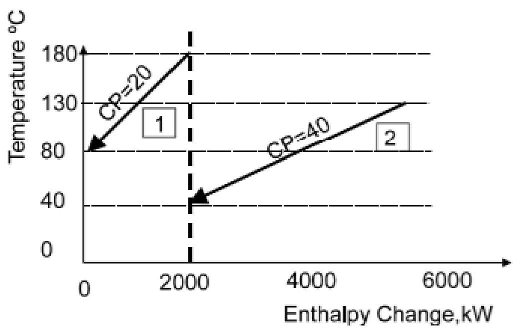

Figure 2.7 Construction of composite curve (Linhoff, 1998).

The construction of the composite curve shown in Figure 2.7 is a hot composite that shown enthalpy changes of streams with temperature intervals. In this case, there are 2 hot streams which have different temperature intervals. In the temperature interval 180°C to 130°C, there is only one stream, thus the CP of the composite curve for this interval is equal to 20. In the temperature interval 130°C to 80°C, both of streams are presented. Therefore, the CP of two streams is equal to 20+40 =60. The other interval is 80°C to 40°C, it has only stream2, and hence the CP of composite is equal to 40 shown in Figure 2.8.

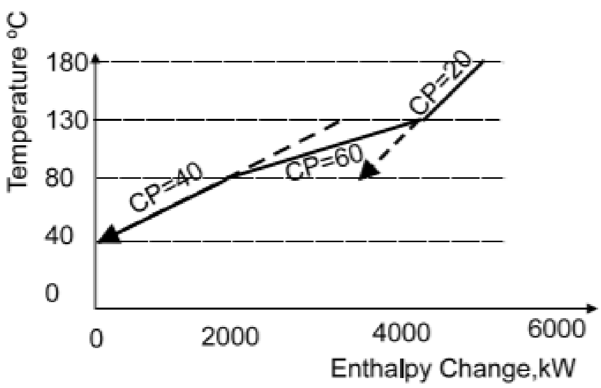

Figure 2.8 Construction of a combined composite curve with two streams (Linhoff, 1998).

A combination of hot-cold composite curves is shown in Figure 2.9. It can be determined the minimum energy target or consumption of utility and also shown the maximum heat recovery for heat exchanger network by using an overlap between hot stream and cold stream.

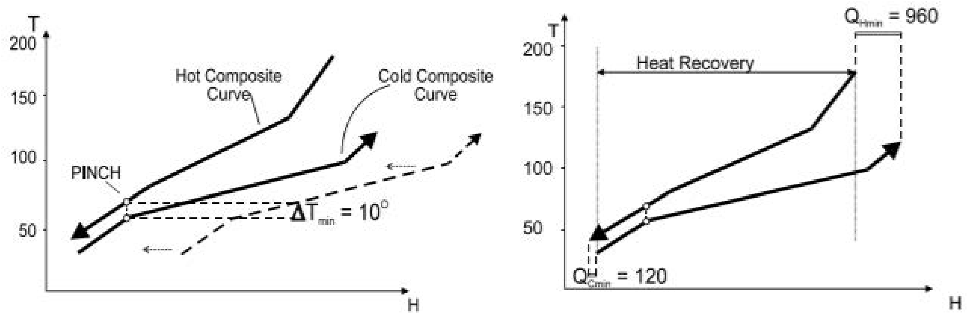

Figure 2.9 Using the hot and cold CCs to determine the energy target (Linhoff, 1998).

The point is shown in Figure 2.9 where ΔT_{min} is known as the "Pinch". It is identified to separate overall system into 2 systems: one is above pinch (heat sink) and the other is below pinch (heat source). The system above pinch required heat in to its system. On the other hand, the system below pinch rejected heat out from its system or cooled as shown in Figure 2.10. In addition, ΔT_{min} can identify utility consumption and area of heat exchanger network.

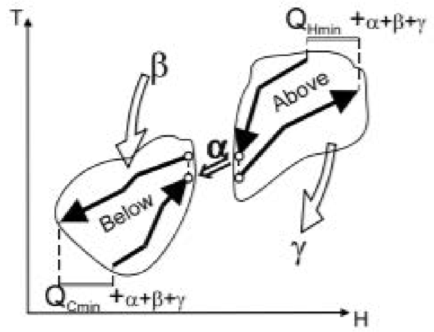

Figure 2.10 Pinch principle (Linhoff, 1998).

Grand Composite Curve is one of tool in pinch analysis method that is used for setting multi utility targets. This tool starts with composite curves as shown in Figure 2.11.

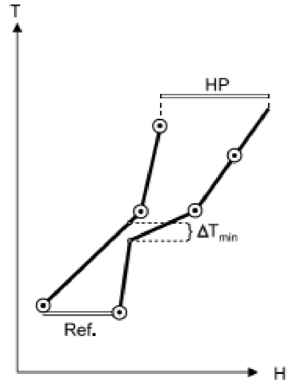

Figure 2.11 Composite curves (Linhoff, 1998).

First, adjust the temperature of composite curve by increasing the cold composite temperature by $\frac{\Delta Tmin}{2}$ and also decreasing the hot composite temperature by $\frac{\Delta Tmin}{2}$. This graph is called Shifted Composite curves as shown in Figure 2.12.

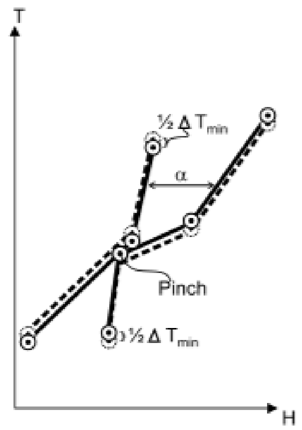

Figure 2.12 Shifted composite curves (Linhoff, 1998).

After that, plot the enthalpy in x-axis with shifted temperature. It is called Grand composite curve that used to provide the overall energy target and identify suitable utility for some part of process to minimize high cost utility using as shown in Figure 2.13.

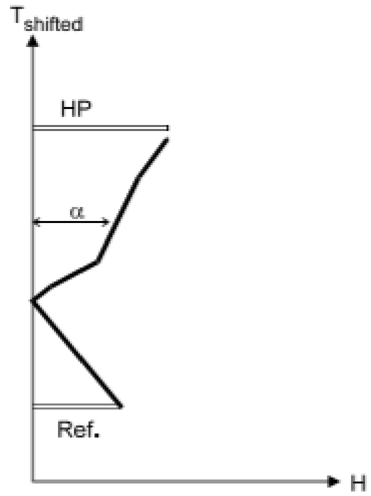

Figure 2.13 Grand composite curves (Linhoff, 1998).

2.2.3 Exergy Analysis

An Exergy is defined as the maximum amount of work that can be obtained from of energy using the environmental parameters as the reference state (Kotas, 1995). The reference state is assumed in equilibrium which is reversible process and to enclose all system. Like energy, exergy can transfer across the boundary system (i.e. heat) when an irreversible process occurs, exergy is destroyed that is called "exergy loss." An exergy is classified by the nature of its origin (i.e. potential, kinetic, or from a material stream) and be decomposed for a more detailed study. Hence there are many authors have proposed different classifications and decompositions of exergy in order to use different term describing for the same type of exergy. The exergy analysis is used to perform on many plants, for example a power station, a chemical processing plant, or a refrigeration facility like a cryogenic process. Exergy analysis uses various different thermodynamic values of different energy forms and quantities (i.e. work, heat).

Aspelund (2007) had proposed classification of exergy that shown in Figure 2.14, there were 2 types of exergy which are mechanical exergy and thermal exergy. The composition of a material stream related to Chemical exergy. The other exergy is Thermo-mechanical exergy as known in physical exergy depended on the temperature and pressure of stream. A mechanical exergy is composed with kinetic and potential similar to mechanical energy. A thermal exergy is composed chemical and thermo-mechanical exergy. In addition, a chemical exergy included when the process had chemical reactions, mixing and separation processes. Therefore, Aspelund focused mainly on thermo-mechanical exergy that based on only temperature and pressure.

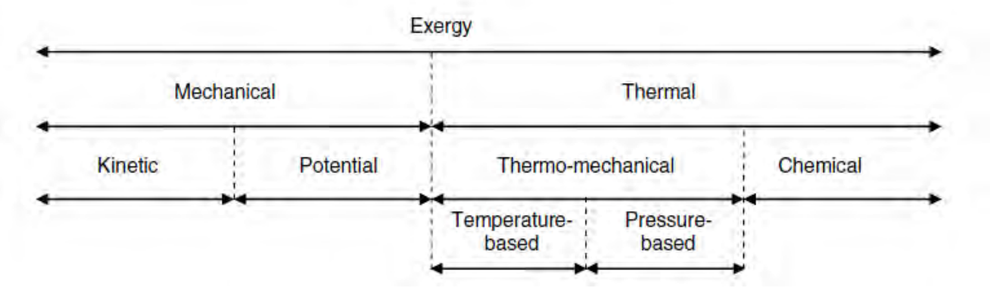

Figure 2.14 Classification of exergy (Aspelund, 2007).

Marmolejo-Correa (2012) had proposed their classification and decomposition using for open and closed system. The first level of classification is based on the type of carrier which are energy streams and material streams. The second level is based on exergy ratio of energy ($\frac{Exergy}{Energy}$) as known in the level of energy. A third level is classified by the exergy's origin as shown in Figure 2.15.

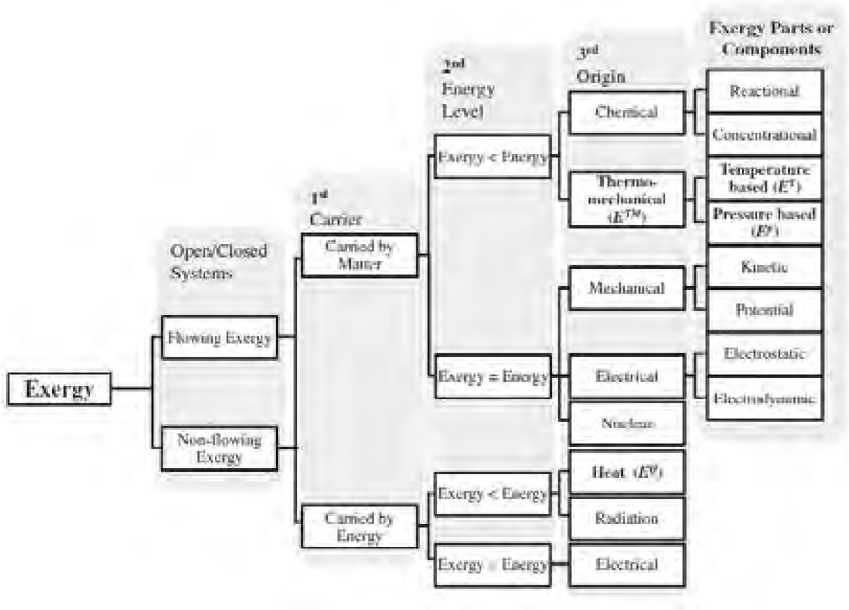

Figure 2.15 Classification and decomposition of exergy (Marmolejo-Correa, 2012).

2.2.3.1 Thermo-Mechanical Exergy

The thermo-mechanical exergy have 2 exergy parts which are temperature and pressure based. If the considered system are not include mechanical; the system rest with the environment, electrical and nuclear energies are not involved, the total exergy in a material stream ($\dot{E}$) can be decomposed into both of thermo-mechanical exergy (e^{TM}) and chemical exergy (e^{CH}) that is given by Eq. (2.8).

$$\dot{E} = \dot{m}(e^{TM} + e^{CH}) \quad (2.8)$$

The specific thermo-mechanical exergy (e^{TM}):

$$e^{TM} = [h(T,p) - h(T_0,p_0)] - T_0[s(T,p) - s(T_0,p_0)] \quad (2.9)$$

Or:

$$e^{TM} = e^{T} + e^{P} \quad (2.10)$$

Marmolejo-Correa (2012) had 2 components as e^{T} and e^{P}, respectively. As decompositions were used to make easier to analyze the exergy transfer in processes.

e^T is referred to a thermal exergy

e^P is referred to a mechanical or pressure exergy

Thus, the two components of thermo-mechanical exergy are defined as:

$$e^T = [h(T,p) - h(T_0,p)] - T_0[s(T,p) - s(T_0,p)] \quad (2.11)$$

$$e^P = [h(T_0,p) - h(T_0,p_0)] - T_0[s(T_0,p) - s(T_0,p_0)] \quad (2.12)$$

Kotas and Brodyansky (1995) had proposed a diagram related between exergy and enthalpy that illustrates the contributions of e^T and e^P as shown in Figure 2.16.

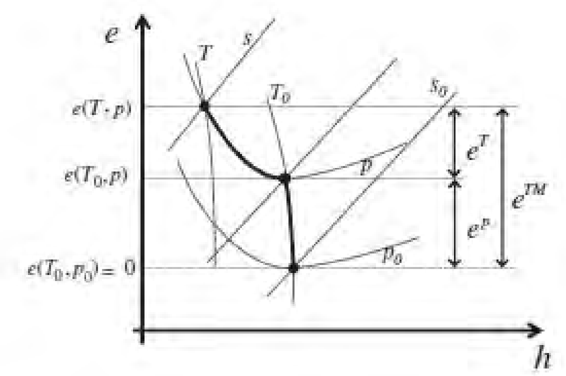

Figure 2.16 Contribution of decomposition in exergy and enthalpy diagram (Kotas and Brodyansky, 1995).

A special behavior below ambient temperature (T_0) is exhibited by the temperature based of thermo-mechanical exergy. According to Figure 2.17, this diagram show the minimum value (exergy = zero) is at ambient temperature. Moreover, both of above and below ambient temperature are positive exergy. Furthermore, whenever temperature more thanT_0, it affects to increase moderately an exergy's quantity. In other hand, temperature is less thanT_0, it afftects to decrease sharply a quantity of exergy as shown in Figure 2.17. Assumptions; firstly specific heat capacity is constant, secondly pressure is constant; are applied to Eq. (2.11). Therefore, it can be re-written as given Eq. (2.13) ($\frac{\dot{E}^T}{\dot{m} \bullet c_p}$) and plotted against temperature ratio ($\frac{T_0}{T}$) in Figure 2.17.

$$E^T = \dot{m} \bullet c_p \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right] = \dot{m} \bullet c_p \bullet T_0 [\frac{T}{T_0} - \ln \frac{T}{T_0} - 1] \qquad (2.13)$$

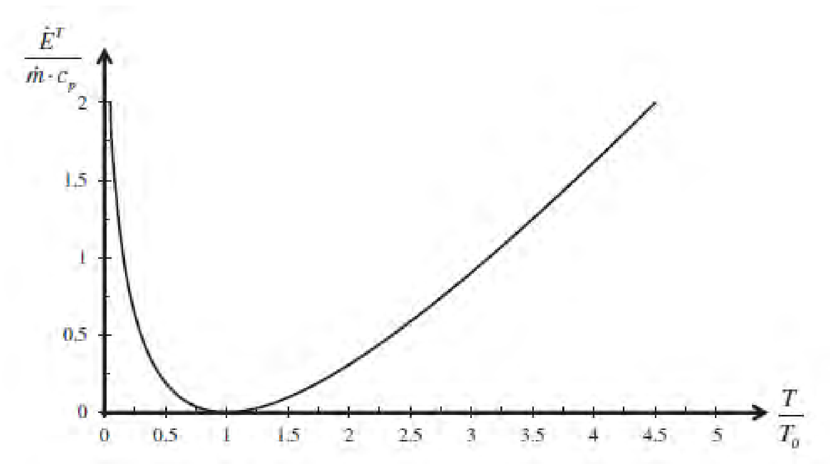

Figure 2.17 Temperature based of thermo-mechanical exergy (Marmolejo-Correa, 2012).

The difference of the required exergy to cool a process stream at below ambient temperature and the necessary exergy to warm the same process at above ambient temperature has a trend to increase further away from ambient temperature because the exergy to cool process stream is always more than the exergy to heat up the same process.

The other way to visualize how the temperature affect to exergy behavior is to analyze the exergy of heat ($\dot{E}^Q$) for below $T_0$and above T_0as shown in Figure 2.18 and given in Eq. (2.14a, 2.14b). Considering in Figure 2.18 at $\frac{T_0}{2}$, the ratio of $\frac{\dot{E}^Q}{\dot{Q}}$ is equal to 1 that means "in a refrigeration cycle, heat and work have the same value". Hence thermal energy (heat or cold) has more than work where $\frac{\dot{E}^Q}{\dot{Q}}>1$, at temperature lower than $\frac{T_0}{2}$. In contrast, at temperature higher than $\frac{T_0}{2}$, thermal energy has less value than work ($\frac{\dot{E}^Q}{\dot{Q}}<1$).

$$\dot{E}^Q = (1 - \frac{T_0}{T})\dot{Q} \ ; \text{if } T \geq T_0 \tag{2.14 a}$$

$$\dot{E}^Q = \left(\frac{T_0}{T} - 1\right)\dot{Q} \ ; \text{if } T \leq T_0 \tag{2.14 b}$$

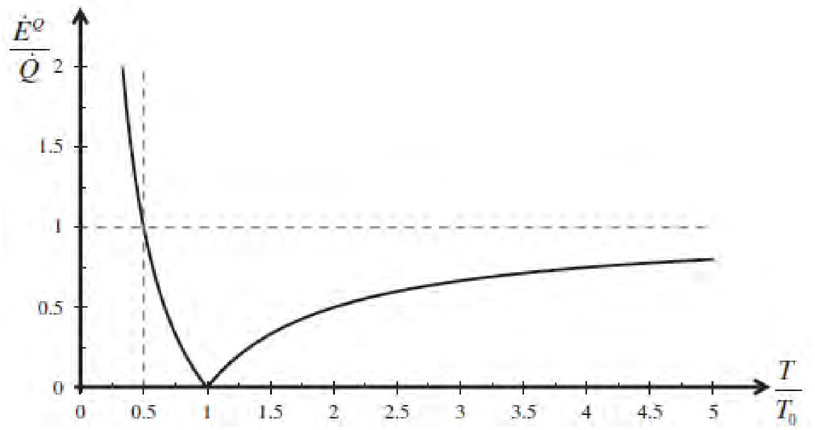

Figure 2.18 Exergy of heat for temperature (Aspelund, 2012).

2.2.3.2 Chemical Exergy

A chemical exergy; is a one types of Thermo-exergy; is represented as the maximum work extractable from system at the pressure and temperature of the reference-environment whenever it have chemical reactions or phase changes. Therefore, the chemical exergy is an important property for analyzing energy of chemical or petrochemical plants.

2.2.3.3 Exergy Efficiency

There are many several definitions for exergy efficiency. Almost definition also use technical terms to describe exergy efficiency; for example "exergy input" and "exergy output" etc. Sciubba and Wall (2007) had summarized the various exergy efficiencies published until 1960. Nevertheless, an exergy efficiency also was ambiguous in their summary. Moreover, many authors proposed clarify the definition and combined mathematical expression to some of units and cyclic processes. Kotas (1995) also had proposed expressions for expansion units (expander and valve) at belowT_0. There are 2 main classes of exergy efficiency. Firstly, the ratio between all exergy flow entering and existing is called input-output efficiency class as shown in Figure 2.19.

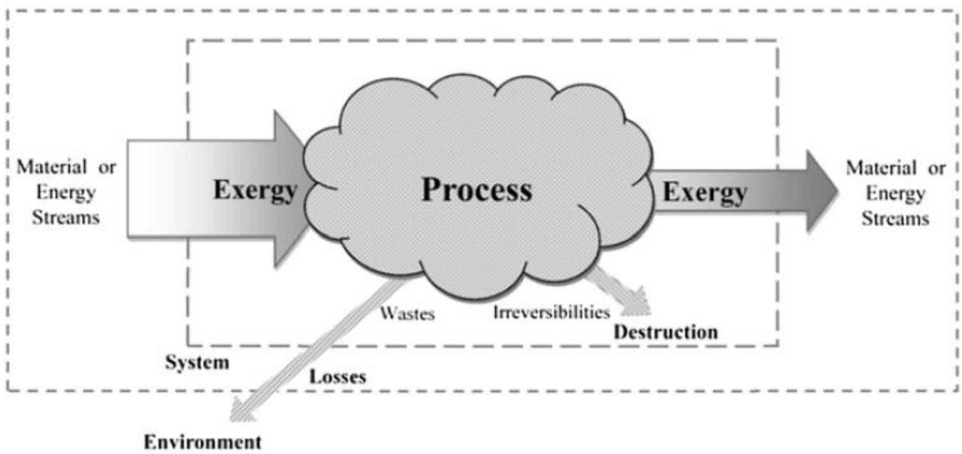

Figure 2.19 Exergy flows through a process or unit operation (Marmolejo-Correa, 2012).

$$\eta = \frac{\sum \text{Energy out}}{\sum \text{Energy in}} = 1 - \frac{\sum \text{Energy destroyed} + \sum \text{Energy lost}}{\sum \text{Energy in}} \tag{2.15}$$

In Eq. (2.15), diffusive heat losses from process equipment and pipelines, heat exchange and unutilized energy content (exhaust gases, purge gases, etc.) are involved in the exergy loss that can be referred to as external losses. An irreversible processes (dissipative effects and spontaneous) is a main cause for the destruction of exergy that shown in Eq. (2.15).

Secondly, to differentiate and utilize the change in exergy of material and energy streams is called consumed-produced efficiency class. Material and energy streams transferred, converted, accepted and produced exergy with in a process as shown in Figure 2.20. Brodyansky et al. (1995) had established Eq. (2.16) to identify exergy efficiency.

$$\eta = \frac{\text{Exergy out} - \text{Transit Exergy}}{\text{Exergy in} - \text{Transit Exergy}} \tag{2.16}$$

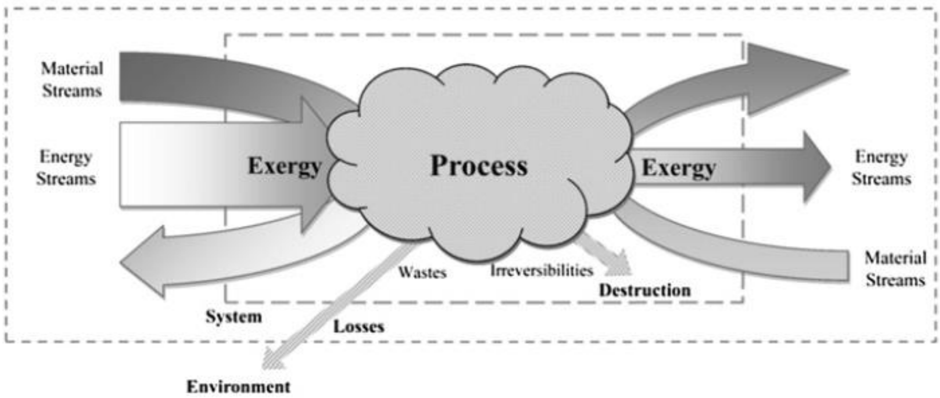

Figure 2.20 Exergy flows for material and energy streams through a process or unit operation (Marmolejo-Correa, 2012).

2.3 Methodologies for Cryogenic Processes

2.3.1 Heuristic Rules

Heuristic rules is similar to rule of thumbs that have been applied to methodologies for guiding by hand based on the experiences.

The 10 heuristic rules (Aspelund, 2007) are follows:-

General heuristics

Heuristic 1: Available pressure ($P_s > P_t$) have been utilized through expansion to reduce cold utility requirements with power generation. In the other hand, lacking of pressure ($P_s < P_t$) requires power, and hence it might be reduced hot utility requirements. Where P_s is a specified pressure and P_t is a target pressure for considering units.

Heuristic 2: The temperature gap ($\Delta T > \Delta T_{min}$) between the hot and cold Composite Curves, results as an unnecessary irreversibility. Hence to manage reducing irreversibility and the need of heating and cooling utilities should be manipulated by the pressure of the streams.

Heuristics for streams with target pressure different from the supply pressure

Heuristic 3: Compression of a vapor stream requires power after that this process adds heat to the system. Therefore, in pinch analysis, compression should preferably be added above the Pinch point.

Heuristic 4: In an expander, the expansion of a vapor stream will produce cooling and generate power into the system at the same time. Therefore, in pinch analysis, expander should preferably be added below the Pinch point. Furthermore, a stream located below the pinch point has a supply pressure higher than target pressure. Thus, this steam should be expanded in the expander that does not include a valve all the times.

Heuristic 5: A valve will be used to minimize the increase in utility consumption, unless the main propose of the expansion is production of work when expansion of a vapor stream above pinch is required.

Heuristics for streams with target pressure equal to supply pressure

Heuristic 6: A hot gas; which is compressed above the Pinch point; is cooled to near the pinch point temperature. After that it's expanded will decrease both of hot and cold utilities. Nevertheless, additional work is still required.

Heuristics for liquid streams and streams with phase change

Heuristic 7: For a fluid with $P_s < P_t$, the fluid might suppose to be compressed to liquid phase as possible to achieve saving compressor works.

Heuristic 8: For a liquid stream with $P_s = P_t$, the Composite curves should be manipulated by the phase transition because the effect of expansion or compression in the liquid phase alone is negligible.

Heuristic 9: If a vaporized cold liquid stream does not create the Pinch point, it might suppose to be pumped avoiding vaporization at constant temperature, reducing the total cooling duty and increasing the pressure based on exergy. Moreover, work and cooling duty ought to be recovered by expansion of the fluid in the vapor phase at the later stage as higher temperature condition.

Heuristic 10: Compression of a condensed hot gas stream is the main process to be increase the condensation temperature as soon and hence the latent heat of vaporization will also reduce. Moreover, work is also used to achieve decreasing the heating requirements and increasing the driving forces.

Aspelund *et al*. (2007) had proposed a set of 10 heuristic rules to solve the design problem of the offshore part for the Liquefied Energy Chain (LEC) in Figure 2.21.

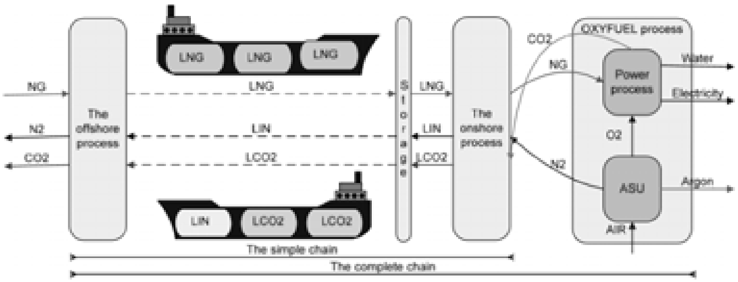

Figure 2.21 Liquefied energy chain (LEC) (Aspelund *et al.,* 2007).

The set of 10 heuristic rules that is already mentioned can conclude as following:

- Compression requires power and may reduce external heating
- Expansion produces power and may reduce external cooling
- Phase changes at constant temperature should be avoided when heating or cooling against a stream with non-constant temperature
- Pressure increase by pumping (liquid) is preferable to compression (vapor)

In conclude, this work shown more work is desired to classify, to systematize, to demonstrate and to further improve these rules to make more value and practical tool for sub-ambient processes.

2.3.2 Combination of Pinch Analysis and Exergy Analysis

The Pinch Analysis has been proposed to be a powerful method for designing minimum consumption of heat requirement. However, this process is limited as using temperature to the main design variable. In sub-ambient process, pressure is very important variable since it can reduce work from compressor or expansion for phase changes. The limitations of pinch analysis are not fulfil the effective requirement. Therefore, the combination of Pinch Analysis and Exergy Analysis was proposed to obtain a better solution.

B. Linnhoff and V. R. Dhole (1992) studied the design of low temperature process. This method was applied with ethylene plant which main components of this process are the pyrolysis furnace, the heat exchange network, and the refrigeration system. The targeting of overall process is a minimizing shaft work or power consumption of the refrigeration system. Procedure started with collecting stream data and developing composite curves (CCs) and grand composite curves (GCCs) which represented graph with temperature and enthalpy. After that, composite curve and grand composite curve were changed to exergy composite curve and exergy grand composite curve. The composite curves can be redrawn by replacing temperature with the Carnot factor(η_c) as shown in Eq. (2.17) and enthalpy (H) that it is called Exergy Composite Curves (ECCs) that might be referred for the appropriate placement of heat engines, heat pumps and refrigeration cycles as energy utilities. Shaded area $(\sigma T_0)_{HEN}$between process stream curve and utility will indicate exergy loss in system because $(\sigma T_0)_{HEN}$ is a proportional to exergy loss in process as shown in Figure 2.22

$$\eta_c = 1 - \frac{T_0}{T} \tag{2.17}$$

Where η_c is the Carnot efficiency and T_0 is the environment temperature.

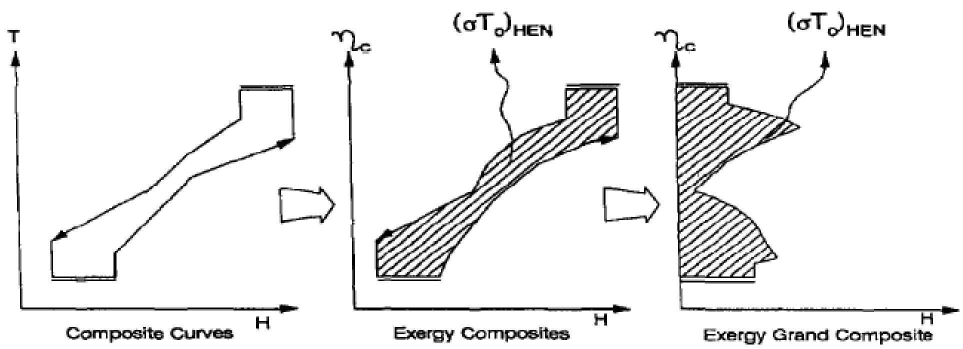

Figure 2.22 Exergy Composite Curves diagram (Linnhoff, 1992).

Hence to use exergy balance identified the refrigeration system and process supplies exergy (ΔEx_r), (ΔEx_p), respectively as shown in Figure 2.23 that represented the concept of exergy in low-temperature process design and assumed with change only in the HEN and refrigeration. Refrigeration system provides exergy (ΔEx_r) to the process. Some part of exergy could lost during heat exchanger network $(\sigma T_0)_{HEN}$ and hence remaining exergy is supplied to the process (ΔEx_p) that meant ΔEx_r must always be higher than ΔEx_p.

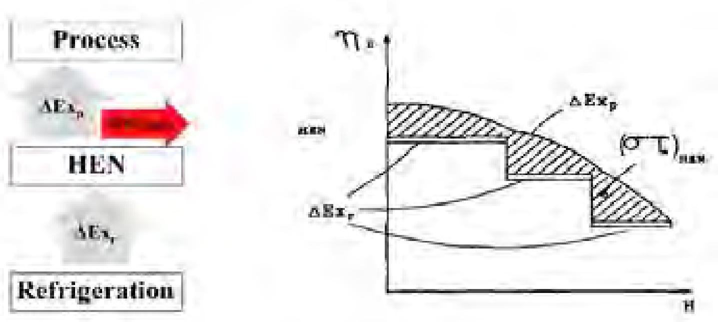

Figure 2.23 Exergy balance diagram in low-temperature process (Linnhoff, 1992).

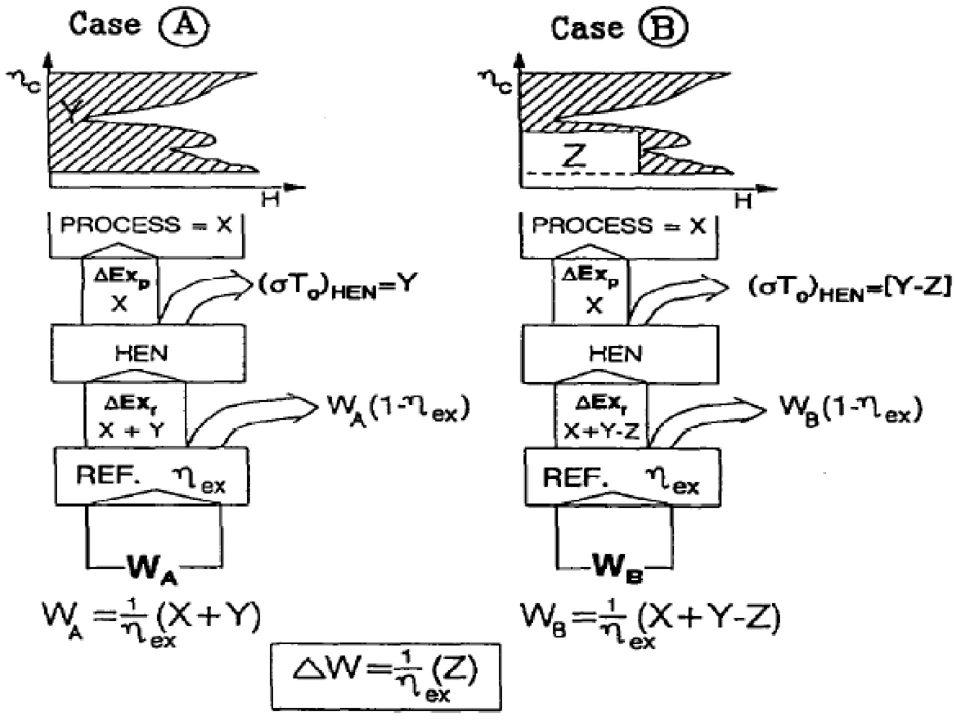

Figure 2.24 Exergy balance diagram of Processes modification (Linnhoff, 1992).

According to Figure 2.24, case A and B had the same EGCCs but they had different refrigeration profiles.

Considering case A in the chart, ΔEx_p = X and $(\sigma T_0)_{HEN}$ or shaded area = Y so ΔEx_r (supplied to HEN) = X+Y. The loss in the refrigeration system represented in Eq. (2.18).

$$W_A = \frac{1}{\eta_{ex}}(X + Y) \tag{2.18}$$

Where η_{ex} is an exergetic efficiency of refrigeration system and W_A is a shaft work for case A

In case B, a new refrigeration level and corresponding modification in HEN were introduced. ΔEx_p still equal to X and $(\sigma T_0)_{HEN}$ was reduced by Z due to considering with the same process. Therefore, ΔEx_r = X+Y-Z because of assuming the same value of η_{ex} from case A. In Equation (2.19) where W_B is the shaft work for case B and ΔW is the reduction in shaft work from case A to case B represents in equation.

$$W_B = \frac{1}{\eta_{ex}}(X + Y - Z) \tag{2.19}$$

$$\Delta W = W_A - W_B = \frac{1}{\eta_{ex}}(Z) \tag{2.20}$$

This procedure could predict the reduced shaft-work by using the shaded area between curves in EGCCs as shown in Figure 2.24 or calculating in Eq. (2.21).It was proportional to exergy loss in the HEN and denoted as $(\sigma T_0)_{HEN}$. In conclude, the amount of work equivalent lost in heat transfer was proportional to the shaded area. Therefore, the reduction of shaded area was $(\sigma T_0)_{HEN}$ and the reduction of the shaft work is defined in Eq. (2.21).

$$\Delta W = \frac{\Delta(\sigma T_0)_{HEN}}{\eta_{ex}} \tag{2.21}$$

A. Aspelund (2007) had proposed an Extended Pinch Analysis (ExPAnD) which combines pinch analysis and exergy analysis. This method utilized Exergy analysis to evaluate the developed of the design. The objective of the ExPAnD methodology is to maximize the utilization of exergy obtained by pressure changes of the streams, minimize work consumption (or maximize work production) and maximizing heat recovery.

The First step of ExPAnD is design procedure for utilizing pressure based exergy in a cold stream for cooling of a hot stream that shown in Figure 2.25.

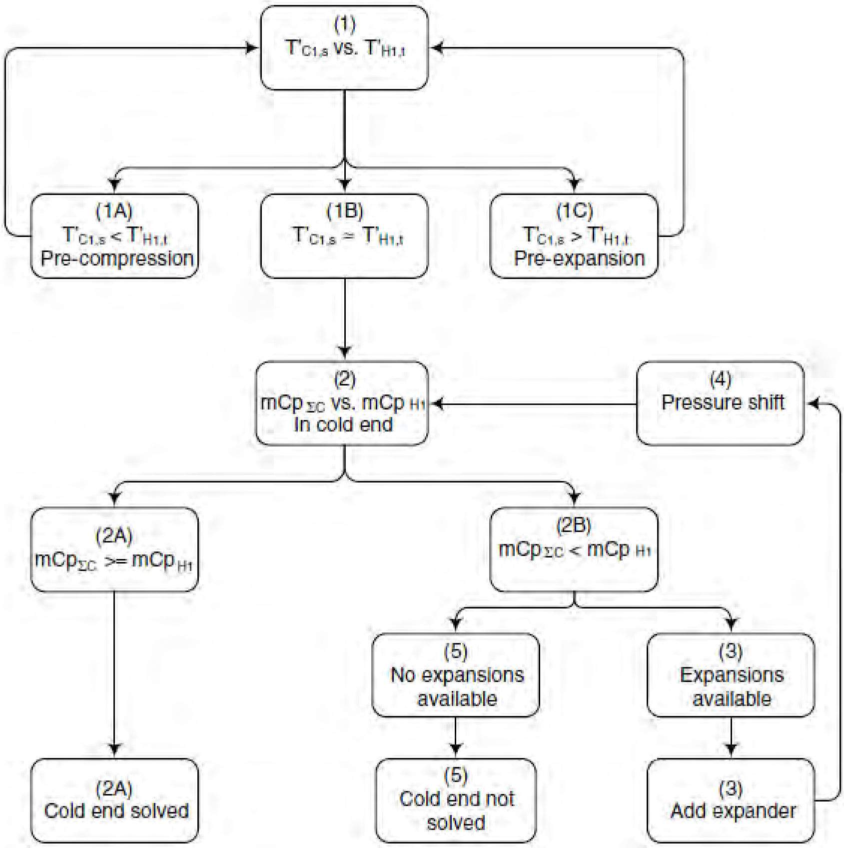

Figure 2.25 Procedure for utilizing pressure based exergy in a cold stream (Aspelund, 2007).

After that, the 10 heuristic rules; that have already mentioned; was applied with ExPAnD to achieve this goal. The ExPAnD methodology was used to design processes operating below ambient (etc. LNG process), where the exergy efficiency was increased from 49.7% to 85.7%. However, this methodology is more complex than the original Pinch analysis since it has to consider pressure and phase in expander and select the order in which to use heuristic rules and procedure.

D. Marmolejo Correa and T. Gundersen (2012) had proposed a new graphical exergy targeting for processes operating above and below ambient temperature with pressure of streams changed by using Composite curves for exergy sources and exergy sinks, adding assumption as one-phase flow and constant specific heat capacity. However, there are many useful diagrams that can indicate energy consumption in process. For example, the Exergy Composite curves; is proposed by Linnhoff in 1989; can use as the reference for the suitable placement of heat engines, heat pumps and refrigeration cycles as shown in Figure 2.26.

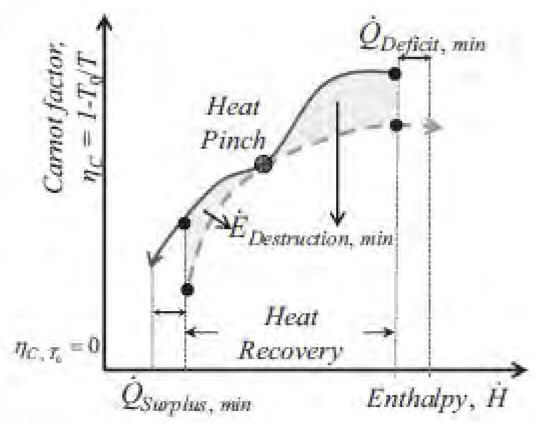

Figure 2.26 Exergy composite curves diagram (Marmolejo-Correa, 2012).

Another one is the Energy Utilitation Diagram (EUD) that was presented by Ishida and Kawamura (1982). The Energy Utilitation Diagram (EUD) could identify energy intensive for all unit operation. The EUD relates to Energy level parameter and enthalpy is shown in Figure 2.27.

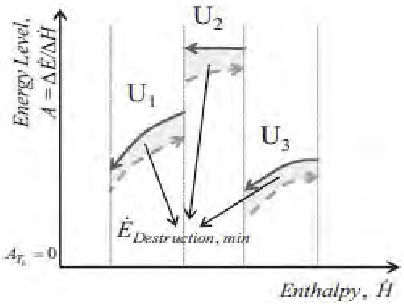

Figure 2.27 Energy utilization diagram (Marmolejo-Correa, 2012).

Nevertheless, in both of two diagrams, the Carnot factor and the energy level are non-linear relation with enthalpy, thus both of diagram are more complicated to identify the exergy destruction by using numerical integration to indicate shaded area. In addition, they cannot indicate explicitly the exergy targets.

In new representation, D. Marmolejo Correa have proposed the new graphical between exergy as x-axis against a new quality parameter referred to as Exergetic- temperature(T^{E^T}) as y-axis. The Exergetic temperature is a linear function with $\dot{E}^T$ which is given by Eq. (2.22)

$$\dot{E}^T = \dot{m}c_p\left[T_0\left(\frac{T}{T_0} - \ln\frac{T}{T_0} - 1\right)\right] = \dot{m}C_pT^{E^T} \tag{2.22}$$

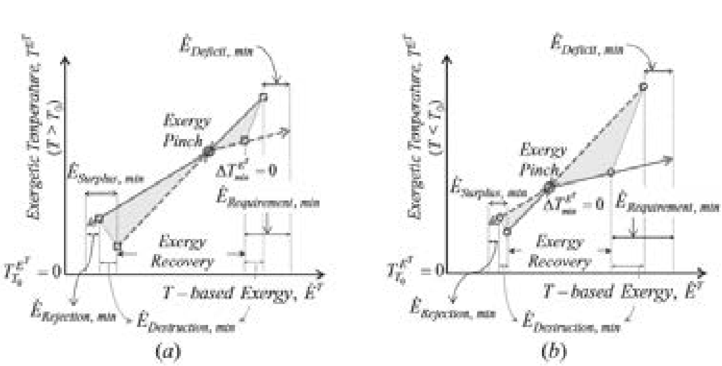

Figure 2.28 $T^{E^T} - \dot{E}^T$ diagram (a) above T_0 (b) below T_0 (Marmolejo-Correaa and Gundersen, 2012).

The calculations of exergy targets are defined in Eq. (2.23) and (2.24).

Above exergy pinch: $\dot{E}_{Requirement,min} = \dot{E}_{Deficit,min} + \dot{E}_{Destrction,min}$ (2.23)

Below exergy pinch: $\dot{E}_{Rejection,min} = \dot{E}_{Surplus,min} - \dot{E}_{Destrction,min}$ (2.24)

2.3.3 Mathematical Programming Method

Deterministic Optimization methods is known as Mathematical Programming for refrigeration cycle; for example Nonlinear programming model (NLP) or Mixed integer linear programming (MINLP); that is a principle to optimize the solution , however , this method is still more complicated to solve for two reasons. The first reason, the non-linear relations are often a non-convex nature, so the solver is trapped in local optimal. Another reason is the discrete (integer or binary) nature of the model causes to be broken as a result. Moreover, it still has problem for optimization in an equation-based way that requires very complex models for calculation of equipment and the thermodynamic behavior of components or mixtures.

Shelton and Grossmann (1983) had proposed algorithmic methods for synthesizing chemical processes. It is shown as the Mixed-integer programing model reviewed for utility systems, heat recovery networks, integrated refrigeration systems and total processing systems as a network model where a large number of alternative multistage structures can be inserted with the used compressors and exchangers for condensers, evaporators and intermediate loads. For example, the objective function for the integrated refrigeration systems were to minimize the total annual cost for which the investment cost of the compressors and the utility costs (steam, cooling water and electricity) were considered. Finally, the optimal solution for this example could be achieved to save annual cost 28% from based case.

The minimum utility cost as objective function was given by Shelton and Grossman (1985) as shown in Eq. (2.25).

$$c_E \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} E_{ij} + \sum_{k=1}^{N_{HU}} c_{H_k} HU_k + \sum_{k=1}^{N_{CU}} c_{C_k} CU_k \quad (2.25)$$

$$E_{ij} = WC_{ij} D_{ij} \; ; i = 1, 2, \ldots, N\text{-}1; j = i+1, i+2, \ldots, N \quad (2.26)$$

Where E_{ij} is the power requirement

D_{ij} corresponds to the heat being passed by compressor between T_i and T_j

WC_{ij} is the work coefficient, c_E is a cost coefficient for electricity

c_{H_k} is the cost coefficient for heating utility

c_{C_k} is the cost coefficient for cooling utility

HU_k is the number of heating utility

CU_k is the number of cooling utility

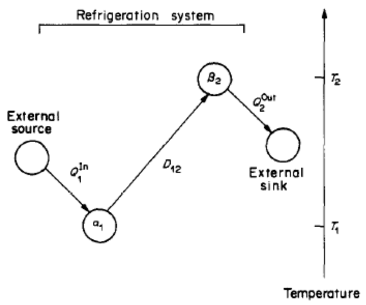

Figure 2.29 Network of refrigeration superstructure for a simple cycle (Shelton and Grossman, 1986).

T. R. Colmenares and W. D. Seider (1989) had proposed the non-linear programing model (NLP) for synthesis of cascade refrigeration system. The NLP model is used to minimize of the total utility cost function as an optimality criterion that was given by Eq. (2.27)

$$C_{util} = \sum_{n=1}^{N} \sum_{k=1}^{NCU} c_k^{CU} Q_{nk}^{CU} + \sum_{m \in HP_T} c_{out}^{HP} Q_{cm}^{HP} + \sum_{m=1}^{P} c_{in}^{HP} W_{in,m}^{HP} \quad (2.27)$$

Where C_{util} is the total cost of utility

c_k^{CU} is the cost of clod utility

Q_{nk}^{CU} is the heat accepted by cold utility k in interval n

c_{out}^{HP} is the cost of condenser heat pump m

Q_{cm}^{HP} is the condenser heat duty in heat pump m

c_{in}^{HP} is the cost of compressor in heat pump m

$W_{in,m}^{HP}$ is the compression work required by heat pump m defined in Eq. (2.28)

$$W_{in,m}^{HP} = M_m^{HP}(h(P_{cm} - T_{2m}) - h(P_{bm} - T_{1m})) \quad (2.28)$$

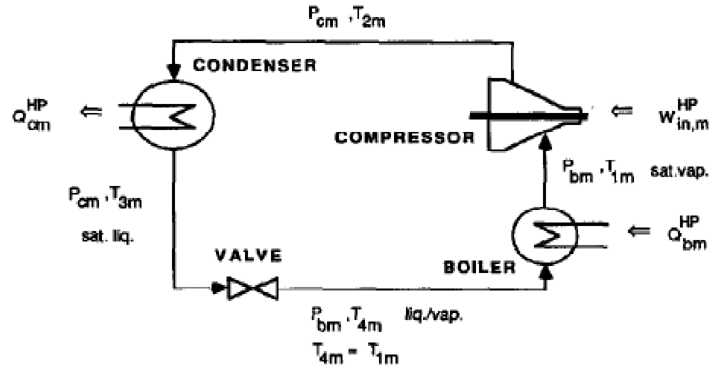

Figure 2.30 Refrigeration cycle for heat pump (Colmenares and Seider, 1989).

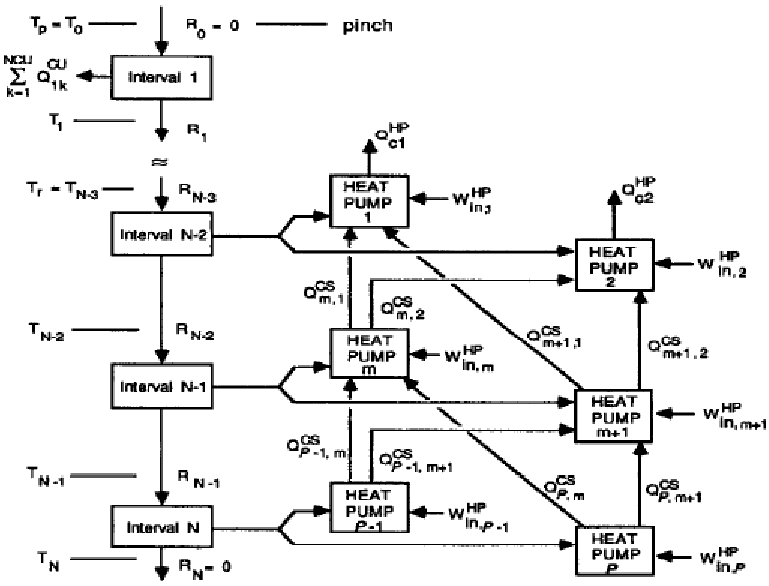

Figure 2.31 Heat integration diagram for cascade refrigeration (Colmenares and Seider, 1989).

In concluded, the nonlinear programing model is an effective implement for synthesis of cascade refrigeration systems with a continuous set of operating temperatures. The size of model without elimination of important alternatives for heat integration can be reduced by lumping of temperature intervals. In addition, to use negative cold deficits below T_r leads to a better design because the compression work required is reduced by the refrigeration system.

Wechsung, A., et al. (2011) presented the optimization formulation for the synthesis of heat exchanger networks by adjusting pressure of process streams to improve heat integration in sub-ambient conditions. This method could achieve to reduce the expensive cold utility and increase exergy efficiency in process by the composite curves yielding to change temperature and pressure. This model consisted of four parts; the pinch operator, the pressure operator , the exergy operator and the objective function.This formulation was applied to the design of an offshore natural gas liquefaction process as a case study as shown in Figure 2.32.

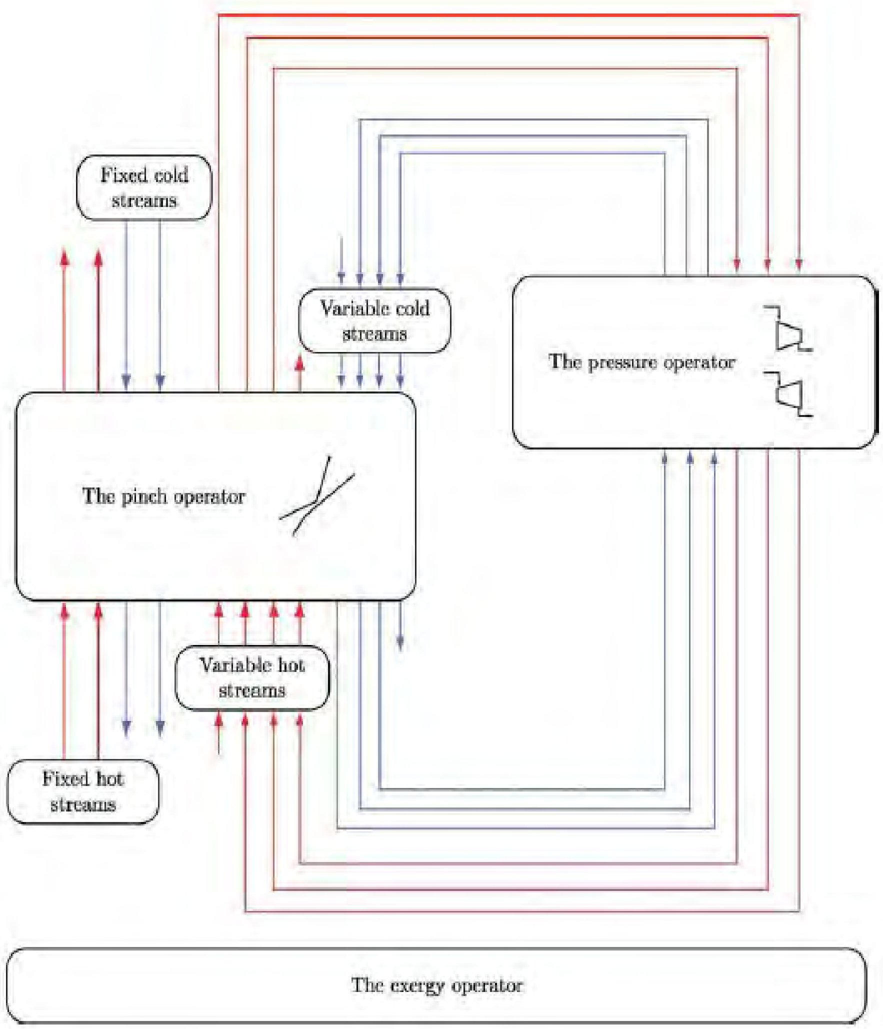

Figure 2.32 Schematic of the model (Wechsung, 2011).

The pinch operator is useful to locate the pinch point and consequently determine the minimum required utilities. In case, the constant heat capacity flow rates affects to the pinch operator that is a linear relation. The pressure operator uses an equation of state in combination with isentropic changes of state to connect streams at different pressure levels and the thermodynamic model; non-convex constraints are introduced that cannot be reformulated. The exergy operator is used to calculate the exergy of the process streams and the utilities and find the exergy conversion efficiency in considered process. Another one is objective function which minimizes the combination of the results from pinch, pressure and exergy in MINLP involving nonconvex functions that is given by Eq. (2.29).

$$\mathrm{ExW} + \mathrm{ExQhu} + \mathrm{ExQcu} \quad (2.29)$$

$$\mathrm{Exw} = \sum_{(S_1,S_2)\in \mathrm{COMPRESSOR}} W_{S_1} - \sum_{(S_1,S_2)\in \mathrm{EXPANDER}} W_{S_1} \quad (2.30)$$

$$\mathrm{ExQhu} = Q_H(1 - \frac{T_0}{T_U^h}) \quad (2.31)$$

$$\mathrm{ExQcu} = Q_c(\frac{T_0}{T_U^c} - 1) \quad (2.32)$$

Where T_0 is the ambeint temperature

T_U^h is the temperature at which hot utility

T_U^c is the temperature at which cold utility

Exw is the exergy of the work provided to the process

W_S is the work required or released by compression or expansion of stream

ExQhu is the exergy of the hot utility

ExQcu is the exergy of the cold utility

Q_H is the hot utility used

Q_C is the cold utility used

Onishi, V. C., et al. (2014) introduced a new mathematical model for the simultaneous synthesis of heat exchanger networks (HENs) to optimize the integration between heat and work by adjusting the pressure of process streams. This model was developed by combination with GAMS (general algebraic modeling system) software, GDP(generalized disjunctive programming) and MINLP formutation. The GDP and MINLP were based on the HEN superstructure which was comprised of various stages of heat exchangers. Furthermore, this model could allow for coupling of the units in process (etc. turbines and compressors and selection of the turbines and valves) to minimize the total annualized cost as the main objective function. It was consisted of the operational and capital expenses that shown in Eq. (2.33). Moreover, the model was tested in a cryogenic application. As a result, the energy integration could reduce the quantity of utilities required which affected to decrease the overall cost.

$$C_{total} = C_{capital} + C_{operational} \tag{2.33}$$

$$C_{operational} = \sum_h \sum_n CC \cdot Q_{h,n} + \sum_m \sum_c CH \cdot Q_{m,c} + \sum_\nu CE \cdot WC_\nu \tag{2.34}$$

$$C_{capital} = f \cdot [\sum_{Hex} CPO_{Hex} \cdot FBM_{Hex} + \sum_{cooler} CPO_{cooler} \cdot FBM_{cooler} + \sum_{Heater} CPO_{Heater} \cdot FBM_{Heater} + \sum_\nu CPO_\nu \cdot FBM_\nu + \sum_t CPO_t \cdot FBM_t + \sum_w CPO_w \cdot FBM_w] \tag{2.35}$$

Where CC, CH, and CE are the cost parameters for the cold and hot utilities and the electricity, respectively. The FBM term is the correlation factor for equipment cost. The CPO term indicates the cost of an equipment unit. The term f is the annual factor for the capital cost. The subscripts of ν, t and w are compressor, expander and valves, respectively.

CHAPTER III
METHODOLOGY

3.1 Motivation

While the oil price has been decreasing dramatically, downstream petrochemical industries using by-products from upstream process like methane, ethane, and others are growing due to demand of domestic products e.g., plastic and resin. The downstream process like LNG or Gas separation process needs refrigeration system for cooling the natural gas to meet the proper condition which requires high energy consumption at compressor, evaporator and condenser. To gain more benefit, reduction of compressor works and utilities is the main goal. Therefore the way to improve the sub-ambient process is challenge. In this research has studied the graphical and mathematical model by using the exergy analysis and energy analysis. The exergy analysis is the one of methodologies used to synthesize the process and gives the potential to minimize energy requirement in process. This model is applied with the energy analysis to improve the process in term of energy consumption. The exergy concept is strongly used for the gas refrigerant at the below ambient condition where the pressure based-exergy can transform into the temperature based-exergy; however, energy analysis is still important to concern with a problem of a dense phase. Moreover, for the typical cooling system using refrigeration system with dense-refrigerant, it cannot be expressed by exergy analysis because of changing phase of refrigerant. Therefore, a cascade refrigerant concept is concerned to manage the case which has dense-refrigerant. This research is powerful to improve the sub-ambient process by adding the turbo-machine (compressor and expander) and manipulating operating conditions and design a new configuration of refrigeration system.

3.2 Objectives

3.2.1 To study methodology for optimizing of sub-ambient process.

3.2.2 To design, synthesize and retrofit refrigeration system.

3.2.2 To optimize energy requirement in process.

3.3 Scope of Research

The scope of this research will cover the following:

3.3.1 Considering mainly in below ambient temperature process.

3.3.2 Using Energy and Exergy analysis to design improved case (grass root-design).

3.3.3 Considering mainly the Thermo-mechanical exergy in Exergy analysis with gas or dense phase.

3.4 Materials and Equipment

3.4.1 Equipment

3.4.1.1 Laptop Computer (Intel® Core™ i7-4720HQ CPU at 2.6 GHz, 16 GB of RAM, 64-bit Windows 10)

3.4.2 Software

3.4.1.1 PRO/ II V 9.4

3.4.1.2 Microsoft Excel 2013

3.4.1.3 Visual Basic for Application

3.5 Methodology

The overview of this research is to synthesize a sub-ambient process in term of turbo-machine (Compressor and Expander) and heat exchanger network by using Energy and Exergy analysis. First model, the combination between ExPAnD method and Exergy composite curves ($T^{E^T} - \dot{E}^T$diagram or ECC) is used for manipulating the pressure and inlet temperature at the turbo machine by graphical method. Second model, mathematical programing has been applied to improve the efficiency of heat exchanger network and irreversibility in sub-ambient process. Third model, synthesis of cascade refrigeration systems has been applied to refrigeration system using refrigerant as dense phase to design new configurations of refrigeration system with alternate working fluids.

3.5.1 Combination with ExPAnD Method and ECCS Diagram

The ExPAnD method has been proposed by Aspelund *et al.* (2007) and the ECC diagram has been proposed by Marmolejo-Correa (2012). These models can improve the process. Especially, they are used for sub-ambient process by manipulating the conditions of turbo-machine and heat exchanger. The procedure of this methodology is shown as Figure 3.1and starts with the following steps-.

3.5.1.1 Create Stream Data

Frist step in this methodology is collection of all stream data in process and create the table which consists of temperature, pressure, mass flow rate with heat capacity and enthalpy.

3.5.1.2 Transform Every Parameters into Exergy Parameters

To transform temperature and pressure into exergy terms by using Eq. (3.1) and Eq. (3.2) and calculate the change of exergy component in term of temperature and pressure which is in linear relation by Eq. (3.3) and Eq. (3.4). Moreover, these equations are used the environmental parameter or reference state as ambient condition (T=25°C and P=1atm).

$$\mathrm{T}^{\mathrm{E}^{\mathrm{T}}} = \left[\mathrm{T}_0\left(\frac{\mathrm{T}}{\mathrm{T}_0} - \ln\frac{\mathrm{T}}{\mathrm{T}_0} - 1\right)\right] \qquad (3.1) \qquad \mathrm{T}^{\mathrm{E}^{\mathrm{P}}} = \left[\mathrm{T}_0 \ln\left(\frac{\mathrm{p}}{\mathrm{p}_0}\right)^{\frac{\kappa-1}{\kappa}}\right] \qquad (3.2)$$

$$\Delta\dot{E}^{T}_{1\to2} = \dot{m}c_p\left[T_0\left(\frac{T_2 - T_1}{T_0} - \ln\frac{T_2}{T_1}\right)\right] \qquad (3.3) \qquad \Delta\dot{E}^{P}_{1\to2} = \dot{m}c_p\left[T_0 \ln\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right] \qquad (3.4)$$

3.5.1.3 Construct Energy Diagram

Using the stream data which are temperature, exergy based temperature, enthalpy and the change of temperature based exergy constructs the traditional composite curves (CCS) and exergetic composite curves (ECCS) at the same time. The ECCS diagram is divided into 2 process. First process is used for the above ambient temperature as shown in Figure3.2 (a). The other is used for the below ambient temperature as shown in Figure3.2 (b).

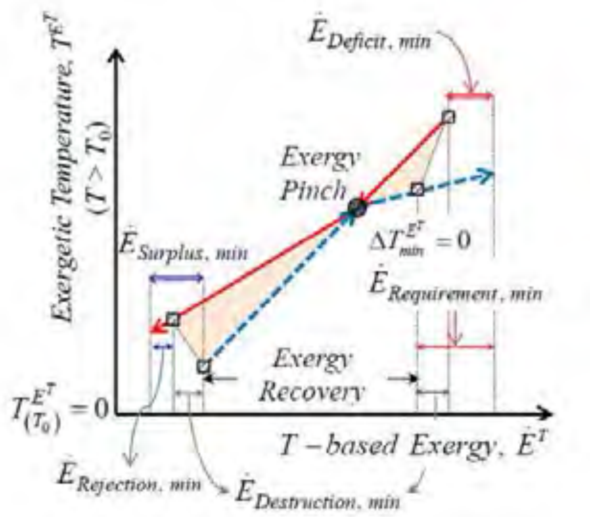

Figure 3.2 (a) Exergetic composite curve for above ambient (Marmolejo, 2012).

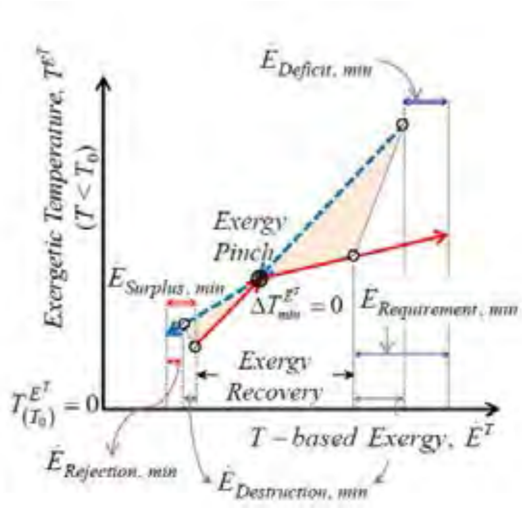

Figure 3.2 (b) Exergetic composite curve for below ambient (Marmolejo, 2012).

3.5.1.4 Determine Exergy Targets

The exergy targets; which are minimum exergy requirement, minimum exergy rejection, minimum exergy destruction and maximum exergy recovery, is defined by using the ECCS diagram. The exergy deficit and surplus are similar to the external utility usage in traditional heat cascade or CCS. The exergy destruction is defined from the boundary temperatures of the overlapping region which obtains from the traditional CCS into exergy based-temperature. The exergy recovery is the amount of overlapping between exergy sink curve and exergy source curve. The calculation of exergy requirement and exergy rejection are given by Eq. (3.5) and Eq. (3.6).

Above exergy pinch: $\dot{E}_{Requirement,min} = \dot{E}_{Deficit,min} + \dot{E}_{Destrction,min}$ (3.5)

Below exergy pinch: $\dot{E}_{Rejection,min} = \dot{E}_{Surplus,min} - \dot{E}_{Destrction,min}$ (3.6)

3.5.1.5 Manipulate The Pressure to Improve Exergy Targets

When manipulating the pressure, the temperature based exergy and the pressure based exergy will be change. Moreover, the work will be consumed in compression process and produced in expansion process. First, choose the stream and decide the temperature which should start in the change of pressure.

Second, for isentropic equation to explain the change in pressure, the corresponding work produced or consumed are given by Eq. (3.7) and Eq. (3.8). When the isentropic efficiency is less than1, then is used the reverse of isentropic efficiency for compression process and isentropic efficiency directly for expansion process. Therefore, the actual exergy component and shaft work is calculated from Eq. (3.9) and Eq. (3.10).

$$\frac{T_{\Delta S=0}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} \quad (3.7) \qquad -\dot{W}_{\Delta S=0} = \Delta\dot{E}^{P}_{\Delta S=0} + \Delta\dot{E}^{T}_{\Delta S=0} \quad (3.8)$$

$$\frac{T_{\Delta S>0}}{T_1} = 1 + f_{is-eff}\left[\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} - 1\right] \quad (3.9) \qquad -\dot{W}_{\Delta S>0} = \Delta\dot{E}^{P}_{\Delta S>0} + \Delta\dot{E}^{T}_{\Delta S>0} + \dot{\sigma}T_0 \quad (3.10)$$

Where T_S is the temperature from the turbo machine

T_1 is the inlet temperature, K

K is heat capacity ratio for ideal gas

P_1 is the inlet pressure, atm

P_2 is the outlet pressure, atm

$\Delta\dot{E}^{P}_{\Delta S}$ is the change in pressure based-exergy, kW

$\Delta\dot{E}^{T}_{\Delta S=0}$ is the change in temperature based-exergy, kW

$\dot{\sigma}T_0$ is the exergy destruction rate, kW

Third, when manipulating the pressure, enthalpy should be added or removed. For example; the compression of the hot stream needs to remove some segments of heating performed by the compressor.

Fourth, check the exergy targets between based-diagram and investigated-diagram which is changed the pressure. However, the change of pressure cannot reduce the exergy targets expected, the temperature at which the pressure change should be proposed the other values. When exergy targets are satisfy, then go to the next step, otherwise continue the next irritation until exergy targets are satisfy (to find the best solution).

3.5.1.6 Design and Simulate The HEN with Pressure Change Unit Operations

Finally, using the lastly CCS and ECCS designs and simulates the actual design of the HEN which is modified from the changes in pressure with the new unit operations (the heat exchanger and the turbo machine).

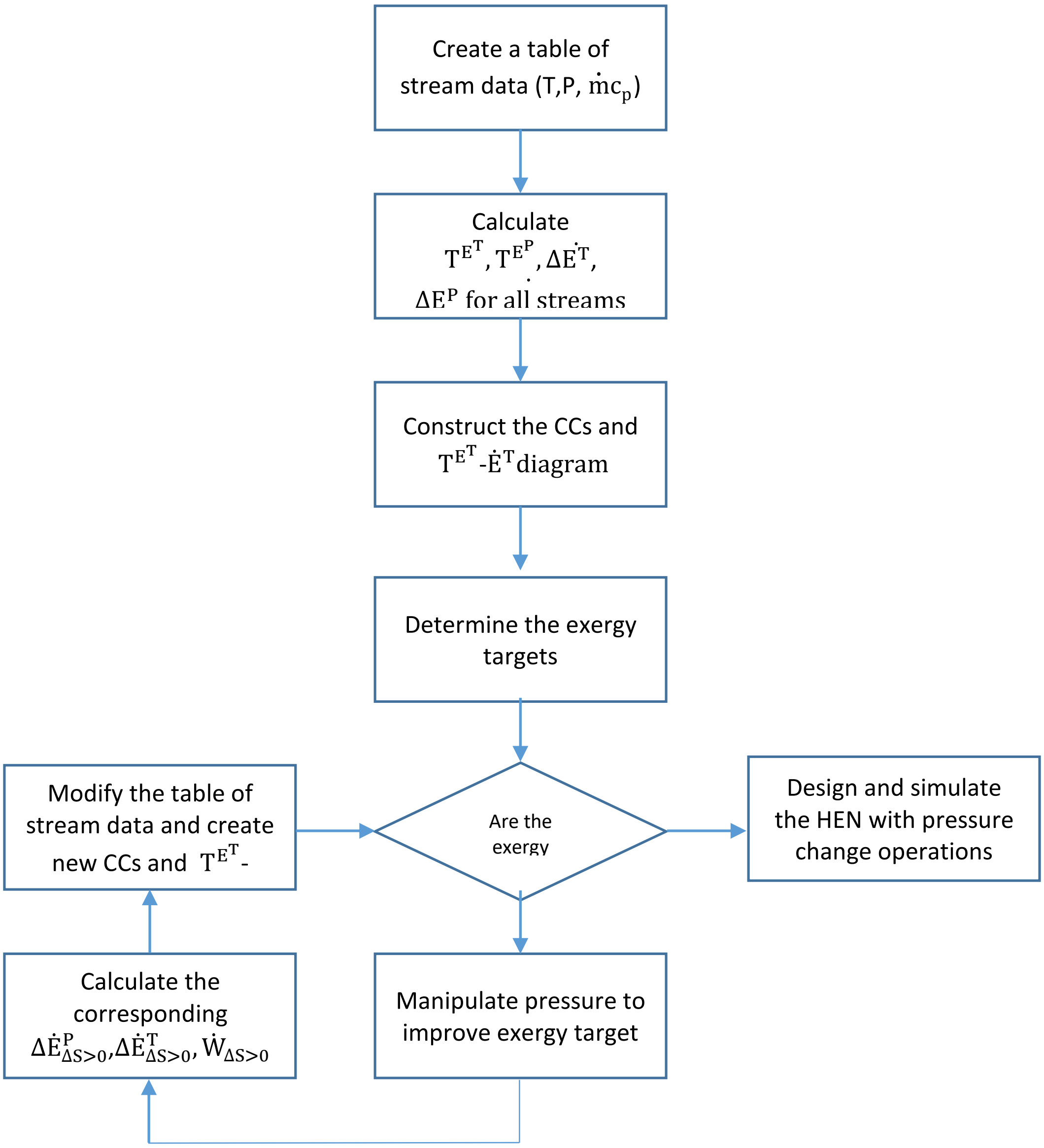

Figure 3.1 Procedure for manipulating the pressure (Marmolejo, 2012).

3.5.2 Mathematical Programming

This model is used mathematical programing to optimize the heating, cooling, compression and expansion (Wechsung, 2011). Moreover, this method can be applied to design process relating to the change of pressure by using optimization model. If there is existing plant, this model can be found the proper condition to improve the efficiency in the process and support the pressure changed for the graphical model as discussed in 3.5.1. This model consists 4 main steps are follows:-

3.5.2.1 Pinch Operator

The pinch operator is the heart of the optimization model because there are many available streams as the fixed stream which is not expanded or compressed and the varied stream which is add the additional expander and compressor to adjust the pressure. Therefore, this model will create a lot of temperature intervals to support varied temperature from optimization and will determine the utility consumption.

3.5.2.2 Pressure Operator

The pressure operator defines the appropriate compressors or expanders defining the proper outlet pressure of these units by manipulating the temperature before turbo-machine and outlet pressure. This calculations are for the reversible and adiabatic compression or expansion of an ideal gas that can be formulated as isentropic equation are given by Eq. (3.12) to Eq. (3.14).

$$\frac{T_S}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} \text{ or } (K-1)\ln P_1 + K\ln T_S = (K-1)\ln P_2 + K\ln T_1 \qquad (3.7)$$

$$(T_1 - \widetilde{T}_S) = (T_1 - T_S)\eta_c \qquad (3.11) \qquad (T_1 - \widetilde{T}_S)\eta_e = (T_1 - T_S) \qquad (3.13)$$

$$W_c = \dot{m}c_p(\widetilde{T}_S - T_1) \qquad (3.12) \qquad W_e = \dot{m}c_p(T_1 - \widetilde{T}_S) \qquad (3.14)$$

Where T_S is the temperature of exiting a ideal turbo machine, K

$\widetilde{T}_S$ is the temperature of exiting a turbo machine, K

$\eta_c$is the efficiency of the compressors

η_e is the efficiency of the expanders

W_c is the work required by compressor, kW

$W_e$is the work produced by expander, kW

3.5.2.3 Exergy Operator

The exergy operator has two main purpose, first purpose is to calculate of the exergy of process streams and exergy efficiency that can reduce the irreversibility in heat exchanger network, which is formulated as Eq. (3.15). Second, the exergy operator is used to find the exergy content from the unit operations in the process which consist heat exchanger and turbo-machine. For a utility with constant temperature, the Carnot efficiency can be defined the exergy content that are formulated as Eq. (3.18) and Eq. (3.19). Let T_0 and P_0 be ambient condition. T_U^h and T_U^C are the temperatures at hot and cold utility, respectively.

$$E_s^{(tm)} = E_s^{(T)} + E_s^{(P)} \quad (3.15)$$

$$\psi = \frac{E_{\text{outlet streams}}^{(tm)} + \sum_{(s_1,s_2)\in EX} W_{s1}}{E_{\text{inlet streams}}^{(tm)} + \sum_{(s_1,s_2)\in CO} W_{s1} + ExQcu + ExQhu} \quad (3.16)$$

$$Exw = \sum_{(S_1,S_2)\in COMPRESSOR} W_{S_1} - \sum_{(S_1,S_2)\in EXPANDER} W_{S_1} \quad (3.17)$$

$$Exhu = Q_H\left(1 - \frac{T_0}{T_U^H}\right) \quad (3.18) \qquad Excu = Q_C\left(\frac{T_0}{T_U^C} - 1\right) \quad (3.19)$$

Where ψ is the exergy conversion efficiency

$E_s^{(tm)}$ is the thermo-mechanical exergy of process steam, kW

$E_s^{(T)}$ is the temperature based-exergy, kW

$E_s^{(P)}$ is the pressure based-exergy, kW

3.5.2.4 Objective Function

The objective function is optimization of the combination of results from pinch operator, pressure operator and exergy operator. In this research, the main goal is minimization in term of energy consumption from the turbo-machine and utility usage. For example, the objective function formulated as Eq. (3.20) can be minimized the exergy content to reduce the irreversible loss in the process. Alternatively, it is possible to concern in capital cost or economic design for every unit operation and utility's cost.

$$ExW + ExQhu + ExQcu \quad (3.20)$$

$$\Delta W + Qh + Qc \quad (3.21)$$

3.5.3 Synthesis of Cascade Refrigeration Systems

The methodology has been proposed by Colmenares (1989). It can be applied to many chemical processes that require a refrigeration system. The purpose of this methodology is to design a configuration of refrigeration system with alternative working fluid. Normally, cryogenic process has refrigeration system or cooling system as the heart of process to control the level of suitable temperature for condensation or separation. The shaft-work from compressor and heat duty from condenser need concerning to find the way decreasing a usage energy. Thus, an integration with cascade of refrigeration systems is one of alternative way to reduce energy consumption setting the same reference temperature. This model is structured to permit heat pump with various working fluid shown in Figure 3.3.

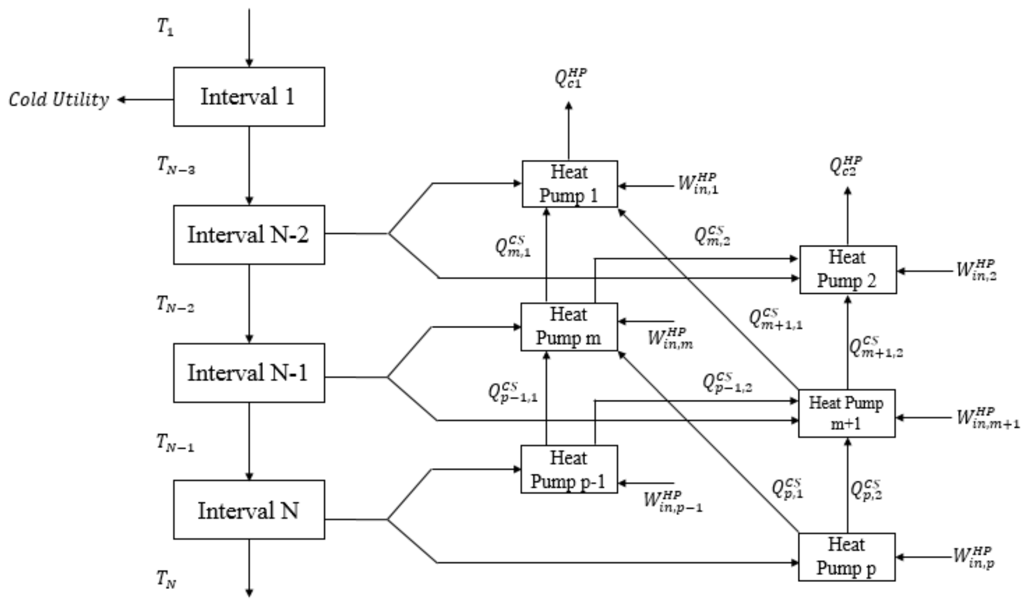

Figure 3.3 Heat integration diagram for a cascade of heat pumps (Colmenares, 1989).

3.5.3.1 Simple Refrigeration System

The simple refrigeration system or heat pump which is shown in Figure 3.4 (a) has one boiler to carry heat of natural gas out, one condenser to transfer heat in this heat pump to other heat pumps or ambient, one compressor to increase pressure and one valve to decrease the pressure. According to Figure 3.4 (a), there are parameters; T_{1m} is the boiler temperature, T_{3m} is the condenser temperature, Q_{bm}^{HP} is the boiler duty, Q_{cm}^{HP} is the condenser duty and $W_{in,m}^{HP}$is the compression work. Besides that, subscript m is heat pump counters and superscript HP is heat pumps. Since the boiler and condenser operate at saturated conditions, an entropy path always touch the saturated envelope at the point 1 and 3 shown in Figure 3.4 (b).

The mass flow rate of working fluid can be expressed in term of energy balance at the boiler:

$$M_m^{HP} = Q_{bm}^{HP}/(h\{P_{bm}, T_{1m}\} - h\{P_{bm}, T_{4m}\}) \quad ;m=1,\ldots,P \qquad (3.22)$$

The outlet temperature from compressor can be expressed in isentropic equation for ideal gas:

$$T_{2m} = T_{1m}\left(\frac{P_{cm}}{P_{bm}}\right)^{\frac{K-1}{K}} \quad ;m=1,\ldots,P \qquad (3.23)$$

The compression work is:

$$W_{in,m}^{HP} = M_m^{HP}(h\{P_{cm}, T_{2m}\} - h\{P_{bm}, T_{1m}\}) \quad ;m=1,\ldots,P \qquad (3.24)$$

The condenser heat duty is:

$$Q_{cm}^{HP} = M_m^{HP}(h\{P_{cm}, T_{3m}\} - h\{P_{cm}, T_{2m}\}) \quad ;m=1,\ldots,P \qquad (3.25)$$

Where $h\{P, T\}$ is the enthalpy, kW $[kg/hr]^{-1}$

M_m^{HP} is the mass flow rate of the working fluid in heat pump m, kg/hr

P_{bm} is the boiler pressure in heat pump m, atm

P_{cm} is the condenser pressure in heat pump m, atm

Q_{bm}^{HP} is the boiler heat duty in heat pump m, kW

Q_{cm}^{HP} is the condenser heat duty in heat pump m, kW

T_{1m} is the boiler outlet temperature in heat pump m, K

T_{2m} is the condenser inlet temperature in heat pump m K

T_{3m} is the condenser outlet temperature in heat pump m, K

$W_{in,m}^{HP}$ is the compression work in heat pump m, kW

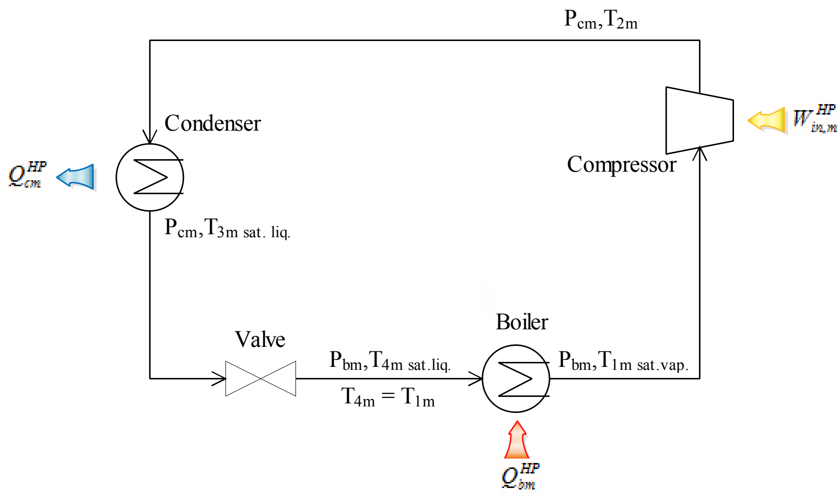

Figure 3.4 (a) Configuration of simple refrigeration cycle for heat pump m.

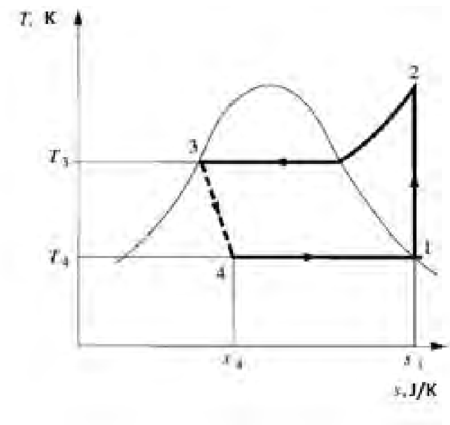

Figure 3.4 (b) T-S diagram of simple refrigeration cycle for heat pump m.

3.5.3.2 Integration with Cascade of Refrigeration Systems

In this section, a model can obtain the better designs when it has the less condenser duty from the cascade refrigeration system. In cascade refrigeration system, there are many heat pumps to satisfy the heat duty from the natural gas stream or hot stream as shown in Figure 3.3. Therefore, the heat released from the heat pumps to external cold sink or ambient needs concerning. The condenser heat duty can transfer from its heat pump to other heat pump at the same stage.

According to Figure 3.3, considering the interval N, there are two heat pumps(heat pump P-1 and heat pump P) removing the heat duty from the hot stream. Besides that, one heat pump can transfer the condenser duty to the other heat pumps in next interval (interval N-1) until the condenser outlet temperature is at least the ambient temperature. Because of that, it can use the environment or external cold sink to keep down the temperature that expressed in Eq. 3.26 where subscript k is temperature interval N of hot stream . The transfer of heat for each temperature interval is expressed by Eq. 3.27 but does not apply at final stage or last temperature interval which is almost the ambient condition.

$$T_{0\,(ambient)} \geq T_{3m,k} \geq T_{3m,1} \qquad ;m=1,\ldots,P\ ;k=1,\ldots,N \qquad (3.26)$$

$$Q^{HP}_{bm,k+1} \geq \sum_{m1}^{P} Q^{CS}_{cm,m1,k} \qquad ;m=1,\ldots,P\ ;m1=1,\ldots,P\ ;k=1,\ldots,N-1 \qquad (3.27)$$

$$Q^{HP}_{cm,k} = \sum_{m1}^{P} Q^{CS}_{cm,m1,k} \qquad ;m=1,\ldots,P\ ;k=1,\ldots,N-1 \qquad (3.28)$$

3.5.3.2 Optimization Model

The objective function is a minimization in terms of the usage energy from compressor and heat duty from condenser by using alternative working fluid with the cascade refrigeration system, which is shown in Eq. 3.31. There are three main variables of optimization; T_{1m}, T_{3m} and Q^{HP}_{cm}, given the alternative way for selecting working fluid. For constraint, there are binary variables to choose the suitable working fluid in heat pumps expressed in Eq. 3.29 and Eq. 3.30 where $z_{is,k}$ is the binary variable denoting; i is the types of working fluid, s is the stage of refrigeration system and k is the interval of hot stream and R is the number of refrigerants.

$$\sum_{i=1}^{R} z_{is,k} = 1 \qquad ;s=1,\ldots,P\ ;k=1,\ldots,N \qquad (3.29)$$

$$\sum_{i=1}^{R} z_{is+1,k} \leq \sum_{i=1}^{R} z_{is,k} \leq \sum_{i=1}^{R} z_{i1,k} \qquad ;s=2,\ldots,P-1\ ;k=1,\ldots,N \qquad (3.30)$$

$$\min\left(\sum_{i=1}^{R}\sum_{s=1}^{P} z_{is,k+1}Q^{HP}_{cs} - \sum_{i=1}^{R}\sum_{s=1}^{P} z_{is,k}Q^{HP}_{cs}\right) + \sum_{i=1}^{R}\sum_{s=1}^{P} z_{is,k}W^{HP}_{is,k} \qquad ;k=1,\ldots,N-1 \qquad (3.31)$$

CHAPTER IV
RESULTS AND DISCUSSION

4.1 LNG Production

The methodologies for minimizing energy consumption are applied to LNG (Liquefied Natural Gas) production or Gas separation process. For this research, the base case process flow diagram of LNG production from Pro/II's tutorial using the Peng-Robinson cubic equation is shown in Figure4.1. It is used to study optimization of energy consumption. There are cascade refrigeration systems which consist ethane and propane as working fluid for cooling without the treatment units. First, Natural gas (NG) is cooled by the pre-cooler, propane as refrigerant in the first refrigeration system and ethane as refrigerant in the second refrigeration system. After cooling process, there are flash drum to separate the product into two phase. For the liquid product (LNG) is sent to storage for transport to the customers or other industries. Other gas product is used as pre-cooler in this process to reduce the cooling requirement. The given information for streams and composition of natural gas are shown in Table4.1 and Table4.2.

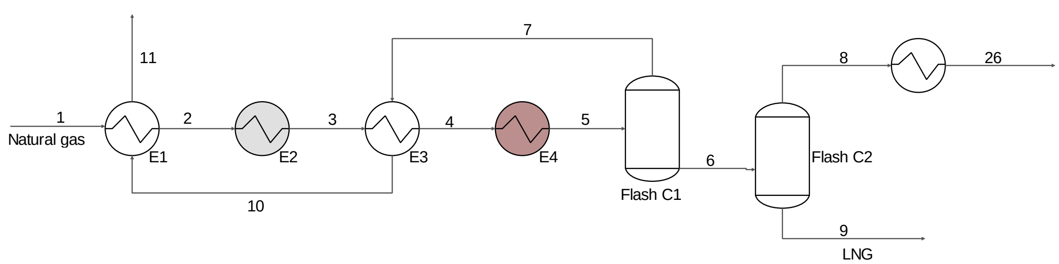

Figure 4.1 (a) Flow diagram of LNG process from Pro/II's tutorial.

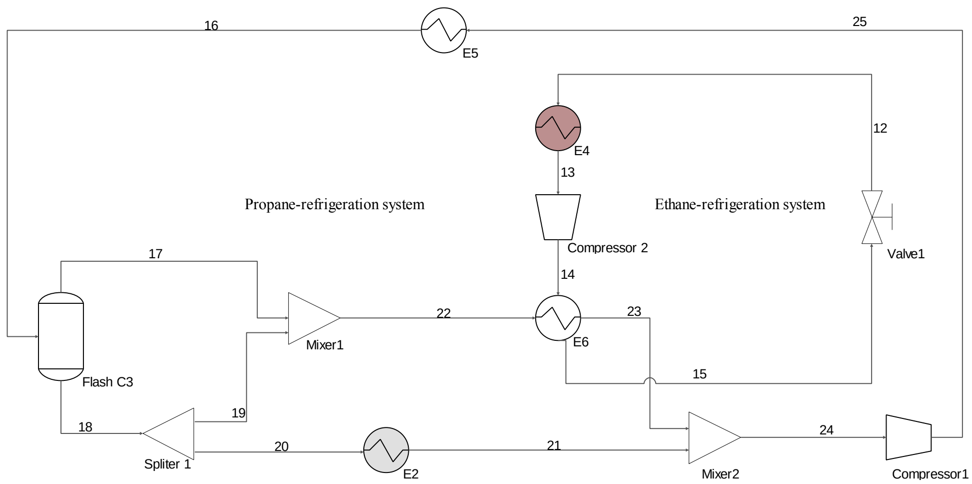

Figure 4.1 (b) Flow diagram of base case refrigeration system.

Table 4.1 Stream data of case study

No. stream	Fcp (kW / K)	T_{in} (K)	T_{out} (K)	P_{in} (atm)	P_{out} (atm)	ΔH (kW)	K
1 → 2	0.60	310.9	292.7	47.63	46.95	-10.92	1.47
2 → 3	0.74	292.7	234.8	46.95	46.27	-42.64	1.69
3 → 4	0.84	234.8	226.2	46.27	45.59	-7.18	1.96
4 → 5	1.87	226.2	197.0	45.59	45.59	-54.54	3.54
25 → 16	1.67	448.7	297.0	17.01	17.01	-252.59	-
14 → 15	0.68	393.6	244.3	42.53	42.19	-101.45	-
7 → 10	0.22	197.0	229.3	45.59	45.25	7.18	3.46
10 → 11	0.14	229.3	305.4	45.25	17.23	10.92	1.65
20 → 21	42.64	233.2	234.2	1.10	1.10	42.64	-
22 → 23	1.15	233.2	321.4	1.10	0.76	101.45	1.14
8 → 26	0.15	167.1	298.2	17.01	1.00	19.73	1.55
12 → 13	70.12	195.4	196.2	1.74	1.74	54.54	1.28

Table 4.2 Natural gas properties

Component	Composition	Mw (kg/kmol)	Mass Flow Rate (kg/hr)
methane	0.7871	16.04	660.7695
ethane	0.0819	30.07	68.7225
propane	0.0453	44.1	37.9925
i-butane	0.0163	58.12	13.7055
n-butane	0.0179	58.12	15.0233
i-pentane	0.00701	72.15	5.8891
n-pentane	0.00779	72.15	6.5435
n-hexane	0.0368	86.18	30.8716

4.1.1 Analysis of Process

According to Table 4.1, these streams construct the composite curves (CCs) to determine the utility requirement shown in Figure 4.2. This graph shows the process need a lot of cooling utility is around 232.85 kW and does not have heating requirement, which shows the non-overlapped zones between the cold streams and hot streams. In addition, the work used by compressor1 and compressor2 are 46.91kW and 108.49kW, respectively. Converting all interval temperature to exergetic temperature which conducts exergetic composite curves (ECCs), the ECCs for below ambient (25°C or T_0) and above ambient are shown in Figure 4.3(a) and Figure 4.3(b), respectively. Below T_0, there is no both exergy requirement and rejection. Above T_0, The exergy requirement and rejection are -56.52 kW and 2.2 kW, respectively. Concerning the Figure 4.3 (a), the cold stream (blue line) overlapped the hot stream (red line). Besides streams which cross each other, the exergy content cannot transfer completely in all intervals. Therefore, the LNG production should be improved by using methodologies. Therefore, there are three approaches that can synthesize the process and design grass-root process for cooling system.

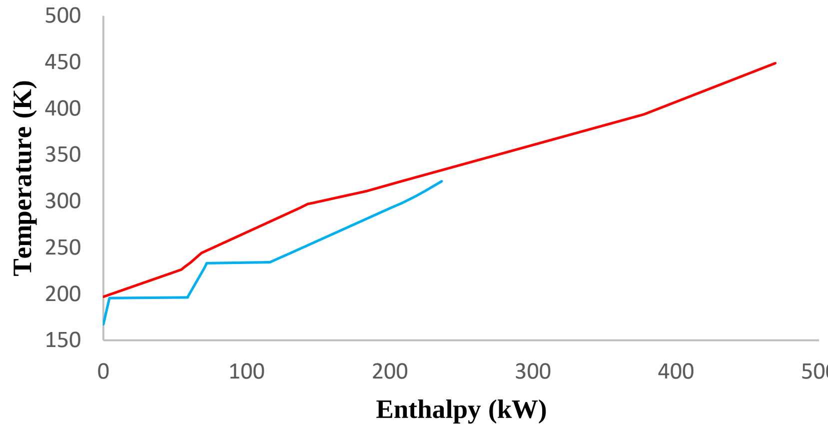

Figure 4.2 Composite curve of base case.

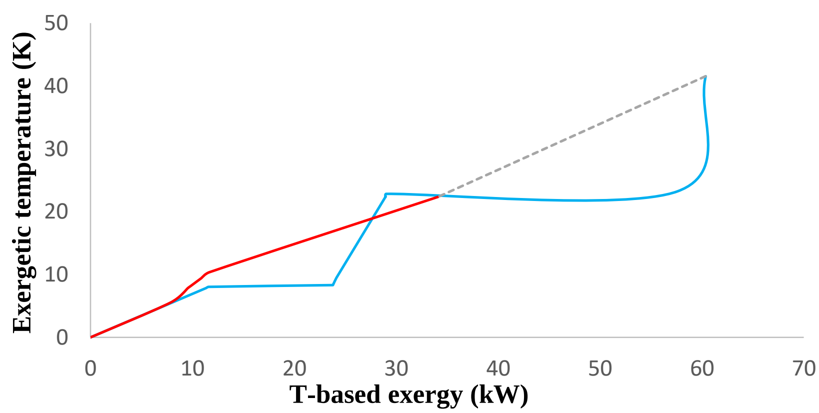

Figure 4.3 (a) Exergetic composite curves of base case for below ambient.

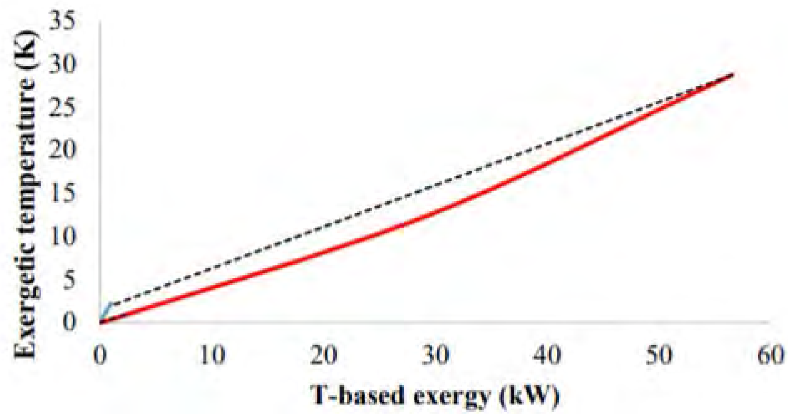

Figure 4.3 (b) Exergetic composite curves of base case for above ambient.

4.1.2 Combination of Heat Exchanger with Expansion and Compression Process

The ExPAnD model is applied to LNG production for indication of the proper sequence of adding expander or compressor to find the optimal conditions which are a reduction of energy consumption without using utilities. The efficiency factors for work by compressor and expander ($\eta_c$andη_e) are constant at 0.8 due to energy loss of these units by gas friction within the compressor and mechanical losses at bearings, seals and gear-box. In addition, the optimization model is used Evolutionary as the solving method to find the optimal solution for several case studies. For parameters in the optimizer, Convergence is 0.0001, Mutation rate is 0.075, Population size is set as 200 and Random seed is 0. Therefore, the objective function is the minimization of energy consumption in term of utility and work from turbo-machine (ΔW + Qh + Qc). Furthermore, the constraints for pressure and temperature are defined with the range of the supply value and the target value. Besides that, this work used stream No.11 and 26 which are in the LNG production because they have a lot of driving forces (ΔT is high). First, the pressure at stream No.11 is expanded from 45.25atm to 17.01atm. Second, the pressure at stream No.26 is expanded from 17.01 atm to 1atm. Especially, there are many alternative streams used in this model to optimize the energy consumption. Moreover, the refrigeration system is can be improved, using the gas or dense stream in refrigeration instead of these streams and changing the pressure at which the compressor state to decrease the cooling requirement are the alternative ways to optimize the base-case. When assuming flow rates and heat capacities be constant, process has 6 available turbo machines that can be added in process, there will be many alternative ways to gain better profits.

In case1, this process added four expanders, two are located between stream No.10 and 11 and the others are located between stream No. 8 and 26 shown in Figure4.4 (a). Furthermore, the decision variables are the inlet temperature at heat exchanger before the added turbo-machines, the pressure at expander1 and expander3. This case is formulated using the objective function given by Eq. (3.21) to find the proper position for adding turbo-machines before testing with exergy analysis to improve this process. Collecting the new stream data from the optimization to construct the new CCS as shown in Figure4.4 (b), there is one heat pinch at 203.36K /195.37 K, the cooling requirement is 183.46 kW and the work produced from the expanders is 39.51 kW. Results for the intermediate state variables are listed in Table4.3. These results indicate the process need more cooling requirement, therefore, this process should be added the extra expander to make the new synthesis of heat exchanger network that will be shown in next case.

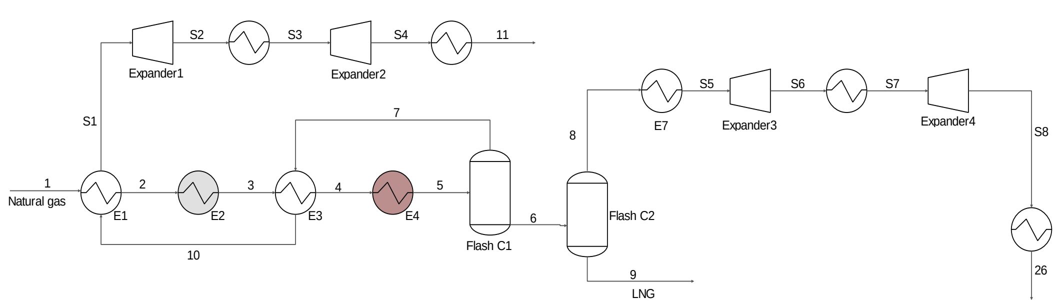

Figure 4.4 (a) Improved LNG process of case 1.

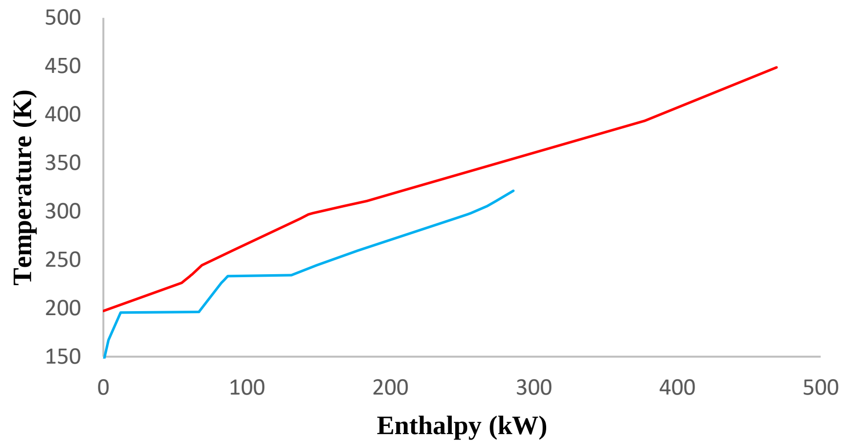

Figure 4.4 (b) Composite curves of improved case 1.

Table 4.3 Temperature and pressure results for improved case 1

Case1	Fc_p (kW / K)	T_{in} (K)	T_{out} (K)	P_{in} (bar)	P_{out} (bar)
10 → S2	0.14	229.26	305.37	45.85	26.05
S2 → S4	0.14	244.26	305.37	26.05	17.24
S4 → 11	0.14	259.43	305.37	17.24	17.24
8 → S6	0.15	167.12	298.15	17.24	7.90
S6 → S8	0.15	226.23	298.15	7.90	1.01
S8 → 26	0.15	144.11	298.15	1.01	1.01

In case2, this process will be added one extra expander from the case 2. Thus, there are five expanders, three expanders are located between stream No.10 and 11 and the others are located between stream No. 8 and 26 shown in Figure4.5 (a). This case is formulated using the objective function given by Eq. (3.21). The result of CCS is shown in Figure4.5 (b) can be defined, there is one heat pinch at 203.36K /195.37 K, the cooling requirement is 174.75 kW and the work produced from the expanders is 39.0 kW. Results for the intermediate state variables are listed in Table4.4. These results indicate the process still need more cooling requirement and no heating utility. Even if this case is installed one extra expander, it cannot reduce the utility consumption as expected.

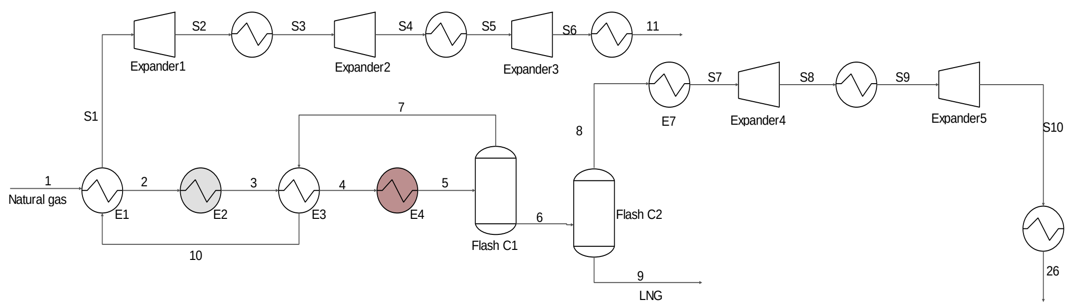

Figure 4.5 (a) Improved LNG process of case 2.

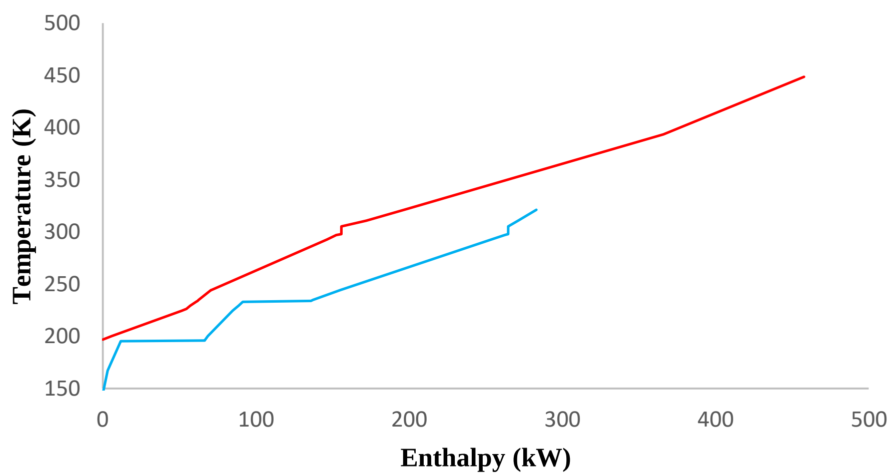

Figure 4.5 (b) Composite curves of improved case 2.

Table 4.4 Temperature and pressure results for improved case 2

Case2	Fc_p (kW / K)	T_{in} (K)	T_{out} (K)	P_{in} (bar)	P_{out} (bar)
10 → S2	0.14	229.26	305.37	45.85	26.05
S2 → S4	0.14	244.26	305.37	26.05	24.28
S4 → S6	0.14	297.04	229.26	24.28	17.24
S6 → 11	0.14	200.23	305.37	17.24	17.24
8 → S8	0.15	167.12	298.15	17.24	7.74
S8 → S10	0.15	224.60	298.15	7.74	1.01
S10 → 26	0.15	145.16	298.15	1.01	1.01

In case3, this process added five expanders and one compressor, 2 expanders and one compressor are located between stream No.10 and 11 and the others are located between stream No. 8 and 26 shown in Figure4.6 (a). This case is also formulated using the objective function given by Eq. (3.21). The CCS is shown in Figure4.6 (b). According to Figure4.6 (b), there is one heat pinch at 203.43K /195.37 K, the heating requirement is 77.05 kW and the work produced from the adding expanders is 41.01 kW, the work consumed from adding compressor is 3.15 kW. Results for the intermediate state variables are listed in Table4.5. These results indicate the improved process does not need more cooling requirement with heating utility as 77.05 kW.

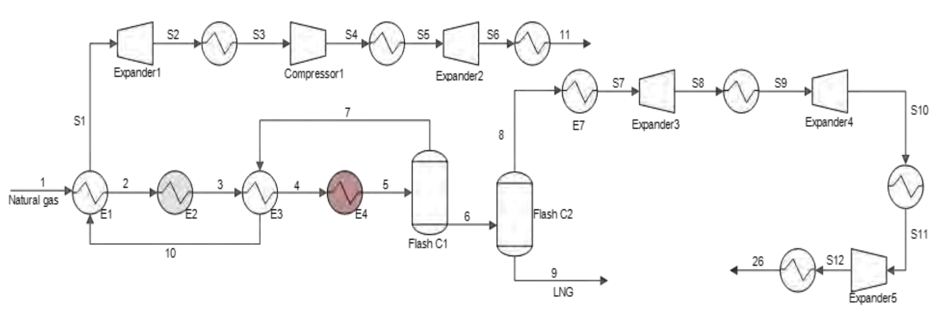

Figure 4.6 (a) Improved LNG process of case 3.

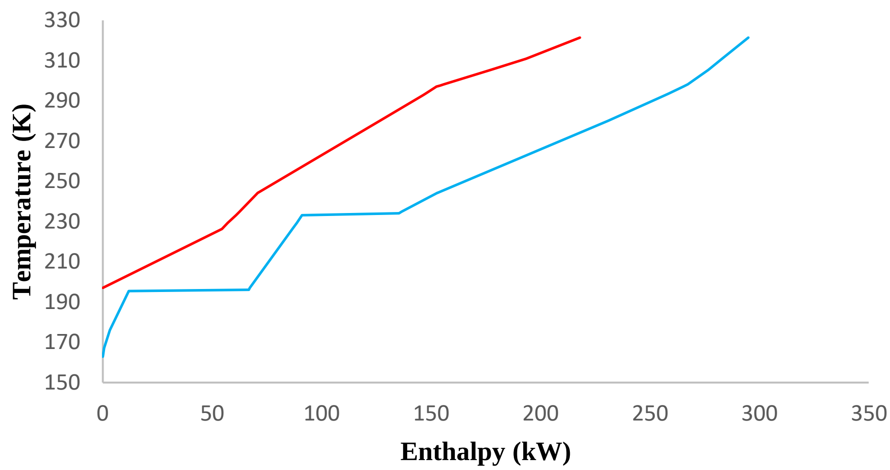

Figure 4.6 (b) Composite curves of improved case 3.

Table 4.5 Temperature and pressure results for improved case 3

Case3	Fc_p (kW / K)	T_{in} (K)	T_{out} (K)	P_{in} (bar)	P_{out} (bar)
10 → S2	0.14	229.26	293.55	45.85	28.84
S2 → S4	0.14	244.44	302.41	28.84	33.64
S4 → S6	0.14	321.36	229.26	33.64	17.24
S6 → 11	0.14	176.06	305.37	17.24	17.24
8 → S8	0.15	167.12	297.97	17.24	9.83
S8 → S10	0.15	244.28	298.15	9.83	5.60
S10 → S12	0.15	244.26	298.15	5.60	1.01
S12 → 26	0.15	162.81	298.15	1.01	1.01

In case4, no utility consumption is included as the constraint is used to optimize the proper design variable using four expanders and two compressors. Two compressors and one expander are added in each stream that shown in Figure4.7 (a). The objective function for this case study is formulated given by Eq. (3.21). The CCS is shown in Figure4.7 (b). There are one heat pinch at 204.04 K /195.37 K, no heating and cooling requirement, the work produced from the adding expanders is 48.14 kW and the work consumed from adding compressor is 18.76. Results for the intermediate state variables are listed in Table4.6.

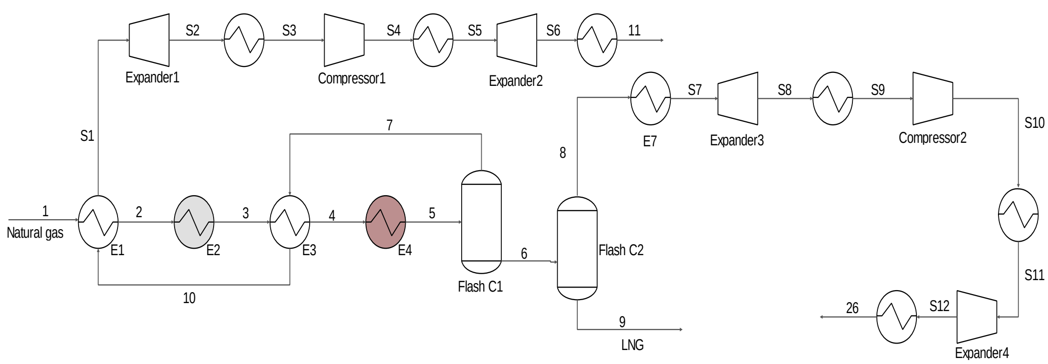

Figure 4.7 (a) Improved LNG process of case 4.

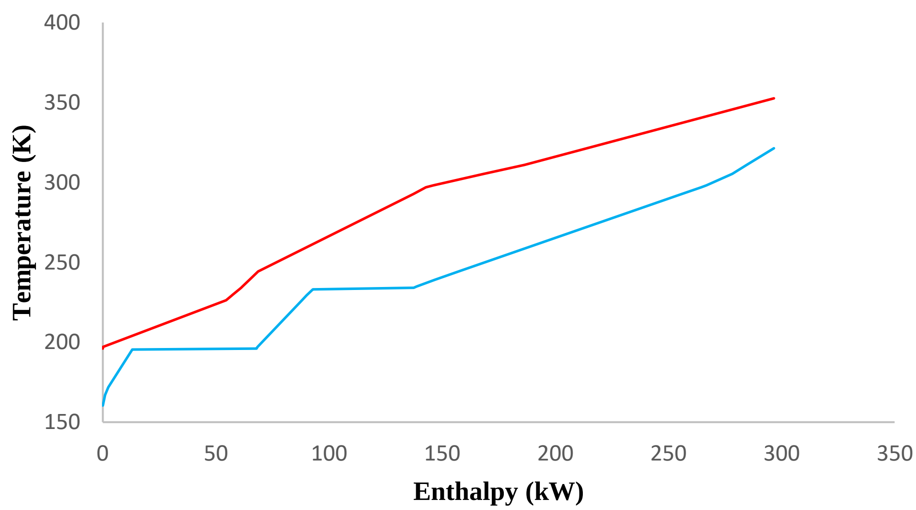

Figure 4.7 (b) Composite curves of improved case 4.

Table 4.6 Temperature and pressure results for improved case 4

Case4	Fc_p (kW / K)	T_{in} (K)	T_{out} (K)	P_{in} (bar)	P_{out} (bar)
10 → S2	0.14	229.26	305.37	45.85	24.67
S2 → S4	0.14	239.09	305.37	24.67	35.54
S4 → S6	0.14	352.70	305.37	35.54	17.24
S6 → 11	0.14	229.48	305.37	17.24	17.24
8 → S8	0.15	167.12	298.15	17.24	3.63
S8 → S10	0.15	171.86	298.15	3.63	5.84
S10 → S12	0.15	352.70	298.15	5.84	1.01
S12 → 26	0.15	160.37	298.15	1.01	1.01

Lastly, in case5, the exergetic composite curves (ECCS) is applied to this part to minimize two terms of energy quality. One term is the energy consumption of turbo-machine and utility. The other term is the exergy targets (exergy requirement, exergy rejection and exergy destruction). The new sequence is similar to the case 3 and T_0 = 298.15 K. Results for the intermediate state variables are listed in Table 4.7. The CCs and ECCs of this improved process are shown in Figure 4. In term of energy analysis, there are one heat pinch at 199.32 /195.37 K, no heating and cooling requirement, the work produced from the adding expanders is 47.51 kW and the work consumed from adding compressor is 9.80. In term of exergy analysis, below ambient case has no both of exergy requirement and exergy rejection. Above ambient case, the exergy requirement is 14.20 kW when exergy destruction is 13.17 kW and exergy deficit is 1.03 kW. The exergy rejection and exergy destruction are 10.43 kW while exergy surplus is 0 kW. In addition, both of above and below case are untraditional ECCs diagram. Because Eq. 3.3 is concerned only change of temperature of interval temperature, not phase change. Besides the phase change, it effects to Fc_p of process stream that must be higher. However the utility and work requirement in this case is lowest in all improved cases.

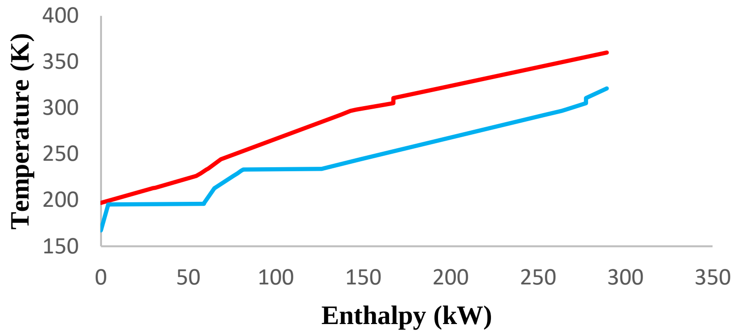

Figure 4.8 (a) Composite curves of improved case 5.

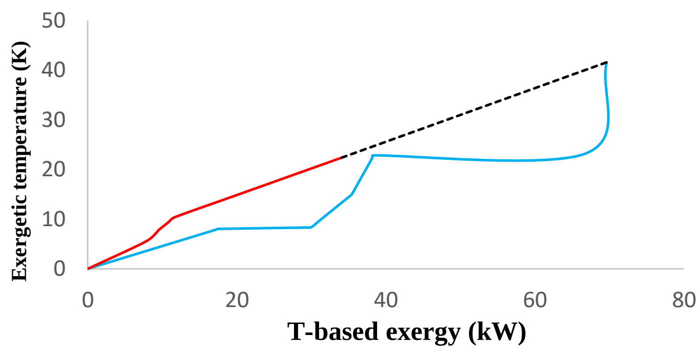

Figure 4.8 (b) Exergetic composite curves of improved case 5 for below ambient.

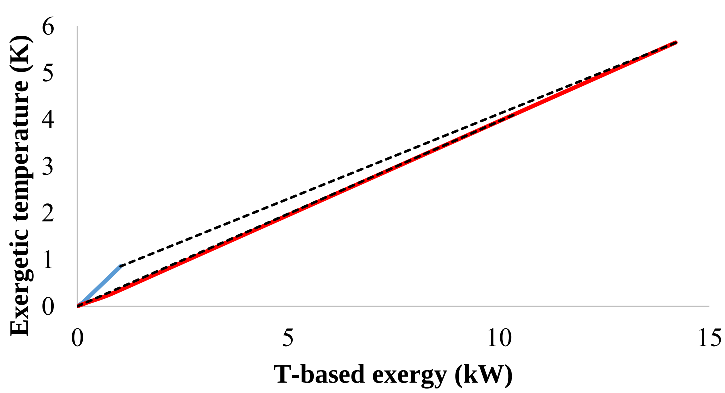

Figure 4.8 (c) Exergetic composite curves of improved case 5 for above ambient.

Table 4.7 Temperature and pressure results for improved case 5

Case5	Fc_p (kW / K)	T_{in} (K)	T_{out} (K)	P_{in} (bar)	P_{out} (bar)
10 → S2	0.14	229.26	305.37	45.85	22.83
S2 → S4	0.14	231.87	305.37	22.83	34.63
S4 → S6	0.14	360.01	305.37	34.63	17.24
S6 → 11	0.14	231.82	305.37	17.24	17.24
8 → S8	0.15	167.12	298.15	17.24	6.72
S8 → S10	0.15	213.64	298.15	6.72	2.62
S10 → S12	0.15	213.64	298.15	2.62	1.01
S12 → 26	0.15	212.98	298.15	1.01	1.01

This section concerned strongly a synthesis of heat integration with turbo-machine by setting the objective function as a minimization of utility consumption ($\Delta W + Qh + Qc$). Moreover, there are many objective functions to improve the case study such as economic. From results, this model can indicate the proper sequence of turbo-machine. Although, this methodology can be applied to reduce the energy consumption and define the proper sequences, this methodology does not concern in the capital cost (the turbo-machine and heat exchanger price) and the operating cost (the utility price). The results of energy consumption and saving for the utility and turbo machine are shown in Table4.8.

Table 4.8 Energy usage and energy saving in each improved case

Case	W_c (kW)	W_e (kW)	Hot Utility (kW)	Cold Utility (kW)	Overall Saving (kW)
Base case	0	0	0	232.85	0
Improved case 1	0	-39.51	0	183.46	88.90
Improved case 2	0	-39.00	0	174.75	97.10
Improved case 3	3.15	-41.01	77.05	0	193.66
Improved case 4	18.76	-48.14	0	0	262.23
Improved case 5	9.80	-47.51	0	0	270.56

4.1.3 Synthesis of Refrigeration System with Nitrogen

In this section, LNG production will be applied with a combination with ExPAnD method and ECCS diagram and mathematic programing to design a new grass-root refrigeration system which uses RB process (Reverse Brayton process) as the based system. In addition, RB process is well-known as liquefaction plants to cool natural gas on LNG ships by change pressure. The RB process flow sheet is shown in Figure 4.9, there are one hot stream: natural gas (stream 6 → 8) and one cooling cycle: nitrogen gas (stream 1 → 5). The RB process can be decomposed into four main parts: one boiler, one compressor, one condenser and one turbine. The evaporator or boiler heats a refrigerant steam in refrigeration cycle, which receives heat from the natural gas stream. The compressor consumes a lot of shaft-work to increase operating pressure to target condition. The condensers cools the working fluid. The turbine expands and cools the refrigerant stream that can produce work. Besides that, the working fluid in the cooling system is nitrogen as gas phase in the entire cooling cycle. Before synthesizing the LNG production, the energy requirement of case study requires cold utility around 232.8 kW and the work consumed by compression process as 155.4 kW. Moreover, inlet and target temperature of natural gas are 37.78 °C, -76.11 °C, respectively. There is no pressure drop in heat exchanger, which pressure is constant as 47.63 atm.

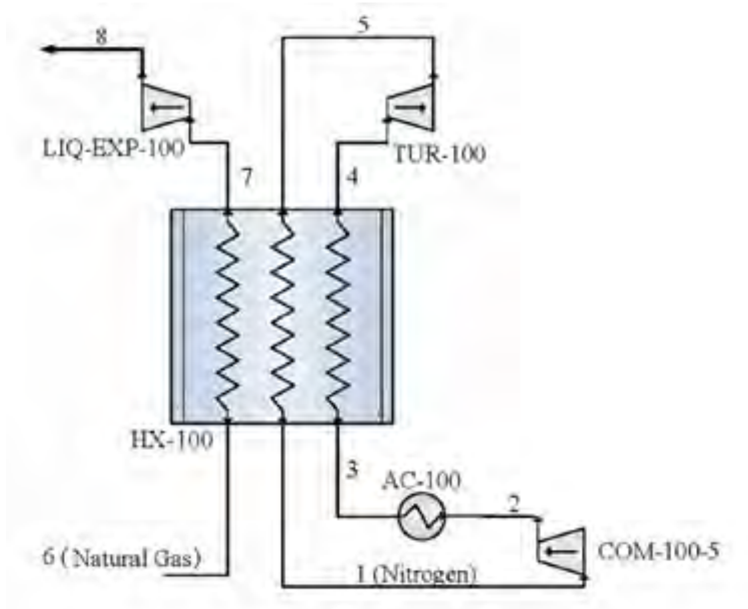

Figure 4.9 Flowsheet of Reverse Brayton process.

Table 4.9 Stream data of simplified design without considering pressure

No. stream	$\dot{\mathbf{M}}$ (kg/hr)	T_{in} (°C)	T_{out} (°C)	$\mathbf{T^{E^T}}_{\mathbf{in}}$ (K)	$\mathbf{T^{E^T}}_{\mathbf{out}}$ (K)	ΔH (kW)	$\Delta\mathbf{E^{E^T}}$ (kW)	K
6 → 7	839.52	37.78	-76.11	0.27	22.38	115.28	22.38	1.96
5 → 1	9749.30	-79.11	37.78	23.95	0.16	-326.40	-68.20	1.2
3 → 4	9749.30	37.78	-76.11	0.16	23.95	326.40	68.20	1.2

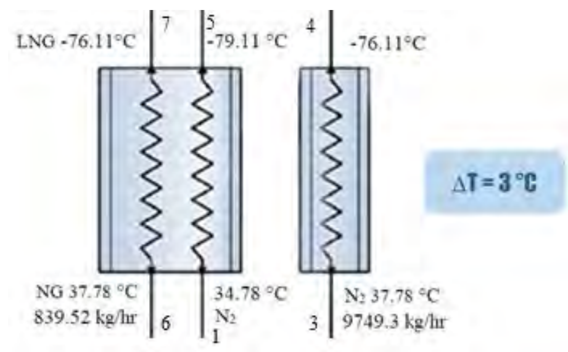

Figure 4.10 Flowsheet of simplified Reverse Brayton process.

Before synthesis of refrigeration system, the streams of RB process are decomposed into three main streams: one cold stream (5→1) and two hot streams (3→4 and 6→7) as shown in Figure 4.10. In order to manipulate operating condition, this process must conduct the simplified design before manipulating pressure. Moreover, the simplified process design will be concerned by setting the difference of temperature at heat exchanger is 3°C due to rules of thumb for design heat exchanger which is used gas as working fluid. Hence the operating temperature of coolant are 34.78°C and -79.11°C ($T_{hot\ stream}$ - 3°C) while mass flow rate of working fluid; which is used Nitrogen; is 9749.3 kg/hr. Stream data of simplified design without considering pressure is listed in Table 4.9 and CCs is shown in Figure 4.11.

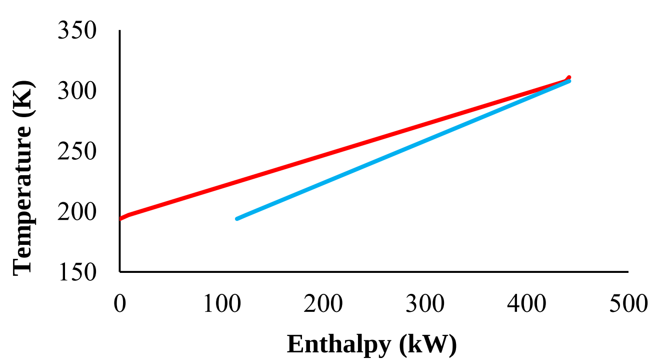

Figure 4.11 (a) Composite curves of simplified design without considering pressure.

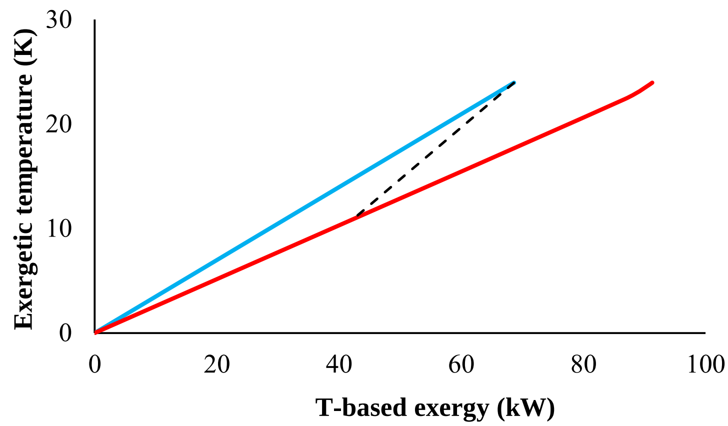

Figure 4.11 (b) Exergetic composite curves of below ambient for simplified design without considering pressure.

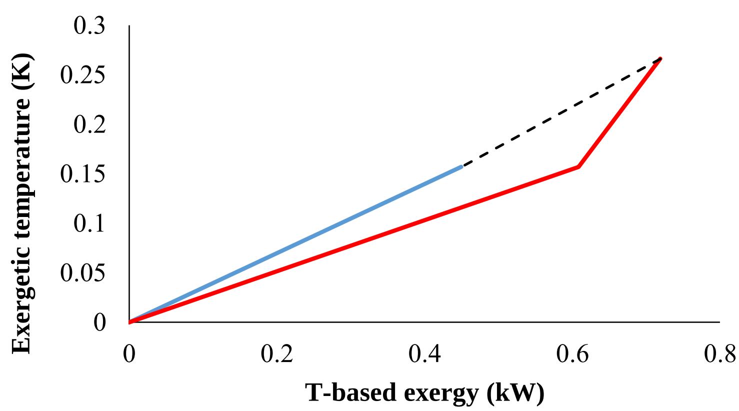

Figure 4.11 (c) Exergetic composite curves of above ambient for simplified design without considering pressure.

According to Figure 4.11 (a), hot utility is not required, cold utility is required around 115.28 kW to cool the temperature of hot process under -48.60 °C. When ambient conditions are 25°C and 1 atm, exergetic composite curves (ECCs) is conducted to two diagrams; below ambient and above ambient as shown in Figure 4.11 (b) and (c), respectively; is defined exergy targets that will be used for design of operating conditions in process that should be operated. Below ambient, the exergy requirement is 48.94 when exergy deficit and exergy destruction are 22.65 kW and 26.28 kW, respectively. While the exergy rejection is 0 kW, exergy surplus and exergy destruction are both 0 kW. Moreover, these streams in process have higher temperature more than ambient condition, so the above ambient case is need to be concerned. Above ambient, the cold stream crosses the hot stream, so this exergy diagram is untraditional because Fc_p of cold stream is quite more than Fc_p of hot streams a lot. In addition, exergy deficit is 0.45 kW while exergy destruction is 0.27 kW. Hence the exergy requirement is 0.72 kW. Moreover, the exergy rejection is 0.07 kW due to exergy destruction as -0.07 kW. Besides that, exergy source (hot streams) should be superior exergy sink (cold streams), thus this process is not feasible and must be improved by energy and exergy analysis.

In order to manipulate operating conditions of working fluid by adding compressor or expander, exergetic concept (Exergetic composite curves) should be applied in this process due to minimize exergy loss (exergy destruction) from heat exchanger and turbo-machine by concerning only the change of temperature and pressure at state 1 to state 2. In this part, design variables are mass flow rate of working fluid ($\dot{M}$), operating temperature (T_1, T_3, T_4) and operating pressure (P_2, P_5). Besides that, the energy recovery in this process is controlled by composite curves (CCs) and the hot process streams must be superior the cold process streams. Moreover, the outlet temperature of compressor and expander (T_2 and T_5) are expressed by isentropic equation (Eq. 3.7) using efficiency of turbo-machine as 0.8. The outlet temperature of expander (T_5) is less than the target temperature of natural gas stream (T_7); $T_5 < T_7$. In addition, the inlet temperature of compressor (T_1) is higher than the supply temperature of natural gas (T_6); $T_1 > T_6$. The temperature after AC-100 (T_3) and temperature before expander (T_4) are higher than temperature of cold stream to cool natural gas (5→1). Furthermore, all streams in cooling cycle are in gas phase, not concerned the phase change. Finally, objective function is minimization of exergy targets and total work requirement of compressor and expander.

Results from manipulating pressure for each streams of heat exchanger and turbo machines are listed in Table 4.10 and Table 4.11. Analysis diagrams are shown in Figure 4.12. The cold utility is required only as 409.40 kW while the heat pinch is located at 34.78 °C/37.86 °C. From ECCs, below ambient, the exergy requirement is 8.53 kW while exergy deficit and destruction are 74.96 kW and -66.43 kW, respectively. Both exergy surplus and destruction are 0 kW, so the exergy rejection is 0 kW. Above ambient, the exergy requirement is 86.67 kW while exergy deficit and destruction are -87.27 kW and 0.6 kW, respectively. The exergy surplus and exergy destruction are 0 kW and -0.05 kW, respectively. Consequently, the exergy rejection is 0.05 kW. In addition, the exergy efficiency is 0.77 calculated by Eq. 3.16 while exergy of heat for hot and cold utility (Exhu and Excu) expressed in Eq. 3.18 and 3.19 are 0 kW and 669.36 kW, respectively. Besides that, the temperature of hot utility and cold utility are 100 °C and -160 °C, respectively. However, this process can be still improved due to high exergy source by adding more expansion processes to increase the exergy sink of above ambient or cold process streams.

Table 4.10 Stream data of RB process with considering pressure for heat exchangers

No. stream	$\dot{M}$ (kg/hr)	T_{in} (°C)	T_{out} (°C)	$T^{E^T}_{in}$ (K)	$T^{E^T}_{out}$ (K)	ΔH (kW)	ΔE^T (kW)	K
6 → 7	839.52	37.78	-76.11	0.27	22.38	115.28	22.38	1.96
5 → 1	9749.3	-123.87	37.78	1.36	1.36	-448.89	-68.20	1.2
2 → 3	9749.3	181.31	37.78	9.43	9.43	409.64	-86.68	1.2
3 → 4	9749.3	37.78	-81.62	9.43	9.43	345.43	-161.92	1.2

Table 4.11 Stream data of RB process with considering pressure for compressor and expander

No. stream	T_{in} (°C)	T_{out} (°C)	P_{in} (atm)	P_{out} (atm)	ΔE^T (kW)	ΔE^P (kW)	W (kW)
1 → 2	34.78	181.31	1.36	9.43	86.07	271.61	413.81
4→ 5	-81.62	-123.87	9.43	1.36	81.66	-245.02	-107.62

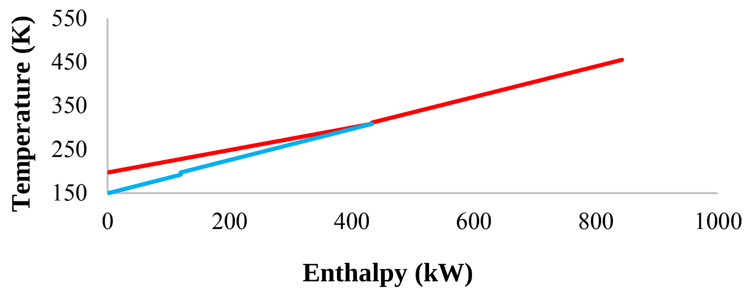

Figure 4.12 (a) Composite curves of RB process with pressure change.

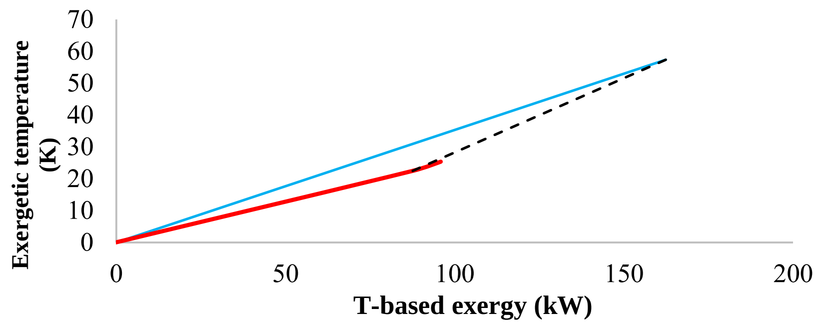

Figure 4.12 (b) Exergetic composite curves of below ambient for RB process with pressure change.

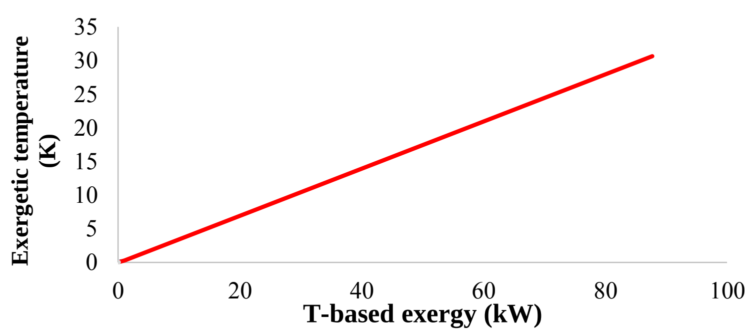

Figure 4.12 (c) Exergetic composite curves of above ambient for RB process with pressure change.

When considering the compression and expansion process, the work used and produced can be improved by adding the new heat exchangers to adjust inlet temperature before turbo-machines that it should be in right position, which means that the process must be installed compressor above pinch temperature or expander below pinch temperature if process is traditional heat recovery. Besides that, above heat pinch of traditional composite curves (CCs) required cooler. In contrast, below heat pinch required heater. Thus, these methodologies are applied to the RB process for designing a new cooling system by adding two new heat exchangers (AH1 and AH2) to control the inlet temperature before coming the compressor and turbine shown in Figure 4.13.

For optimization model, the operating condition or optimal solution will be indicated by the optimizer of evolutionary method in solver of excel. In addition, the evolutionary method is set parameters: convergence=0.0001, mutation rate=0.075, population size=200 and random seed=0. Design variables are listed as mass flow rate of refrigerant ($M_{Nitrogen}$), operating temperature at heat exchanger (T_{N1}, T_{N2}, T_{N4}, T_{N5}, T_{N6}) and operating pressure at turbine and compressor (P_{N3}, P_{N7}).

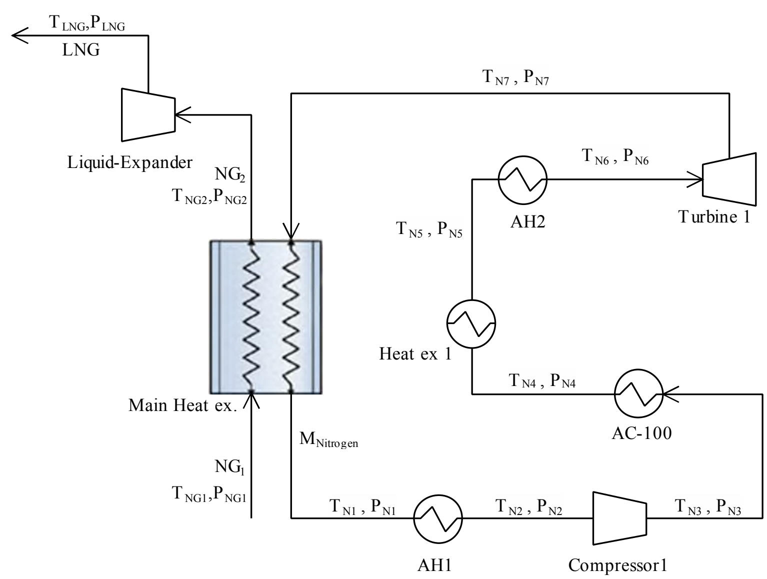

Figure 4.13 Synthesis of Reverse Brayton process.

For parameters, ΔT_{min} is set at least 3 K, T_0 is 298.15 K, the duty heat from boiler is constant as 115 kW, the mass flow rate of natural gas stream is 839.52 kg/hr, the efficiency of compressor and turbine (η_c and η_e) are 0.8 and the ratio of specific heats of nitrogen (k) is 1.2. In addition, enthalpy database of nitrogen come from Pro/II V9.4 (commercial software) by using Soave-Reddlich-Kwong (SRK) as thermodynamic model shown in App. A; Table A6. And, temperature which can indicate phase of nitrogen is shown in App. B; Table B6 and B7; come from Pro/II by using Soave-Reddlich-Kwong (SRK) as thermodynamic model.

For assumptions in optimization model, first, all heat exchanger do not have pressure drop. Second, the outlet temperature from turbo-machine (T_{N3} or T_{N7}) is expressed by isentropic equation (Eq. 3.7). Third, the duty heat from boiler must be transferred completely to cool in main heat exchanger. Finally, the relationship between enthalpy and temperature of nitrogen is linear. Besides that, the relationship between enthalpy and pressure of nitrogen is linear as well.

For constraints, first, a heat recovery must be transferred when cold streams overlapped and not crossed the hot streams in composite curves (CCs) and temperature of process stream between natural gas and coolant at main heat exchanger is not cross ($T_{NG1} \geq T_{N1}$ and $T_{NG2} \leq T_{N7}$). Second, a heating system is not added above the heat pinch or pinch temperature. Besides that, a cooling system is not added below the heat pinch as well. Third, mass flow rate of coolant is not more than 20 times of mass flow rate of natural gas stream ($20 \leq \frac{M_{Nitrogen}}{M_{Natural\ gas}} \leq 1$). In addition, for below pressure at critical point, the refrigerant is in gas phase or is above dew point temperature (sat. vapor) at concerned pressure using data from App. B; Table B6. Finally, for above pressure at critical point, the refrigerant which is in dense phase can indicate its phase by using data from App. B; Table B7. Moreover, the upper and lower boundary of design variables are shown in Table 4.12.

Table 4.12 Upper and lower boundary of design variable

Design variable Name	Upper Boundary	Lower Boundary
T_{N1} (°C)	200	-160
T_{N2} (°C)	200	-160
T_{N3} (°C)	200	-160
T_{N4} (°C)	200	-160
T_{N5} (°C)	200	-160
T_{N6} (°C)	200	-160
P_{N3}(atm)	120	1
P_{N7} (atm)	120	1

After optimizing, a composite curves (CCS) shown in Figure 4.14 (a) can be defined; this process has one heat pinch at 298.36K /301.37 K, the cooling requirement is 383.75 kW. The required work of compressor and produced work from turbine are 367.73 kW and 134.52 kW, respectively. For exergy analysis, an exergetic composite curves for below ambient (25°C) and above ambient are shown in Figure 4.14 (b) and Figure 4.14 (c), respectively. For overall process, the exergy requirement and rejection are -64.49 kW and 0 kW, respectively. Below ambient, the exergy requirement is 0 kW when exergy deficit and destruction are 44.76 kW and -44.76 kW, respectively. While the exergy rejection is 0 kW because both exergy surplus and exergy destruction are 0 kW. Above ambient, the exergy requirement is –64.42 kW while exergy deficit and exergy destruction are -64.49 kW and 0.07 kW, respectively. Exergy surplus is 0 kW and exergy destruction is -0.06 kW. Hence the exergy rejection is 0.06 kW. In addition, the operating results is shown in Table 4.13. Moreover, above ambient process after optimizing has more exergy source, so above ambient process is either required more exergy sink or energy sink (cold utility) or improved process by adding expander instead of using cold utility.

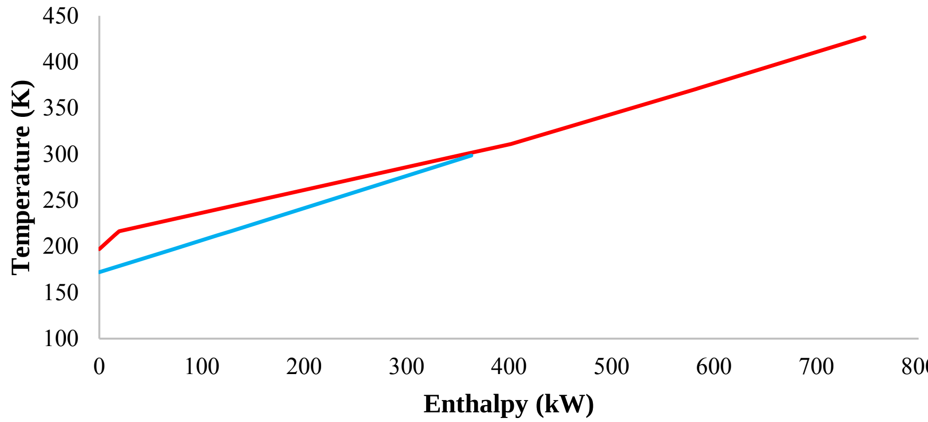

Figure 4.14 (a) Composite curves for synthesis of Reverse Brayton process.

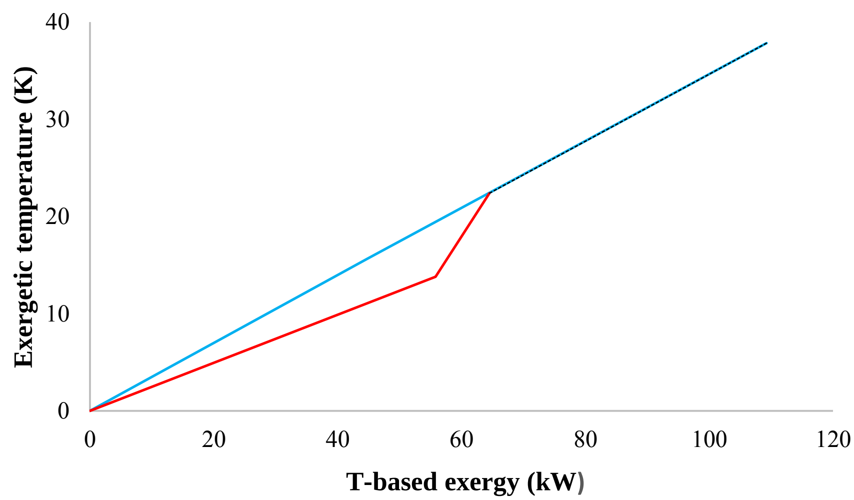

Figure 4.14 (b) Exergetic composite curves of below ambient for synthesis of Reverse Brayton process.

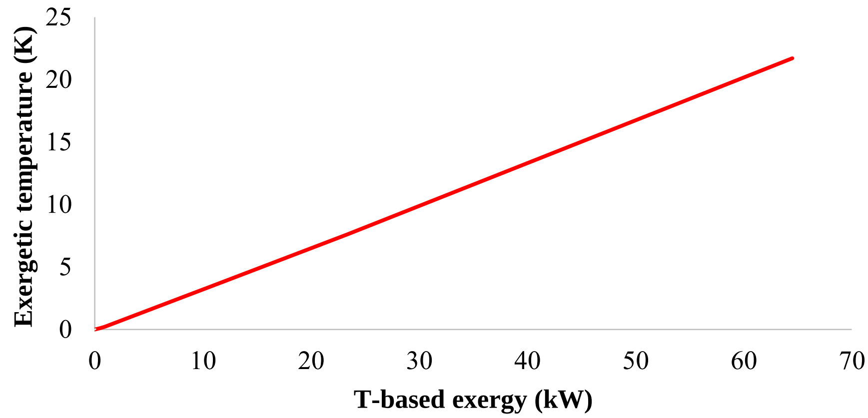

Figure 4.14 (c) Exergetic composite curves of above ambient for synthesis of Reverse Brayton process.

Table 4.13 Operating results of synthesis of RB process

Stream Name	Phase of Stream	Mass Flow Rate (kg/hr)	Temperature (°C)	Pressure (atm)
NG_1	Gas	839.52	37.78	47.63
NG_2	Mixed	839.52	-76.11	47.63
N_1	Gas	9749.30	-61.44	6.17
N_2	Gas	9749.30	25.22	6.17
N_3	Gas	9749.30	153.68	36.43
N_4	Gas	9749.30	97.98	36.43
N_5	Gas	9749.30	97.36	36.43
N_6	Gas	9749.30	-56.76	36.43
N_7	Gas	9749.30	-101.11	6.17

4.1.4 Design of Cascade Refrigeration Systems

When concerning typical cryogenic processes, most processes have been used cascade refrigeration systems to cool hot streams with dense-working fluid. Thus, a synthesis of cascade refrigeration systems is the typical model for designing new efficient cooling systems when there are alternative refrigerants. The condenser heat duty of LNG production is used as 232.85 kW to cool natural gas stream from 37.78 °C to -76.11 °C. In this work, the temperature of natural gas is divided into two intervals. First temperature interval is 37.78 °C to -38.15 °C. Second temperature interval is -38.15 °C to -76.11 °C. In addition, each interval can be cooled by five possible heat pumps. After applying the synthesis of cascade refrigeration systems to the LNG production, a new possible configuration is shown in Figure 4.15 when there are five types of refrigerant: Ethane, Ethylene, Propane, Propylene, R-12 (Dichlorodifluoromethane). Enthalpy data of all refrigerants is shown in App. A come from Pro/II by using SRK as thermodynamic model. Furthermore, each heat pump has simple refrigeration system as shown in Figure 4.16.

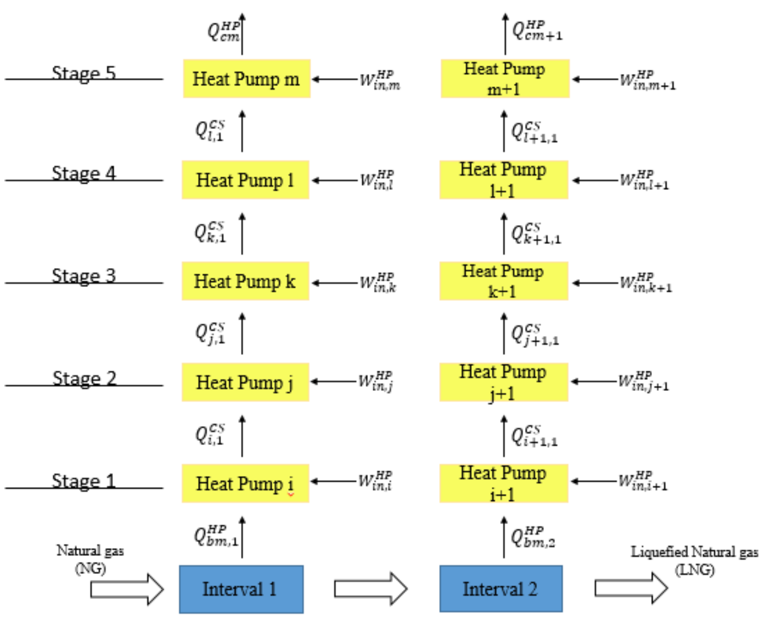

Figure 4.15 Configuration of cascade refrigeration system.

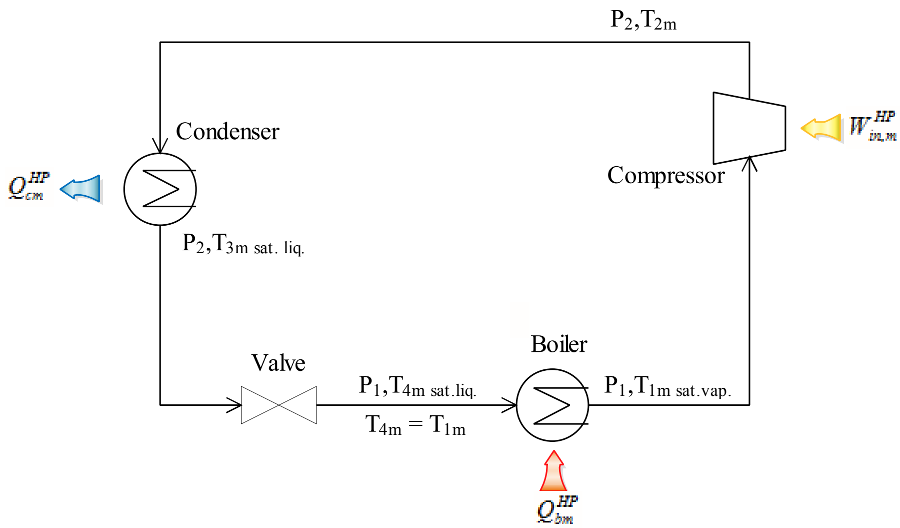

Figure 4.16 Diagram of simple refrigeration system.

According to Figure 4.16 (simple cooling system), there are five main steps for identifying shaft-work and heat duty at compressor and condenser, respectively. First, outlet temperature of refrigerant at boiler (T_{1m}) can be indicated by minimum temperature of hot stream follow by ΔT (T_{hot} -T_{cold}). Second, the saturated pressure (P_1) can be indicated by T_{1m} from App. B (Thermodynamic property of refrigerant). After randomization of outlet temperature from condenser (T_{3m}), the saturated pressure after compression (P_2) can be indicated by these design variables. Third, the outlet temperature after compression process (T_{2m}) can be expressed by Eq 3.7 using P_1, P_2, T_{1m} and k (ratio of specific heats or c_p / c_v) as parameters. Forth, the outlet enthalpy at valve is equal to enthalpy before entering the valve ($H_{l@t3m}$=H_3=H_4). Finally, mass of refrigerant (M_m^{HP}) will be calculated by Eq. 4.1. After five steps, the shaft work (W_{in}^{HP}) can be expressed in Eq. 4.2 by using the different value of enthalpy between inlet and outlet at compression process and mass of refrigerant. In addition, the heat duty (Q_c^{HP}) also can calculated by Eq. 4.3.

$$M_{m}^{HP} = Q_{bm}^{HP}/\left(h\{P_1, T_{1m}\} - h\{P_2, T_{3m,\text{sat vap.}}\}\right) \quad (4.1)$$

$$W_{in}^{HP} = M_{m}^{HP}\left(h\{P_2, T_{2m}\} - h\{P_1, T_{1m,\text{sat liq.}}\}\right) \quad (4.2)$$

$$Q_{c}^{HP} = M_{m}^{HP}\left(h\{P_2, T_{3m,\text{sat vap.}}\} - h\{P_2, T_{2m}\}\right) \quad (4.3)$$

The operating condition or optimal solution will be indicated by the optimizer (evolutionary method) in solver of excel. In addition, the evolutionary method is set parameters: convergence=0.0001, mutation rate=0.075, population size=200 and random seed=0. There are binary variables for selecting suitable working-fluid ($z_{is,k}$); denoting if cooling system chooses ethane as working fluid (i=1), chooses propane (i=2), chooses ethylene (i=3), chooses propylene (i=4), or chooses R-12 (i=5); and design variables for operating conditions which are outlet temperature from condenser (T_{3m}). The upper and lower boundary of design variables are shown in Table 4.14.

Table 4.14 Upper and lower boundary of design variables of cascade system

Design Variable	Upper Boundary	Lower Boundary
T_{3m} (°C) (i=1) Ethane	32.17	-88.28
T_{3m} (°C) (i=2) Propane	96.68	-41.88
T_{3m} (°C) (i=3) Ethylene	9.19	-103.61
T_{3m} (°C) (i=4) Propylene	92.42	-47.58
T_{3m} (°C) (i=5) R-12	111.8	-29.57
$z_{is,k}$ (i=1) Ethane (binary)	1	0
$z_{is,k}$ (i=2) Propane (binary)	1	0
$z_{is,k}$ (i=3) Ethylene (binary)	1	0
$z_{is,k}$ (i=4) Propylene (binary)	1	0
$z_{is,k}$ (i=5) R-12 (binary)	1	0

For assumptions, first, the different between hot stream and cold stream is 3 °C (ΔT=3 °C). Second, there are no pressure drop in all heat exchangers and no loss in all valves. In addition, T3m is always at saturated vapor condition. Besides that, T1m is always at saturated liquid condition. Furthermore, all of k value (c_p / c_v) are constant; k_{ethane} is 1.24, $k_{propane}$ is 1.11, $k_{ethylene}$ is 1.31, $k_{propylene}$ is 1.13 and $k_{R\text{-}12}$ is 1.12. Finally, a relationship between enthalpy and temperature of refrigerants is linear. Besides that, a relationship between enthalpy and pressure is also linear.

For constraints, Pressure before compression (P1) and Pressure after compression (P2) are between 1atm and P_{max} (Cricondenbar) shown in Table 4.15. Second, P_2 is always more than P_1 due to compress at compressor. Third, temperature at ambient condition is 25 °C, which means outlet temperature of condenser (T_{3m}) is always 28 °C if ΔT is 3 °C. Moreover, $\sum_{i=1}^{5} z_{is,k} \leq 1$, for each state of refrigeration systems, it can choose only one refrigerant that is propose the best shaft-work and heat duty for this state. Hence possible solution is 0 or 1. If solution is 0, there is no cooling system. If solution is 1, this state use one refrigerant in cooling system. Furthermore, $\sum_{i=1}^{R} z_{is+1,k} \leq \sum_{i=1}^{R} z_{is,k} \leq \sum_{i=1}^{R} z_{i1,k}$, this constraint means it does not allow to use cross state of cooling systems. In addition, $Q_{bs,k+1}^{HP} = Q_{cs,k}^{HP}$, next stage's heat pump can receive heat duty from condenser. Finally, $\frac{Q_{cm,s+1,k}^{CS}}{m_{s+1,k}} < \frac{Q_{cm,s,k}^{CS}}{m_{s,k}}$, which means the rate of heat duty at next state of condenser must be lower than its state.

Table 4.15 Constraints of pressure of refrigerants at saturated condition

Types of refrigerant	Upper Boundary for Pressure (atm)	Lower Boundary for Pressure (atm)
Ethane (i=1)	48.08	1
Propane (i=2)	41.92	1
Ethylene (i=3)	49.74	1
Propylene (i=4)	46.04	1
R-12 (i=5)	40.71	1

The objective function is minimum energy requirement in terms of heat duty of condensers and required work of compressors $\left(\sum_{i=1}^{R}\sum_{s=1}^{P} z_{is,k+1}Q_{cs}^{HP} - \sum_{i=1}^{R}\sum_{s=1}^{P} z_{is,k}Q_{cs}^{HP} + \sum_{i=1}^{R}\sum_{s=1}^{P} z_{is,k}W_{is,k}^{HP}\right)$, which is the net energy used by condenser and compressor. After optimization, results are shown in Figure 4.17, that first interval has four stages of cooling system using propane, propene, propane and propene as working fluid, respectively. Second, there are five stages of refrigeration systems using ethane, ethane, ethane, propane and propane as working fluid for each stage, respectively. For overall cascade refrigeration system, there is cooling utility around 176.49 kW, shaft-work by compressor as 57.38 kW and no work produced. In addition, operating results for each refrigeration system are shown in Table 4.16 and energy results are shown in Table 4.17.

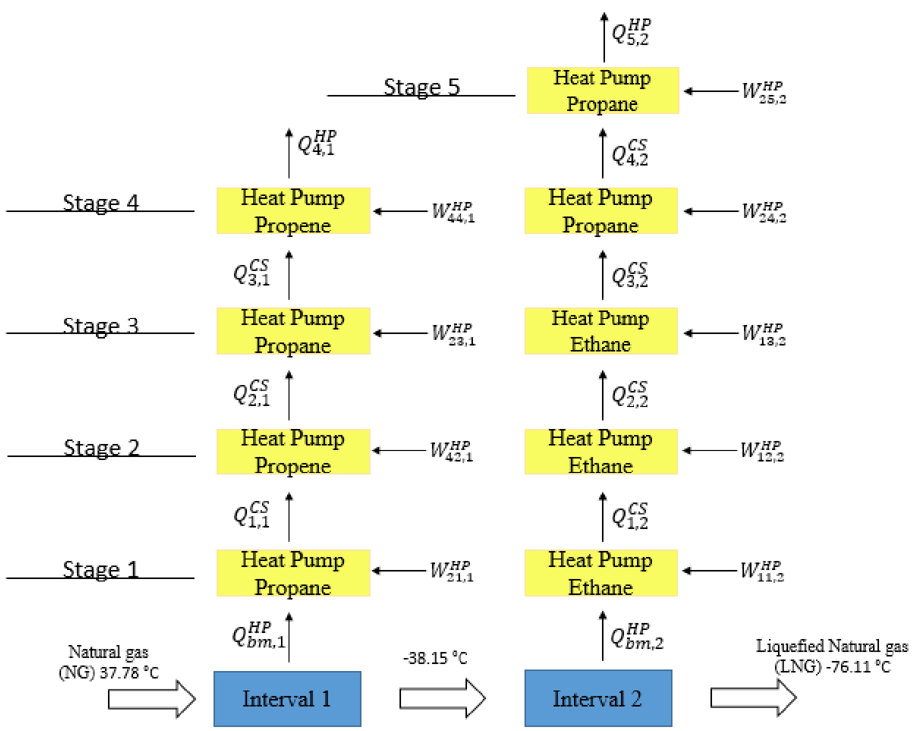

Figure 4.17 Configuration of cascade refrigeration system by optimization of energy used.

Table 4.16 (a) Operating results of interval 1 in cascade refrigeration system

Variable	Interval 1 (37.78 °C to -38.15 °C)			
	Stage1	Stage2	Stage3	Stage4
Mass flow rate (kg/hr)	521.47	551.93	681.41	689.39
T1m (°C)	-41.15	-16.46	-9.35	15.78
T2m (°C)	-8.72	-3.98	18.98	28.84
T3m (°C)	-13.46	-6.35	18.78	28.00
T4m (°C)	-41.15	-16.46	-9.35	15.78
P1 (atm)	1.04	3.46	3.48	9.11
P2 (atm)	3.04	4.82	8.00	12.41

Table 4.16 (b) Operating results of interval 2 in cascade refrigeration system

Variable	Interval 2 (-38.15 °C to -76.11 °C)				
	Stage1	Stage2	Stage3	Stage4	Stage5
Mass flow rate (kg/hr)	552.57	646.45	724.13	849.40	1204.07
T1m (°C)	-79.11	-61.26	-50.11	-41.38	-16.80
T2m (°C)	-32.31	-32.44	-27.48	-9.03	28.07
T3m (°C)	-58.26	-47.11	-38.38	-13.80	28.00
T4m (°C)	-79.11	-57.89	-41.61	-41.52	-16.28
P1 (atm)	1.62	3.56	5.43	1.03	2.70
P2 (atm)	4.00	6.03	8.09	3.00	10.15

Table 4.17 Energy results in cascade refrigeration system

	Interval 1 (37.78 °C to -38.15 °C)				Interval 2 (-38.15 °C to -76.11 °C)				
	Stage				Stage				
	1	2	3	4	1	2	3	4	5
Q_{bm}(kW)	53.02	58.74	60.75	62.17	66.08	75.62	81.40	86.51	95.70
Q_{cm}(kW)	58.74	60.75	62.17	64.32	75.62	81.40	86.51	95.70	112.17
Cold utility (kW)	64.32				112.17				
Shaft work(kW)	11.30				46.08				

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The growth of petrochemical industries has been increasing, so the methods which can reduce energy consumption are interesting. In this research, there are two types of analysis: an exergy and energy analysis. The exergy analysis is interesting when pressure and temperature are changed in term of thermo-mechanical exergy. For the exergy analysis, it represents a new energy parameter called exergetic temperature. These exergetic temperature can be conducted a new energy diagram called exergetic composite curves (ECCS). The ECCS can represent the exergy targets: exergy requirement, exergy rejection, exergy destruction, exergy deficit and exergy surplus. These exergy targets can be used for reducing the energy consumption of LNG production. In addition, the energy analysis is also important because it can support the analysis of process. For example, it can conduct the composite curves to check the overlap between hot streams and cold streams which does not cross each other. Thus, both exergy and energy analysis are very useful as following:-

An exergetic concept (exergy analysis) can be applied to the cooling system with gas coolant where both temperature and pressure are changed as design variables to decrease utility consumption.

An Extended Pinch Analysis and Design (ExPAnD) method and exergetic composite curves (ECCS) diagram can be used for designing a synthesis of heat exchanger networks with compression and expansion of process stream.

An ECCS and mathematic programing can be used for designing a new synthesis of LNG production with RB process (Reverse Brayton process) and improving the energy usage in term of shaft-work and utility consumption.

A synthesis of cascade refrigeration systems can design new cooling systems with efficient working fluid that uses cold utility less than base case and also uses lower shaft work.

Overall results from these methodologies are shown in Table 5.1.

Table 5.1 Summary of energy usage and energy saving for improved case and new design of cooling system

Case	W_c (kW)	W_e (kW)	Hot Utility (kW)	Cold Utility (kW)	Overall Saving (kW)
A Combination of Heat Exchanger with Expansion and Compression Process					
Base case	155.40	0	0	232.85	0
Improved case 1	155.40	-39.51	0	183.46	88.90
Improved case 2	155.40	-39.00	0	174.75	97.10
Improved case 3	158.55	-41.01	77.05	0	193.66
Improved case 4	174.16	-48.14	0	0	262.23
Improved case 5	165.20	-47.51	0	0	270.56
Cascade Refrigeration System with Alternative Refrigerants					
Grass-root design	57.38	0	0	176.49	0
Synthesis of Refrigeration System with Reverse Brayton Process					
Simplified design (RB process)	413.81	-107.62	0	409.40	0
Grass-root design	367.73	-134.52	0	383.75	98.63

5.2 Recommendations

The LNG production will be applied with the exergetic composite curves and the mathematic programing to synthesize the new design refrigeration system by using nitrogen as working fluid. These methodologies are consisted of energy and exergy analysis to minimize the consumed work from compressor and utility usage and to maximize the produced.

5.2.1 Synthesis of Heat Exchanger Networks with Compression and Expansion of Process Stream

Assuming the heat of capacity of streams is constant, these streams in case study are in gas phase. Thus, this model needs more acurate by concerning the effect of changing temperature for all gas streams.

5.2.2 Synthesis of Refrigeration System with RB Process

Database of nitrogen used as refrigerant come from Pro/II is large, so the opimizer (Evolutionary method) spent time a lot to find the opitimal solution. Therefore, regression of the data of enthalpy is neccessary.

5.2.3 Synthesis of Cascade Refrigeration Systems

In this model, there are many trial solutions and sub-problems in optimization due to many design variables, when concerning a large problem. Thus, the regression of enthalpy data for all refrigerants is important to reduce the time for solving the problem.

5.2.4 Optimization Model

An optimization model in this research is set an objective function as energy consumption and does not concern the capital cost for installed equipment. When the objective function is changed, the optimal solution will be changed as well. The energy consumption might be higher although the overall cost is lower than the case that does not concern the cost in objective function. So the change of objective function is interesting.

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APPENDICES

Appendix A Enthalpy Table of Refrigerants from Pro/II V 9.4

Table A1 Enthalpy database of ethane, x 10^6 [J/day] $[kg/hr]^{-1}$

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-250	-16.314	-16.299	-16.281	-16.263	-16.244	-16.226	-16.208	-16.190	-16.171	-16.153	-16.135	-16.117	-16.099
-245	-15.933	-15.918	-15.900	-15.882	-15.863	-15.845	-15.827	-15.809	-15.791	-15.772	-15.754	-15.736	-15.718
-240	-15.568	-15.554	-15.535	-15.517	-15.499	-15.481	-15.463	-15.445	-15.426	-15.408	-15.390	-15.372	-15.354
-235	-15.216	-15.202	-15.184	-15.165	-15.147	-15.129	-15.111	-15.093	-15.075	-15.057	-15.038	-15.020	-15.002
-230	-14.874	-14.860	-14.842	-14.824	-14.806	-14.787	-14.769	-14.751	-14.733	-14.715	-14.697	-14.679	-14.661
-225	-14.541	-14.526	-14.508	-14.490	-14.472	-14.454	-14.436	-14.418	-14.400	-14.381	-14.363	-14.345	-14.327
-220	-14.214	-14.199	-14.181	-14.163	-14.145	-14.127	-14.109	-14.091	-14.073	-14.055	-14.037	-14.019	-14.001
-215	-13.892	-13.878	-13.860	-13.842	-13.824	-13.806	-13.788	-13.770	-13.752	-13.734	-13.716	-13.698	-13.680
-210	-13.576	-13.561	-13.544	-13.526	-13.508	-13.490	-13.472	-13.454	-13.436	-13.418	-13.400	-13.382	-13.364
-205	-13.263	-13.249	-13.231	-13.213	-13.195	-13.177	-13.159	-13.142	-13.124	-13.106	-13.088	-13.070	-13.052
-200	-12.955	-12.940	-12.922	-12.905	-12.887	-12.869	-12.851	-12.833	-12.815	-12.797	-12.779	-12.761	-12.744
-195	-12.649	-12.634	-12.617	-12.599	-12.581	-12.563	-12.545	-12.528	-12.510	-12.492	-12.474	-12.456	-12.438
-190	-12.345	-12.331	-12.314	-12.296	-12.278	-12.260	-12.243	-12.225	-12.207	-12.189	-12.172	-12.154	-12.136
-185	-12.045	-12.030	-12.013	-11.995	-11.977	-11.960	-11.942	-11.924	-11.907	-11.889	-11.871	-11.854	-11.836
-180	-11.745	-11.731	-11.714	-11.696	-11.679	-11.661	-11.644	-11.626	-11.608	-11.591	-11.573	-11.556	-11.538
-175	-11.448	-11.434	-11.417	-11.399	-11.382	-11.364	-11.347	-11.329	-11.312	-11.294	-11.277	-11.259	-11.242
-170	-11.152	-11.138	-11.121	-11.104	-11.086	-11.069	-11.051	-11.034	-11.017	-10.999	-10.982	-10.964	-10.947
-165	-10.857	-10.844	-10.826	-10.809	-10.792	-10.774	-10.757	-10.740	-10.723	-10.705	-10.688	-10.671	-10.653
-160	-10.564	-10.550	-10.533	-10.516	-10.498	-10.481	-10.464	-10.447	-10.430	-10.413	-10.395	-10.378	-10.361

Table A1 Enthalpy database of ethane, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-155	-10.270	-10.257	-10.240	-10.223	-10.206	-10.189	-10.172	-10.155	-10.138	-10.121	-10.104	-10.086	-10.069
-150	-9.978	-9.964	-9.948	-9.931	-9.914	-9.897	-9.880	-9.863	-9.846	-9.829	-9.812	-9.796	-9.779
-145	-9.686	-9.672	-9.656	-9.639	-9.622	-9.606	-9.589	-9.572	-9.555	-9.539	-9.522	-9.505	-9.488
-140	-9.394	-9.380	-9.364	-9.347	-9.331	-9.314	-9.298	-9.281	-9.265	-9.248	-9.232	-9.215	-9.198
-135	-9.102	-9.089	-9.072	-9.056	-9.040	-9.023	-9.007	-8.991	-8.974	-8.958	-8.942	-8.925	-8.909
-130	-8.809	-8.797	-8.781	-8.765	-8.748	-8.732	-8.716	-8.700	-8.684	-8.668	-8.652	-8.635	-8.619
-125	-8.517	-8.504	-8.489	-8.473	-8.457	-8.441	-8.425	-8.409	-8.393	-8.377	-8.362	-8.346	-8.330
-120	-8.224	-8.211	-8.196	-8.180	-8.165	-8.149	-8.134	-8.118	-8.102	-8.087	-8.071	-8.055	-8.040
-115	-7.930	-7.918	-7.903	-7.888	-7.872	-7.857	-7.842	-7.826	-7.811	-7.796	-7.780	-7.765	-7.749
-110	-7.635	-7.624	-7.609	-7.594	-7.579	-7.564	-7.549	-7.534	-7.519	-7.504	-7.489	-7.474	-7.459
-105	-7.340	-7.328	-7.314	-7.299	-7.285	-7.270	-7.256	-7.241	-7.226	-7.212	-7.197	-7.182	-7.167
-100	-7.042	-7.031	-7.017	-7.003	-6.989	-6.975	-6.961	-6.947	-6.933	-6.918	-6.904	-6.889	-6.875
-95	-6.744	-6.733	-6.720	-6.706	-6.693	-6.679	-6.665	-6.651	-6.638	-6.624	-6.610	-6.596	-6.582
-90	-6.443	-6.433	-6.420	-6.407	-6.394	-6.381	-6.368	-6.355	-6.341	-6.328	-6.314	-6.301	-6.287
-85	5.717	-6.131	-6.119	-6.107	-6.094	-6.082	-6.069	-6.056	-6.043	-6.031	-6.018	-6.005	-5.991
-80	5.890	-5.827	-5.815	-5.804	-5.792	-5.780	-5.768	-5.756	-5.744	-5.732	-5.719	-5.707	-5.694
-75	6.063	-5.520	-5.509	-5.498	-5.487	-5.476	-5.465	-5.454	-5.442	-5.431	-5.419	-5.407	-5.395
-70	6.235	-5.210	-5.200	-5.190	-5.180	-5.170	-5.160	-5.149	-5.138	-5.127	-5.116	-5.105	-5.094
-65	6.410	-4.895	-4.886	-4.877	-4.868	-4.859	-4.850	-4.840	-4.830	-4.820	-4.810	-4.800	-4.789
-60	6.585	-4.575	-4.567	-4.560	-4.552	-4.544	-4.535	-4.527	-4.518	-4.509	-4.500	-4.491	-4.481
-55	6.762	-4.248	-4.242	-4.236	-4.230	-4.223	-4.216	-4.209	-4.201	-4.193	-4.185	-4.177	-4.168
-50	6.940	6.630	-3.911	-3.907	-3.902	-3.896	-3.891	-3.885	-3.879	-3.872	-3.865	-3.858	-3.851
-45	7.119	6.821	-3.572	-3.570	-3.567	-3.563	-3.559	-3.555	-3.550	-3.545	-3.540	-3.534	-3.528

Table A1 Enthalpy database of ethane, x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-40	7.301	7.014	-3.224	-3.224	-3.224	-3.223	-3.221	-3.218	-3.216	-3.212	-3.209	-3.204	-3.200
-35	7.484	7.207	-2.867	-2.870	-2.872	-2.873	-2.874	-2.874	-2.873	-2.872	-2.870	-2.868	-2.865
-30	7.669	7.402	7.015	-2.504	-2.510	-2.515	-2.518	-2.521	-2.523	-2.524	-2.525	-2.525	-2.524
-25	7.855	7.598	7.228	-2.126	-2.136	-2.144	-2.152	-2.158	-2.163	-2.167	-2.171	-2.173	-2.175
-20	8.044	7.795	7.442	-1.732	-1.747	-1.761	-1.773	-1.783	-1.792	-1.800	-1.807	-1.812	-1.817
-15	8.235	7.994	7.656	7.256	-1.341	-1.361	-1.379	-1.395	-1.409	-1.421	-1.432	-1.442	-1.450
-10	8.428	8.194	7.870	7.493	-0.912	-0.942	-0.968	-0.991	-1.011	-1.029	-1.045	-1.059	-1.072
-5	8.623	8.397	8.085	7.728	7.295	-0.496	-0.534	-0.566	-0.595	-0.620	-0.643	-0.663	-0.681
0	8.820	8.601	8.301	7.961	7.560	-0.015	-0.069	-0.116	-0.156	-0.192	-0.223	-0.251	-0.275
5	9.019	8.807	8.518	8.194	7.819	7.356	0.438	0.369	0.312	0.262	0.219	0.181	0.147
10	9.221	9.015	8.736	8.427	8.075	7.653	7.095	0.907	0.820	0.749	0.688	0.636	0.591
15	9.425	9.225	8.956	8.660	8.327	7.939	7.455	1.534	1.393	1.284	1.196	1.123	1.061
20	9.632	9.438	9.178	8.894	8.578	8.218	7.785	7.210	2.085	1.896	1.760	1.653	1.565
25	9.841	9.652	9.401	9.128	8.828	8.490	8.097	7.609	6.894	2.669	2.416	2.245	2.116
30	10.053	9.869	9.625	9.363	9.077	8.759	8.397	7.967	7.410	6.452	3.281	2.946	2.737
35	10.267	10.088	9.852	9.599	9.326	9.025	8.689	8.302	7.830	7.193	5.847	3.893	3.477
40	10.483	10.309	10.081	9.837	9.575	9.290	8.975	8.621	8.207	7.695	6.983	5.645	4.454
45	10.702	10.533	10.311	10.076	9.824	9.553	9.257	8.929	8.557	8.120	7.578	6.836	5.778
50	10.924	10.759	10.544	10.316	10.074	9.816	9.536	9.230	8.890	8.504	8.052	7.499	6.796
55	11.148	10.987	10.778	10.558	10.325	10.078	9.813	9.526	9.212	8.864	8.470	8.014	7.478
60	11.375	11.218	11.015	10.802	10.577	10.340	10.088	9.817	9.525	9.206	8.854	8.461	8.017
65	11.604	11.452	11.254	11.047	10.831	10.603	10.362	10.106	9.832	9.537	9.217	8.868	8.484
70	11.836	11.687	11.495	11.295	11.086	10.866	10.636	10.393	10.135	9.860	9.565	9.249	8.907
75	12.071	11.926	11.738	11.544	11.342	11.131	10.910	10.678	10.434	10.176	9.902	9.612	9.303

Table A1 Enthalpy database of ethane, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
80	12.308	12.166	11.984	11.795	11.599	11.396	11.184	10.962	10.730	10.487	10.231	9.962	9.679
85	12.547	12.409	12.232	12.049	11.859	11.662	11.458	11.246	11.025	10.795	10.554	10.303	10.041
90	12.790	12.655	12.482	12.304	12.120	11.930	11.734	11.530	11.319	11.100	10.873	10.637	10.392
95	13.035	12.903	12.734	12.561	12.383	12.199	12.010	11.814	11.612	11.403	11.188	10.965	10.735
100	13.282	13.154	12.989	12.821	12.648	12.470	12.287	12.098	11.905	11.705	11.500	11.289	11.072
105	13.532	13.407	13.246	13.082	12.914	12.742	12.565	12.383	12.197	12.006	11.810	11.610	11.404
110	13.785	13.662	13.506	13.346	13.183	13.015	12.844	12.669	12.490	12.307	12.119	11.928	11.733
115	14.040	13.920	13.768	13.612	13.453	13.291	13.125	12.956	12.783	12.607	12.427	12.244	12.059
120	14.298	14.181	14.032	13.880	13.726	13.568	13.407	13.244	13.077	12.907	12.735	12.560	12.382
125	14.558	14.444	14.298	14.150	14.000	13.847	13.691	13.533	13.372	13.208	13.042	12.874	12.704
130	14.821	14.709	14.567	14.423	14.276	14.128	13.976	13.823	13.667	13.509	13.349	13.188	13.024
135	15.087	14.977	14.838	14.698	14.555	14.410	14.263	14.114	13.964	13.811	13.657	13.501	13.344
140	15.355	15.248	15.112	14.975	14.836	14.695	14.552	14.408	14.262	14.114	13.965	13.815	13.664
145	15.625	15.520	15.388	15.254	15.118	14.981	14.842	14.702	14.561	14.418	14.274	14.129	13.983
150	15.898	15.796	15.666	15.535	15.403	15.269	15.134	14.998	14.861	14.722	14.583	14.443	14.302
155	16.174	16.073	15.947	15.819	15.690	15.560	15.428	15.296	15.163	15.028	14.893	14.758	14.622
160	16.451	16.353	16.230	16.105	15.979	15.852	15.724	15.595	15.466	15.335	15.205	15.073	14.942
165	16.732	16.636	16.515	16.393	16.270	16.146	16.022	15.896	15.770	15.644	15.517	15.390	15.263
170	17.015	16.921	16.802	16.683	16.563	16.443	16.321	16.199	16.077	15.954	15.831	15.707	15.584
175	17.300	17.208	17.092	16.976	16.859	16.741	16.622	16.504	16.384	16.265	16.145	16.026	15.906
180	17.588	17.498	17.384	17.271	17.156	17.041	16.926	16.810	16.694	16.578	16.461	16.345	16.229
185	17.878	17.790	17.679	17.568	17.456	17.344	17.231	17.118	17.005	16.892	16.779	16.666	16.553
190	18.171	18.084	17.976	17.867	17.758	17.648	17.538	17.428	17.318	17.208	17.098	16.988	16.878
195	18.466	18.381	18.275	18.168	18.061	17.954	17.847	17.740	17.632	17.525	17.418	17.311	17.205
200	18.763	18.680	18.576	18.472	18.367	18.263	18.158	18.053	17.949	17.844	17.740	17.636	17.532

Table A1 Enthalpy database of ethane, x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
205	19.063	18.981	18.880	18.778	18.676	18.573	18.471	18.369	18.267	18.165	18.063	17.962	17.861
210	19.365	19.285	19.186	19.086	18.986	18.886	18.786	18.686	18.587	18.487	18.388	18.290	18.192
215	19.669	19.591	19.494	19.396	19.298	19.201	19.103	19.006	18.908	18.812	18.715	18.619	18.523
220	19.976	19.900	19.804	19.708	19.613	19.517	19.422	19.327	19.232	19.137	19.043	18.950	18.857
225	20.285	20.210	20.117	20.023	19.930	19.836	19.743	19.650	19.557	19.465	19.373	19.282	19.191
230	20.597	20.523	20.431	20.340	20.248	20.157	20.066	19.975	19.885	19.794	19.705	19.616	19.527
235	20.910	20.838	20.749	20.659	20.569	20.480	20.391	20.302	20.214	20.126	20.038	19.951	19.865
240	21.226	21.156	21.068	20.980	20.892	20.805	20.718	20.631	20.545	20.459	20.373	20.288	20.204
245	21.545	21.476	21.389	21.303	21.217	21.132	21.047	20.962	20.877	20.793	20.710	20.627	20.545
250	21.865	21.797	21.713	21.629	21.545	21.461	21.377	21.295	21.212	21.130	21.048	20.968	20.887
255	22.188	22.122	22.039	21.956	21.874	21.792	21.710	21.629	21.549	21.468	21.389	21.310	21.231
260	22.513	22.448	22.367	22.286	22.205	22.125	22.045	21.966	21.887	21.809	21.731	21.654	21.577
265	22.840	22.777	22.697	22.618	22.539	22.460	22.382	22.304	22.227	22.151	22.075	21.999	21.924
270	23.170	23.107	23.029	22.952	22.874	22.797	22.721	22.645	22.569	22.495	22.420	22.347	22.273
275	23.502	23.440	23.364	23.288	23.212	23.137	23.062	22.987	22.914	22.840	22.768	22.696	22.624
280	23.836	23.775	23.700	23.626	23.552	23.478	23.405	23.332	23.260	23.188	23.117	23.046	22.977
285	24.172	24.113	24.039	23.966	23.893	23.821	23.749	23.678	23.608	23.537	23.468	23.399	23.331
290	24.510	24.452	24.380	24.308	24.237	24.167	24.096	24.027	23.957	23.889	23.821	23.753	23.687
295	24.851	24.794	24.723	24.653	24.583	24.514	24.445	24.377	24.309	24.242	24.175	24.109	24.044
300	25.193	25.137	25.068	24.999	24.931	24.863	24.796	24.729	24.663	24.597	24.532	24.467	24.404
305	25.538	25.483	25.415	25.348	25.281	25.214	25.148	25.083	25.018	24.954	24.890	24.827	24.765
310	25.885	25.831	25.765	25.699	25.633	25.568	25.503	25.439	25.376	25.313	25.250	25.189	25.127
315	26.234	26.181	26.116	26.051	25.987	25.923	25.860	25.797	25.735	25.673	25.612	25.552	25.492
320	26.585	26.534	26.470	26.406	26.343	26.280	26.218	26.157	26.096	26.036	25.976	25.917	25.858

Table A1 Enthalpy database of ethane, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
325	26.938	26.888	26.825	26.763	26.701	26.640	26.579	26.519	26.459	26.400	26.341	26.284	26.226
330	27.294	27.244	27.183	27.122	27.061	27.001	26.941	26.882	26.824	26.766	26.709	26.652	26.596
335	27.651	27.603	27.542	27.482	27.423	27.364	27.306	27.248	27.191	27.134	27.078	27.023	26.968
340	28.011	27.963	27.904	27.845	27.787	27.729	27.672	27.616	27.560	27.504	27.449	27.395	27.341
345	28.373	28.326	28.268	28.210	28.153	28.096	28.040	27.985	27.930	27.876	27.822	27.769	27.716
350	28.736	28.690	28.633	28.577	28.521	28.466	28.411	28.356	28.303	28.249	28.197	28.145	28.093
355	29.102	29.057	29.001	28.946	28.891	28.837	28.783	28.730	28.677	28.625	28.573	28.522	28.472
360	29.470	29.426	29.371	29.317	29.263	29.210	29.157	29.105	29.053	29.002	28.952	28.902	28.852
365	29.840	29.796	29.743	29.689	29.637	29.584	29.533	29.482	29.431	29.381	29.332	29.283	29.235
370	30.211	30.169	30.116	30.064	30.012	29.961	29.911	29.861	29.811	29.762	29.714	29.666	29.619
375	30.585	30.544	30.492	30.441	30.390	30.340	30.290	30.241	30.193	30.145	30.097	30.051	30.004
380	30.961	30.920	30.869	30.819	30.770	30.721	30.672	30.624	30.576	30.529	30.483	30.437	30.392
385	31.339	31.299	31.249	31.200	31.151	31.103	31.055	31.008	30.962	30.916	30.870	30.825	30.781
390	31.719	31.679	31.631	31.582	31.535	31.487	31.441	31.395	31.349	31.304	31.259	31.215	31.172
395	32.100	32.062	32.014	31.967	31.920	31.874	31.828	31.783	31.738	31.694	31.650	31.607	31.565
400	32.484	32.446	32.399	32.353	32.307	32.262	32.217	32.173	32.129	32.086	32.043	32.001	31.959

Table A2 Enthalpy database of ethylene, x 10^6 [J/day] [kg/hr]$^{-1}$

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-250	-15.807	-15.793	-15.775	-15.758	-15.740	-15.723	-15.705	-15.688	-15.670	-15.653	-15.636	-15.618	-15.601
-245	-15.455	-15.441	-15.423	-15.406	-15.389	-15.371	-15.354	-15.336	-15.319	-15.301	-15.284	-15.267	-15.249
-240	-15.119	-15.105	-15.088	-15.070	-15.053	-15.035	-15.018	-15.001	-14.983	-14.966	-14.948	-14.931	-14.914
-235	-14.796	-14.782	-14.764	-14.747	-14.730	-14.712	-14.695	-14.677	-14.660	-14.643	-14.625	-14.608	-14.590
-230	-14.482	-14.468	-14.451	-14.433	-14.416	-14.399	-14.381	-14.364	-14.346	-14.329	-14.312	-14.294	-14.277
-225	-14.176	-14.162	-14.145	-14.127	-14.110	-14.093	-14.075	-14.058	-14.041	-14.023	-14.006	-13.989	-13.972
-220	-13.876	-13.863	-13.845	-13.828	-13.811	-13.794	-13.776	-13.759	-13.742	-13.724	-13.707	-13.690	-13.673
-215	-13.582	-13.569	-13.551	-13.534	-13.517	-13.500	-13.482	-13.465	-13.448	-13.431	-13.414	-13.396	-13.379
-210	-13.293	-13.280	-13.262	-13.245	-13.228	-13.211	-13.194	-13.176	-13.159	-13.142	-13.125	-13.108	-13.091
-205	-13.008	-12.994	-12.977	-12.960	-12.943	-12.925	-12.908	-12.891	-12.874	-12.857	-12.840	-12.823	-12.806
-200	-12.725	-12.712	-12.695	-12.678	-12.661	-12.643	-12.626	-12.609	-12.592	-12.575	-12.558	-12.541	-12.524
-195	-12.446	-12.432	-12.415	-12.398	-12.381	-12.364	-12.347	-12.330	-12.313	-12.296	-12.279	-12.262	-12.245
-190	-12.169	-12.155	-12.138	-12.121	-12.104	-12.088	-12.071	-12.054	-12.037	-12.020	-12.003	-11.986	-11.969
-185	-11.893	-11.880	-11.863	-11.846	-11.830	-11.813	-11.796	-11.779	-11.762	-11.746	-11.729	-11.712	-11.695
-180	-11.620	-11.607	-11.590	-11.573	-11.557	-11.540	-11.523	-11.506	-11.490	-11.473	-11.456	-11.439	-11.423
-175	-11.348	-11.335	-11.318	-11.301	-11.285	-11.268	-11.252	-11.235	-11.218	-11.202	-11.185	-11.169	-11.152
-170	-11.077	-11.064	-11.047	-11.031	-11.014	-10.998	-10.981	-10.965	-10.948	-10.932	-10.915	-10.899	-10.882
-165	-10.807	-10.794	-10.777	-10.761	-10.745	-10.728	-10.712	-10.696	-10.679	-10.663	-10.647	-10.630	-10.614
-160	-10.537	-10.524	-10.508	-10.492	-10.476	-10.459	-10.443	-10.427	-10.411	-10.395	-10.378	-10.362	-10.346
-155	-10.268	-10.255	-10.239	-10.223	-10.207	-10.191	-10.175	-10.159	-10.143	-10.127	-10.111	-10.095	-10.079
-150	-9.998	-9.986	-9.970	-9.954	-9.939	-9.923	-9.907	-9.891	-9.875	-9.859	-9.843	-9.828	-9.812
-145	-9.729	-9.717	-9.701	-9.686	-9.670	-9.654	-9.639	-9.623	-9.608	-9.592	-9.576	-9.560	-9.545
-140	-9.459	-9.447	-9.432	-9.417	-9.401	-9.386	-9.371	-9.355	-9.340	-9.324	-9.309	-9.293	-9.278
-135	-9.189	-9.177	-9.162	-9.147	-9.132	-9.117	-9.102	-9.087	-9.071	-9.056	-9.041	-9.026	-9.010
-130	-8.918	-8.906	-8.891	-8.877	-8.862	-8.847	-8.832	-8.817	-8.803	-8.788	-8.773	-8.758	-8.743

Table A2 Enthalpy database of ethylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-125	-8.645	-8.634	-8.620	-8.605	-8.591	-8.576	-8.562	-8.547	-8.533	-8.518	-8.503	-8.489	-8.474
-120	-8.372	-8.360	-8.346	-8.332	-8.318	-8.304	-8.290	-8.276	-8.262	-8.248	-8.233	-8.219	-8.204
-115	-8.096	-8.085	-8.072	-8.058	-8.044	-8.031	-8.017	-8.003	-7.989	-7.976	-7.962	-7.948	-7.934
-110	-7.818	-7.808	-7.795	-7.782	-7.769	-7.755	-7.742	-7.729	-7.715	-7.702	-7.688	-7.675	-7.661
-105	-7.538	-7.528	-7.516	-7.503	-7.490	-7.478	-7.465	-7.452	-7.439	-7.426	-7.413	-7.400	-7.387
-100	4.334	-7.245	-7.234	-7.222	-7.210	-7.198	-7.186	-7.173	-7.161	-7.149	-7.136	-7.123	-7.111
-95	4.484	-6.960	-6.949	-6.937	-6.926	-6.915	-6.903	-6.892	-6.880	-6.868	-6.856	-6.844	-6.832
-90	4.634	-6.670	-6.660	-6.649	-6.639	-6.628	-6.618	-6.607	-6.596	-6.585	-6.574	-6.562	-6.551
-85	4.785	-6.376	-6.367	-6.358	-6.348	-6.338	-6.328	-6.318	-6.308	-6.298	-6.288	-6.277	-6.266
-80	4.937	-6.077	-6.069	-6.061	-6.053	-6.044	-6.035	-6.026	-6.017	-6.008	-5.998	-5.988	-5.979
-75	5.089	-5.773	-5.766	-5.759	-5.752	-5.745	-5.737	-5.729	-5.721	-5.713	-5.704	-5.696	-5.687
-70	5.243	4.942	-5.457	-5.452	-5.446	-5.440	-5.434	-5.427	-5.420	-5.413	-5.406	-5.398	-5.391
-65	5.397	5.109	-5.140	-5.137	-5.133	-5.129	-5.124	-5.119	-5.114	-5.108	-5.102	-5.096	-5.090
-60	5.552	5.276	-4.815	-4.814	-4.813	-4.810	-4.808	-4.805	-4.801	-4.797	-4.793	-4.788	-4.783
-55	5.709	5.443	-4.481	-4.482	-4.483	-4.484	-4.483	-4.482	-4.481	-4.479	-4.477	-4.474	-4.470
-50	5.867	5.611	5.242	-4.139	-4.144	-4.147	-4.150	-4.151	-4.153	-4.153	-4.153	-4.152	-4.151
-45	6.026	5.780	5.429	-3.783	-3.792	-3.799	-3.805	-3.810	-3.815	-3.818	-3.821	-3.822	-3.824
-40	6.186	5.949	5.614	-3.411	-3.425	-3.437	-3.448	-3.457	-3.465	-3.472	-3.478	-3.483	-3.488
-35	6.348	6.119	5.800	5.424	-3.039	-3.058	-3.075	-3.090	-3.103	-3.114	-3.125	-3.134	-3.141
-30	6.511	6.290	5.985	5.632	-2.628	-2.657	-2.682	-2.704	-2.724	-2.742	-2.757	-2.771	-2.783
-25	6.676	6.463	6.170	5.836	5.438	-2.226	-2.263	-2.296	-2.325	-2.351	-2.373	-2.394	-2.412
-20	6.843	6.636	6.355	6.039	5.670	5.210	-1.810	-1.858	-1.900	-1.937	-1.969	-1.998	-2.023
-15	7.011	6.811	6.541	6.240	5.896	5.482	-1.302	-1.377	-1.439	-1.493	-1.539	-1.579	-1.615
-10	7.182	6.988	6.727	6.440	6.117	5.739	5.263	-0.825	-0.925	-1.006	-1.073	-1.131	-1.181

Table A2 Enthalpy database of ethylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-5	7.354	7.166	6.915	6.640	6.335	5.986	5.566	5.003	-0.316	-0.452	-0.557	-0.642	-0.713
0	7.527	7.345	7.103	6.840	6.551	6.226	5.848	5.377	4.681	0.231	0.044	-0.092	-0.199
5	7.703	7.527	7.293	7.041	6.766	6.461	6.115	5.703	5.171	4.253	0.823	0.561	0.386
10	7.881	7.709	7.483	7.241	6.979	6.693	6.372	6.003	5.557	4.958	3.689	1.458	1.096
15	8.061	7.894	7.675	7.442	7.192	6.921	6.622	6.286	5.896	5.418	4.762	3.476	2.088
20	8.242	8.081	7.869	7.644	7.405	7.148	6.867	6.558	6.208	5.801	5.301	4.625	3.595
25	8.426	8.269	8.064	7.847	7.618	7.373	7.108	6.821	6.502	6.143	5.726	5.221	4.578
30	8.612	8.459	8.260	8.051	7.831	7.597	7.347	7.077	6.784	6.461	6.097	5.680	5.192
35	8.800	8.651	8.458	8.256	8.044	7.820	7.583	7.330	7.057	6.761	6.436	6.076	5.671
40	8.989	8.845	8.658	8.462	8.258	8.044	7.818	7.578	7.323	7.050	6.754	6.434	6.083
45	9.182	9.041	8.859	8.670	8.473	8.267	8.051	7.824	7.584	7.329	7.058	6.767	6.455
50	9.376	9.239	9.062	8.879	8.689	8.491	8.284	8.068	7.841	7.602	7.350	7.084	6.801
55	9.572	9.438	9.267	9.089	8.905	8.715	8.517	8.311	8.095	7.870	7.635	7.388	7.129
60	9.770	9.640	9.473	9.301	9.123	8.940	8.750	8.552	8.348	8.135	7.913	7.682	7.443
65	9.971	9.844	9.682	9.515	9.343	9.165	8.982	8.793	8.598	8.396	8.187	7.970	7.746
70	10.174	10.050	9.892	9.730	9.563	9.392	9.216	9.034	8.847	8.655	8.456	8.252	8.042
75	10.378	10.258	10.104	9.946	9.785	9.619	9.449	9.275	9.096	8.912	8.723	8.530	8.332
80	10.585	10.468	10.318	10.165	10.008	9.848	9.684	9.516	9.344	9.168	8.988	8.804	8.616
85	10.795	10.680	10.534	10.385	10.233	10.078	9.919	9.757	9.592	9.423	9.251	9.076	8.898
90	11.006	10.894	10.752	10.607	10.459	10.309	10.155	9.999	9.840	9.678	9.513	9.346	9.176
95	11.219	11.110	10.971	10.830	10.687	10.541	10.392	10.242	10.088	9.932	9.774	9.614	9.451
100	11.435	11.328	11.193	11.056	10.916	10.775	10.631	10.485	10.337	10.187	10.034	9.881	9.725
105	11.653	11.548	11.417	11.283	11.147	11.010	10.870	10.729	10.586	10.441	10.295	10.147	9.998
110	11.872	11.771	11.642	11.512	11.380	11.246	11.111	10.974	10.836	10.696	10.555	10.412	10.269

Table A2 Enthalpy database of ethylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
115	12.094	11.995	11.870	11.743	11.614	11.484	11.353	11.220	11.086	10.951	10.815	10.678	10.540
120	12.318	12.221	12.099	11.975	11.850	11.724	11.596	11.467	11.338	11.207	11.075	10.943	10.810
125	12.545	12.450	12.330	12.209	12.088	11.965	11.841	11.716	11.590	11.463	11.336	11.208	11.080
130	12.773	12.680	12.563	12.446	12.327	12.207	12.087	11.965	11.843	11.721	11.598	11.474	11.350
135	13.003	12.913	12.799	12.684	12.568	12.451	12.334	12.216	12.098	11.979	11.860	11.740	11.620
140	13.236	13.147	13.036	12.924	12.811	12.697	12.583	12.469	12.354	12.238	12.123	12.007	11.891
145	13.470	13.384	13.275	13.165	13.055	12.945	12.834	12.722	12.610	12.498	12.386	12.274	12.162
150	13.707	13.622	13.516	13.409	13.302	13.194	13.086	12.977	12.868	12.760	12.651	12.542	12.433
155	13.945	13.863	13.759	13.654	13.550	13.444	13.339	13.233	13.128	13.022	12.916	12.811	12.705
160	14.186	14.105	14.003	13.902	13.799	13.697	13.594	13.491	13.388	13.286	13.183	13.080	12.978
165	14.429	14.349	14.250	14.151	14.051	13.951	13.851	13.751	13.650	13.550	13.450	13.351	13.251
170	14.673	14.596	14.499	14.401	14.304	14.206	14.109	14.011	13.914	13.816	13.719	13.622	13.526
175	14.920	14.844	14.749	14.654	14.559	14.464	14.369	14.273	14.178	14.084	13.989	13.895	13.801
180	15.169	15.095	15.002	14.909	14.816	14.723	14.630	14.537	14.445	14.352	14.260	14.168	14.077
185	15.419	15.347	15.256	15.165	15.074	14.984	14.893	14.802	14.712	14.622	14.532	14.443	14.355
190	15.672	15.601	15.512	15.423	15.335	15.246	15.157	15.069	14.981	14.893	14.806	14.719	14.633
195	15.927	15.857	15.770	15.683	15.597	15.510	15.424	15.337	15.252	15.166	15.081	14.996	14.912
200	16.183	16.115	16.030	15.945	15.860	15.776	15.691	15.607	15.523	15.440	15.357	15.275	15.193
205	16.442	16.375	16.292	16.209	16.126	16.043	15.961	15.879	15.797	15.716	15.635	15.554	15.474
210	16.702	16.637	16.555	16.474	16.393	16.312	16.232	16.152	16.072	15.992	15.914	15.835	15.757
215	16.964	16.900	16.821	16.741	16.662	16.583	16.504	16.426	16.348	16.271	16.194	16.117	16.042
220	17.229	17.166	17.088	17.010	16.933	16.856	16.779	16.702	16.626	16.551	16.475	16.401	16.327
225	17.495	17.433	17.357	17.281	17.205	17.130	17.055	16.980	16.906	16.832	16.758	16.686	16.614
230	17.763	17.703	17.628	17.553	17.479	17.405	17.332	17.259	17.186	17.114	17.043	16.972	16.901

Table A2 Enthalpy database of ethylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
235	18.033	17.974	17.901	17.828	17.755	17.683	17.611	17.540	17.469	17.399	17.329	17.259	17.191
240	18.304	18.247	18.175	18.104	18.033	17.962	17.892	17.822	17.753	17.684	17.616	17.548	17.481
245	18.578	18.521	18.451	18.381	18.312	18.243	18.174	18.106	18.038	17.971	17.905	17.839	17.773
250	18.853	18.798	18.729	18.661	18.593	18.525	18.458	18.392	18.325	18.260	18.195	18.130	18.066
255	19.130	19.076	19.009	18.942	18.876	18.810	18.744	18.679	18.614	18.550	18.486	18.423	18.361
260	19.410	19.357	19.291	19.225	19.160	19.095	19.031	18.967	18.904	18.841	18.779	18.718	18.657
265	19.690	19.638	19.574	19.510	19.446	19.383	19.320	19.258	19.196	19.134	19.074	19.014	18.954
270	19.973	19.922	19.859	19.796	19.734	19.672	19.610	19.549	19.489	19.429	19.370	19.311	19.253
275	20.257	20.208	20.146	20.084	20.023	19.963	19.902	19.843	19.784	19.725	19.667	19.610	19.553
280	20.544	20.495	20.434	20.374	20.314	20.255	20.196	20.138	20.080	20.023	19.966	19.910	19.854
285	20.831	20.784	20.724	20.665	20.607	20.549	20.491	20.434	20.378	20.322	20.266	20.211	20.157
290	21.121	21.074	21.016	20.958	20.901	20.844	20.788	20.732	20.677	20.622	20.568	20.514	20.461
295	21.413	21.367	21.310	21.253	21.197	21.142	21.086	21.032	20.978	20.924	20.871	20.818	20.767
300	21.706	21.661	21.605	21.550	21.495	21.440	21.386	21.333	21.280	21.227	21.176	21.124	21.074
305	22.001	21.957	21.902	21.848	21.794	21.741	21.688	21.636	21.584	21.532	21.482	21.432	21.382
310	22.297	22.254	22.201	22.147	22.095	22.043	21.991	21.940	21.889	21.839	21.789	21.740	21.692
315	22.595	22.553	22.501	22.449	22.397	22.346	22.296	22.245	22.196	22.147	22.098	22.050	22.003
320	22.895	22.854	22.803	22.752	22.701	22.651	22.602	22.553	22.504	22.456	22.409	22.362	22.315
325	23.197	23.157	23.106	23.056	23.007	22.958	22.909	22.861	22.814	22.767	22.721	22.675	22.629
330	23.500	23.461	23.411	23.362	23.314	23.266	23.219	23.172	23.125	23.079	23.034	22.989	22.945
335	23.805	23.766	23.718	23.670	23.623	23.576	23.530	23.484	23.438	23.393	23.349	23.305	23.261
340	24.112	24.074	24.027	23.980	23.933	23.887	23.842	23.797	23.752	23.708	23.665	23.622	23.579
345	24.420	24.383	24.336	24.291	24.245	24.200	24.156	24.112	24.068	24.025	23.983	23.941	23.899
350	24.730	24.693	24.648	24.603	24.559	24.515	24.471	24.428	24.385	24.343	24.302	24.261	24.220

Table A2 Enthalpy database of ethylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
355	25.042	25.006	24.961	24.917	24.874	24.831	24.788	24.746	24.704	24.663	24.622	24.582	24.542
360	25.355	25.319	25.276	25.233	25.190	25.148	25.106	25.065	25.024	24.984	24.944	24.905	24.866
365	25.669	25.635	25.592	25.550	25.508	25.467	25.426	25.386	25.346	25.306	25.267	25.229	25.191
370	25.986	25.952	25.910	25.869	25.828	25.787	25.747	25.708	25.669	25.630	25.592	25.554	25.517
375	26.303	26.270	26.229	26.189	26.149	26.109	26.070	26.032	25.993	25.956	25.918	25.881	25.845
380	26.623	26.590	26.550	26.511	26.472	26.433	26.395	26.357	26.319	26.282	26.246	26.210	26.174
385	26.944	26.912	26.873	26.834	26.796	26.758	26.720	26.683	26.647	26.610	26.575	26.540	26.505
390	27.266	27.235	27.197	27.159	27.121	27.084	27.047	27.011	26.975	26.940	26.905	26.871	26.837
395	27.590	27.560	27.522	27.485	27.448	27.412	27.376	27.341	27.306	27.271	27.237	27.203	27.170
400	27.916	27.886	27.849	27.813	27.777	27.741	27.706	27.671	27.637	27.603	27.570	27.537	27.505

Table A3 Enthalpy database of propane, x 10^6 [J/day] [kg/hr]$^{-1}$

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-250	-13.451	-13.437	-13.419	-13.402	-13.385	-13.368	-13.350	-13.333	-13.316	-13.299	-13.281	-13.264	-13.247
-245	-13.112	-13.098	-13.081	-13.064	-13.046	-13.029	-13.012	-12.994	-12.977	-12.960	-12.943	-12.925	-12.908
-240	-12.788	-12.774	-12.757	-12.740	-12.722	-12.705	-12.688	-12.671	-12.653	-12.636	-12.619	-12.602	-12.584
-235	-12.475	-12.462	-12.444	-12.427	-12.410	-12.393	-12.376	-12.358	-12.341	-12.324	-12.307	-12.289	-12.272
-230	-12.172	-12.158	-12.141	-12.124	-12.107	-12.090	-12.072	-12.055	-12.038	-12.021	-12.003	-11.986	-11.969
-225	-11.876	-11.863	-11.845	-11.828	-11.811	-11.794	-11.777	-11.759	-11.742	-11.725	-11.708	-11.691	-11.673
-220	-11.587	-11.573	-11.556	-11.539	-11.522	-11.504	-11.487	-11.470	-11.453	-11.436	-11.419	-11.401	-11.384
-215	-11.303	-11.289	-11.272	-11.255	-11.238	-11.220	-11.203	-11.186	-11.169	-11.152	-11.135	-11.117	-11.100
-210	-11.023	-11.009	-10.992	-10.975	-10.958	-10.941	-10.924	-10.907	-10.890	-10.872	-10.855	-10.838	-10.821
-205	-10.747	-10.734	-10.717	-10.700	-10.682	-10.665	-10.648	-10.631	-10.614	-10.597	-10.580	-10.563	-10.546
-200	-10.475	-10.462	-10.445	-10.427	-10.410	-10.393	-10.376	-10.359	-10.342	-10.325	-10.308	-10.291	-10.274
-195	-10.206	-10.192	-10.175	-10.158	-10.141	-10.124	-10.107	-10.090	-10.073	-10.056	-10.039	-10.022	-10.005
-190	-9.940	-9.926	-9.909	-9.892	-9.875	-9.858	-9.841	-9.824	-9.807	-9.790	-9.773	-9.756	-9.739
-185	-9.676	-9.662	-9.645	-9.628	-9.611	-9.594	-9.577	-9.560	-9.543	-9.526	-9.510	-9.493	-9.476
-180	-9.414	-9.400	-9.383	-9.366	-9.349	-9.333	-9.316	-9.299	-9.282	-9.265	-9.248	-9.231	-9.214
-175	-9.154	-9.140	-9.123	-9.106	-9.090	-9.073	-9.056	-9.039	-9.022	-9.005	-8.988	-8.972	-8.955
-170	-8.895	-8.882	-8.865	-8.848	-8.831	-8.815	-8.798	-8.781	-8.764	-8.747	-8.731	-8.714	-8.697
-165	-8.638	-8.625	-8.608	-8.592	-8.575	-8.558	-8.541	-8.525	-8.508	-8.491	-8.474	-8.458	-8.441
-160	-8.383	-8.370	-8.353	-8.336	-8.320	-8.303	-8.286	-8.270	-8.253	-8.236	-8.219	-8.203	-8.186
-155	-8.129	-8.115	-8.099	-8.082	-8.065	-8.049	-8.032	-8.016	-7.999	-7.982	-7.966	-7.949	-7.933
-150	-7.875	-7.862	-7.846	-7.829	-7.812	-7.796	-7.779	-7.763	-7.746	-7.730	-7.713	-7.697	-7.680
-145	-7.623	-7.610	-7.593	-7.577	-7.560	-7.544	-7.528	-7.511	-7.495	-7.478	-7.462	-7.445	-7.429
-140	-7.371	-7.358	-7.342	-7.325	-7.309	-7.293	-7.276	-7.260	-7.244	-7.227	-7.211	-7.195	-7.178
-135	-7.120	-7.107	-7.091	-7.075	-7.059	-7.042	-7.026	-7.010	-6.994	-6.977	-6.961	-6.945	-6.928
-130	-6.870	-6.857	-6.841	-6.825	-6.809	-6.792	-6.776	-6.760	-6.744	-6.728	-6.712	-6.695	-6.679

Table A3 Enthalpy database of propane, x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-125	-6.620	-6.607	-6.591	-6.575	-6.559	-6.543	-6.527	-6.511	-6.495	-6.479	-6.463	-6.447	-6.431
-120	-6.370	-6.358	-6.342	-6.326	-6.310	-6.294	-6.278	-6.262	-6.246	-6.230	-6.215	-6.199	-6.183
-115	-6.121	-6.109	-6.093	-6.077	-6.061	-6.046	-6.030	-6.014	-5.998	-5.982	-5.967	-5.951	-5.935
-110	-5.872	-5.860	-5.844	-5.829	-5.813	-5.797	-5.782	-5.766	-5.750	-5.735	-5.719	-5.703	-5.687
-105	-5.623	-5.611	-5.595	-5.580	-5.565	-5.549	-5.534	-5.518	-5.503	-5.487	-5.472	-5.456	-5.440
-100	-5.374	-5.362	-5.347	-5.332	-5.316	-5.301	-5.286	-5.270	-5.255	-5.240	-5.224	-5.209	-5.193
-95	-5.125	-5.113	-5.098	-5.083	-5.068	-5.053	-5.038	-5.023	-5.007	-4.992	-4.977	-4.962	-4.946
-90	-4.876	-4.864	-4.849	-4.834	-4.820	-4.805	-4.790	-4.775	-4.760	-4.745	-4.730	-4.715	-4.700
-85	-4.626	-4.615	-4.600	-4.586	-4.571	-4.556	-4.541	-4.527	-4.512	-4.497	-4.482	-4.467	-4.453
-80	-4.376	-4.365	-4.351	-4.336	-4.322	-4.308	-4.293	-4.279	-4.264	-4.249	-4.235	-4.220	-4.205
-75	-4.126	-4.115	-4.101	-4.087	-4.073	-4.058	-4.044	-4.030	-4.016	-4.001	-3.987	-3.973	-3.958
-70	-3.875	-3.864	-3.850	-3.837	-3.823	-3.809	-3.795	-3.781	-3.767	-3.753	-3.739	-3.725	-3.710
-65	-3.622	-3.611	-3.598	-3.584	-3.571	-3.557	-3.543	-3.530	-3.516	-3.502	-3.488	-3.475	-3.461
-60	-3.366	-3.355	-3.342	-3.329	-3.316	-3.303	-3.290	-3.276	-3.263	-3.249	-3.236	-3.222	-3.209
-55	-3.107	-3.097	-3.084	-3.072	-3.059	-3.046	-3.033	-3.020	-3.007	-2.994	-2.981	-2.967	-2.954
-50	-2.845	-2.836	-2.823	-2.811	-2.799	-2.786	-2.774	-2.761	-2.749	-2.736	-2.723	-2.710	-2.697
-45	-2.580	-2.571	-2.559	-2.547	-2.536	-2.524	-2.512	-2.499	-2.487	-2.475	-2.462	-2.450	-2.437
-40	8.010	-2.303	-2.292	-2.281	-2.269	-2.258	-2.246	-2.234	-2.223	-2.211	-2.199	-2.187	-2.175
-35	8.180	-2.031	-2.021	-2.010	-1.999	-1.988	-1.977	-1.966	-1.955	-1.944	-1.932	-1.920	-1.909
-30	8.352	-1.756	-1.746	-1.736	-1.726	-1.715	-1.705	-1.694	-1.684	-1.673	-1.662	-1.651	-1.640
-25	8.526	-1.476	-1.467	-1.457	-1.448	-1.438	-1.429	-1.419	-1.409	-1.398	-1.388	-1.378	-1.367
-20	8.703	-1.191	-1.183	-1.175	-1.166	-1.157	-1.148	-1.139	-1.130	-1.120	-1.111	-1.101	-1.091
-15	8.882	-0.902	-0.895	-0.888	-0.880	-0.872	-0.864	-0.855	-0.847	-0.838	-0.829	-0.820	-0.810
-10	9.063	-0.608	-0.602	-0.595	-0.589	-0.582	-0.575	-0.567	-0.559	-0.551	-0.543	-0.535	-0.526

Table A3 Enthalpy database of propane, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-5	9.247	-0.308	-0.303	-0.298	-0.293	-0.287	-0.280	-0.274	-0.267	-0.260	-0.253	-0.245	-0.238
0	9.434	-0.002	0.001	0.005	0.009	0.014	0.019	0.024	0.030	0.036	0.042	0.049	0.055
5	9.623	9.325	0.312	0.314	0.317	0.320	0.323	0.327	0.332	0.337	0.342	0.347	0.353
10	9.815	9.526	0.629	0.630	0.630	0.632	0.634	0.637	0.640	0.643	0.647	0.651	0.656
15	10.009	9.730	0.954	0.952	0.951	0.951	0.951	0.952	0.953	0.955	0.957	0.960	0.964
20	10.207	9.936	1.287	1.283	1.279	1.276	1.275	1.273	1.273	1.273	1.274	1.275	1.277
25	10.407	10.145	1.630	1.622	1.615	1.610	1.606	1.602	1.599	1.598	1.597	1.596	1.596
30	10.610	10.355	9.981	1.971	1.961	1.952	1.945	1.938	1.933	1.929	1.926	1.923	1.922
35	10.815	10.568	10.209	2.331	2.316	2.304	2.293	2.283	2.275	2.268	2.262	2.257	2.254
40	11.024	10.784	10.439	2.704	2.684	2.666	2.651	2.637	2.625	2.615	2.606	2.599	2.592
45	11.235	11.002	10.670	10.263	3.065	3.041	3.020	3.002	2.985	2.971	2.959	2.948	2.939
50	11.449	11.223	10.902	10.517	3.463	3.431	3.402	3.378	3.356	3.337	3.321	3.306	3.293
55	11.666	11.446	11.136	10.771	3.882	3.838	3.801	3.768	3.740	3.715	3.693	3.673	3.656
60	11.886	11.671	11.372	11.024	10.589	4.269	4.218	4.175	4.138	4.105	4.077	4.052	4.029
65	12.109	11.900	11.611	11.278	10.873	4.732	4.661	4.603	4.553	4.511	4.474	4.442	4.413
70	12.334	12.131	11.851	11.532	11.153	10.656	5.139	5.057	4.991	4.934	4.887	4.845	4.809
75	12.563	12.364	12.093	11.787	11.430	10.981	5.672	5.550	5.457	5.381	5.318	5.265	5.219
80	12.794	12.600	12.337	12.043	11.705	11.293	10.724	6.104	5.963	5.858	5.773	5.704	5.645
85	13.028	12.839	12.583	12.301	11.979	11.598	11.104	6.784	6.536	6.377	6.259	6.167	6.090
90	13.265	13.080	12.832	12.559	12.253	11.897	11.456	10.821	7.244	6.963	6.788	6.660	6.559
95	13.504	13.324	13.083	12.820	12.527	12.192	11.791	11.265	10.289	7.683	7.382	7.195	7.058
100	13.746	13.571	13.336	13.082	12.801	12.485	12.116	11.658	11.000	8.920	8.094	7.789	7.595
105	13.992	13.820	13.592	13.345	13.076	12.776	12.433	12.023	11.492	10.641	9.072	8.478	8.183
110	14.239	14.072	13.849	13.611	13.352	13.066	12.745	12.372	11.915	11.301	10.317	9.314	8.842

Table A3 Enthalpy database of propane, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
115	14.490	14.326	14.110	13.878	13.629	13.356	13.053	12.709	12.304	11.802	11.126	10.250	9.580
120	14.743	14.583	14.372	14.148	13.907	13.646	13.359	13.039	12.673	12.239	11.705	11.039	10.356
125	14.999	14.842	14.637	14.419	14.186	13.936	13.664	13.364	13.028	12.643	12.191	11.657	11.068
130	15.257	15.104	14.904	14.692	14.467	14.227	13.967	13.685	13.373	13.024	12.628	12.177	11.679
135	15.518	15.369	15.173	14.967	14.750	14.518	14.270	14.003	13.712	13.391	13.036	12.642	12.211
140	15.782	15.636	15.445	15.245	15.034	14.811	14.573	14.319	14.045	13.748	13.424	13.071	12.692
145	16.049	15.905	15.719	15.524	15.320	15.104	14.876	14.634	14.375	14.098	13.799	13.478	13.137
150	16.318	16.177	15.995	15.806	15.607	15.399	15.180	14.948	14.703	14.442	14.164	13.869	13.558
155	16.589	16.452	16.274	16.089	15.896	15.695	15.484	15.262	15.028	14.782	14.521	14.247	13.961
160	16.863	16.728	16.555	16.375	16.187	15.992	15.789	15.576	15.352	15.119	14.873	14.617	14.351
165	17.140	17.008	16.838	16.662	16.480	16.291	16.094	15.889	15.676	15.453	15.221	14.980	14.732
170	17.419	17.290	17.124	16.952	16.775	16.591	16.401	16.204	15.999	15.786	15.566	15.338	15.104
175	17.700	17.574	17.411	17.244	17.072	16.893	16.709	16.519	16.322	16.119	15.909	15.693	15.471
180	17.984	17.860	17.702	17.538	17.370	17.197	17.019	16.835	16.645	16.450	16.249	16.044	15.834
185	18.271	18.149	17.994	17.834	17.671	17.502	17.329	17.151	16.969	16.781	16.589	16.393	16.193
190	18.559	18.440	18.288	18.133	17.973	17.809	17.641	17.469	17.293	17.112	16.928	16.740	16.549
195	18.851	18.734	18.585	18.433	18.277	18.118	17.955	17.788	17.617	17.443	17.266	17.086	16.903
200	19.144	19.030	18.884	18.736	18.583	18.428	18.270	18.108	17.943	17.775	17.604	17.431	17.256
205	19.440	19.328	19.186	19.040	18.892	18.740	18.586	18.429	18.269	18.107	17.942	17.775	17.607
210	19.739	19.629	19.489	19.347	19.202	19.054	18.904	18.752	18.597	18.439	18.280	18.119	17.958
215	20.039	19.932	19.795	19.656	19.514	19.370	19.224	19.076	18.925	18.773	18.619	18.464	18.308
220	20.342	20.237	20.103	19.966	19.828	19.688	19.545	19.401	19.255	19.107	18.958	18.808	18.658
225	20.648	20.544	20.413	20.279	20.144	20.007	19.868	19.728	19.586	19.442	19.298	19.153	19.008
230	20.955	20.854	20.725	20.594	20.462	20.328	20.193	20.056	19.918	19.779	19.639	19.498	19.358

Table A3 Enthalpy database of propane, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
235	21.265	21.165	21.039	20.911	20.782	20.651	20.519	20.386	20.252	20.116	19.981	19.844	19.708
240	21.577	21.479	21.356	21.230	21.104	20.976	20.847	20.717	20.587	20.455	20.323	20.191	20.059
245	21.892	21.795	21.674	21.552	21.428	21.303	21.177	21.050	20.923	20.795	20.667	20.538	20.410
250	22.208	22.114	21.995	21.875	21.754	21.632	21.509	21.385	21.261	21.136	21.012	20.887	20.762
255	22.527	22.434	22.318	22.200	22.081	21.962	21.842	21.721	21.600	21.479	21.357	21.236	21.115
260	22.848	22.757	22.642	22.527	22.411	22.294	22.177	22.059	21.941	21.823	21.705	21.587	21.469
265	23.171	23.082	22.969	22.856	22.743	22.629	22.514	22.399	22.284	22.168	22.053	21.938	21.824
270	23.496	23.409	23.298	23.188	23.076	22.965	22.852	22.740	22.628	22.515	22.403	22.291	22.179
275	23.824	23.738	23.629	23.521	23.412	23.302	23.193	23.083	22.973	22.863	22.754	22.645	22.536
280	24.153	24.069	23.963	23.856	23.749	23.642	23.535	23.427	23.320	23.213	23.106	23.000	22.894
285	24.485	24.402	24.298	24.193	24.089	23.984	23.879	23.774	23.669	23.564	23.460	23.356	23.253
290	24.819	24.737	24.635	24.533	24.430	24.327	24.224	24.122	24.019	23.917	23.815	23.714	23.613
295	25.154	25.074	24.974	24.874	24.773	24.672	24.572	24.471	24.371	24.271	24.172	24.073	23.975
300	25.492	25.414	25.315	25.217	25.118	25.020	24.921	24.823	24.725	24.627	24.530	24.433	24.338
305	25.832	25.755	25.658	25.562	25.465	25.368	25.272	25.176	25.080	24.984	24.890	24.795	24.702
310	26.174	26.098	26.004	25.909	25.814	25.719	25.625	25.531	25.437	25.343	25.251	25.159	25.067
315	26.518	26.444	26.351	26.258	26.165	26.072	25.979	25.887	25.795	25.704	25.613	25.523	25.434
320	26.864	26.791	26.700	26.609	26.517	26.426	26.336	26.245	26.155	26.066	25.977	25.889	25.802
325	27.213	27.141	27.051	26.961	26.872	26.783	26.694	26.605	26.517	26.430	26.343	26.257	26.172
330	27.563	27.492	27.404	27.316	27.228	27.141	27.054	26.967	26.881	26.795	26.710	26.626	26.543
335	27.915	27.845	27.759	27.672	27.586	27.501	27.415	27.330	27.246	27.162	27.079	26.996	26.915
340	28.269	28.201	28.116	28.031	27.946	27.862	27.778	27.695	27.613	27.530	27.449	27.369	27.289
345	28.625	28.558	28.474	28.391	28.308	28.226	28.144	28.062	27.981	27.901	27.821	27.742	27.664
350	28.983	28.917	28.835	28.753	28.672	28.591	28.510	28.430	28.351	28.272	28.194	28.117	28.041

Table A3 Enthalpy database of propane, x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
355	29.343	29.278	29.198	29.117	29.037	28.958	28.879	28.801	28.723	28.646	28.569	28.494	28.419
360	29.705	29.641	29.562	29.483	29.405	29.327	29.249	29.172	29.096	29.021	28.946	28.872	28.799
365	30.068	30.006	29.928	29.851	29.774	29.697	29.621	29.546	29.471	29.397	29.324	29.251	29.180
370	30.434	30.373	30.296	30.220	30.145	30.070	29.995	29.921	29.848	29.775	29.704	29.633	29.562
375	30.802	30.741	30.666	30.592	30.518	30.444	30.371	30.298	30.226	30.155	30.085	30.015	29.946
380	31.171	31.112	31.038	30.965	30.892	30.820	30.748	30.677	30.606	30.537	30.468	30.399	30.332
385	31.543	31.484	31.412	31.340	31.268	31.197	31.127	31.057	30.988	30.920	30.852	30.785	30.719
390	31.916	31.859	31.787	31.717	31.646	31.577	31.508	31.439	31.371	31.304	31.238	31.173	31.108
395	32.291	32.235	32.165	32.095	32.026	31.958	31.890	31.823	31.756	31.691	31.626	31.561	31.498
400	32.668	32.612	32.544	32.475	32.408	32.341	32.274	32.208	32.143	32.078	32.015	31.952	31.890

Table A4 Enthalpy database of propylene, x 10^6 [J/day] [kg/hr]$^{-1}$

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-250	-12.548	-12.535	-12.518	-12.502	-12.486	-12.470	-12.453	-12.437	-12.421	-12.404	-12.388	-12.372	-12.356
-245	-12.236	-12.223	-12.207	-12.191	-12.175	-12.158	-12.142	-12.126	-12.109	-12.093	-12.077	-12.061	-12.044
-240	-11.940	-11.927	-11.911	-11.894	-11.878	-11.862	-11.846	-11.829	-11.813	-11.797	-11.781	-11.764	-11.748
-235	-11.655	-11.642	-11.626	-11.609	-11.593	-11.577	-11.561	-11.544	-11.528	-11.512	-11.496	-11.479	-11.463
-230	-11.379	-11.366	-11.350	-11.334	-11.317	-11.301	-11.285	-11.269	-11.252	-11.236	-11.220	-11.204	-11.187
-225	-11.111	-11.098	-11.081	-11.065	-11.049	-11.033	-11.017	-11.000	-10.984	-10.968	-10.952	-10.936	-10.919
-220	-10.849	-10.836	-10.819	-10.803	-10.787	-10.771	-10.755	-10.738	-10.722	-10.706	-10.690	-10.674	-10.657
-215	-10.592	-10.579	-10.563	-10.547	-10.530	-10.514	-10.498	-10.482	-10.466	-10.449	-10.433	-10.417	-10.401
-210	-10.340	-10.327	-10.311	-10.294	-10.278	-10.262	-10.246	-10.230	-10.214	-10.197	-10.181	-10.165	-10.149
-205	-10.091	-10.078	-10.062	-10.046	-10.030	-10.014	-9.998	-9.982	-9.966	-9.949	-9.933	-9.917	-9.901
-200	-9.847	-9.834	-9.818	-9.801	-9.785	-9.769	-9.753	-9.737	-9.721	-9.705	-9.689	-9.673	-9.657
-195	-9.605	-9.592	-9.576	-9.560	-9.544	-9.528	-9.512	-9.496	-9.480	-9.463	-9.447	-9.431	-9.415
-190	-9.366	-9.353	-9.337	-9.321	-9.305	-9.289	-9.273	-9.257	-9.241	-9.225	-9.209	-9.193	-9.177
-185	-9.129	-9.116	-9.100	-9.084	-9.068	-9.052	-9.036	-9.020	-9.004	-8.988	-8.972	-8.956	-8.940
-180	-8.894	-8.881	-8.866	-8.850	-8.834	-8.818	-8.802	-8.786	-8.770	-8.754	-8.738	-8.722	-8.706
-175	-8.661	-8.649	-8.633	-8.617	-8.601	-8.585	-8.569	-8.553	-8.538	-8.522	-8.506	-8.490	-8.474
-170	-8.430	-8.418	-8.402	-8.386	-8.370	-8.354	-8.339	-8.323	-8.307	-8.291	-8.275	-8.259	-8.244
-165	-8.201	-8.188	-8.172	-8.157	-8.141	-8.125	-8.109	-8.093	-8.078	-8.062	-8.046	-8.030	-8.015
-160	-7.972	-7.960	-7.944	-7.928	-7.913	-7.897	-7.881	-7.866	-7.850	-7.834	-7.818	-7.803	-7.787
-155	-7.745	-7.733	-7.717	-7.701	-7.686	-7.670	-7.654	-7.639	-7.623	-7.608	-7.592	-7.576	-7.561
-150	-7.519	-7.506	-7.491	-7.475	-7.460	-7.444	-7.429	-7.413	-7.398	-7.382	-7.366	-7.351	-7.335
-145	-7.294	-7.281	-7.266	-7.250	-7.235	-7.219	-7.204	-7.188	-7.173	-7.157	-7.142	-7.126	-7.111
-140	-7.069	-7.057	-7.041	-7.026	-7.011	-6.995	-6.980	-6.965	-6.949	-6.934	-6.918	-6.903	-6.887
-135	-6.845	-6.832	-6.817	-6.802	-6.787	-6.771	-6.756	-6.741	-6.725	-6.710	-6.695	-6.679	-6.664
-130	-6.620	-6.608	-6.593	-6.578	-6.563	-6.547	-6.532	-6.517	-6.502	-6.486	-6.471	-6.456	-6.441

Table A4 Enthalpy database of propylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-125	-6.395	-6.383	-6.368	-6.353	-6.338	-6.323	-6.308	-6.293	-6.278	-6.263	-6.248	-6.233	-6.217
-120	-6.170	-6.158	-6.143	-6.128	-6.114	-6.099	-6.084	-6.069	-6.054	-6.039	-6.024	-6.009	-5.994
-115	-5.944	-5.933	-5.918	-5.903	-5.888	-5.873	-5.859	-5.844	-5.829	-5.814	-5.799	-5.784	-5.769
-110	-5.718	-5.706	-5.691	-5.677	-5.662	-5.647	-5.633	-5.618	-5.603	-5.589	-5.574	-5.559	-5.544
-105	-5.490	-5.478	-5.464	-5.450	-5.435	-5.421	-5.406	-5.391	-5.377	-5.362	-5.348	-5.333	-5.318
-100	-5.261	-5.250	-5.235	-5.221	-5.207	-5.192	-5.178	-5.164	-5.149	-5.135	-5.120	-5.106	-5.091
-95	-5.031	-5.019	-5.005	-4.991	-4.977	-4.963	-4.949	-4.935	-4.920	-4.906	-4.892	-4.878	-4.863
-90	-4.799	-4.787	-4.774	-4.760	-4.746	-4.732	-4.718	-4.704	-4.690	-4.676	-4.662	-4.648	-4.633
-85	-4.565	-4.554	-4.540	-4.526	-4.513	-4.499	-4.485	-4.471	-4.458	-4.444	-4.430	-4.416	-4.402
-80	-4.329	-4.318	-4.305	-4.291	-4.278	-4.264	-4.251	-4.237	-4.224	-4.210	-4.196	-4.183	-4.169
-75	-4.090	-4.080	-4.067	-4.054	-4.040	-4.027	-4.014	-4.001	-3.987	-3.974	-3.961	-3.947	-3.934
-70	-3.850	-3.839	-3.827	-3.814	-3.801	-3.788	-3.775	-3.762	-3.749	-3.736	-3.723	-3.710	-3.696
-65	-3.606	-3.596	-3.584	-3.571	-3.559	-3.546	-3.534	-3.521	-3.508	-3.495	-3.482	-3.470	-3.457
-60	-3.360	-3.350	-3.338	-3.326	-3.314	-3.302	-3.289	-3.277	-3.265	-3.252	-3.240	-3.227	-3.214
-55	-3.111	-3.102	-3.090	-3.078	-3.066	-3.054	-3.043	-3.031	-3.018	-3.006	-2.994	-2.982	-2.970
-50	-2.858	-2.849	-2.838	-2.827	-2.816	-2.804	-2.793	-2.781	-2.769	-2.758	-2.746	-2.734	-2.722
-45	7.990	-2.594	-2.583	-2.572	-2.562	-2.551	-2.539	-2.528	-2.517	-2.506	-2.494	-2.483	-2.471
-40	8.145	-2.335	-2.325	-2.314	-2.304	-2.294	-2.283	-2.272	-2.262	-2.251	-2.240	-2.229	-2.218
-35	8.303	-2.072	-2.062	-2.053	-2.043	-2.033	-2.023	-2.013	-2.003	-1.992	-1.982	-1.971	-1.961
-30	8.463	-1.805	-1.796	-1.787	-1.778	-1.769	-1.759	-1.750	-1.740	-1.730	-1.720	-1.710	-1.700
-25	8.625	-1.533	-1.525	-1.517	-1.509	-1.500	-1.492	-1.483	-1.474	-1.465	-1.455	-1.446	-1.436
-20	8.789	-1.257	-1.250	-1.243	-1.235	-1.228	-1.220	-1.212	-1.203	-1.195	-1.186	-1.177	-1.169
-15	8.956	-0.976	-0.970	-0.964	-0.957	-0.950	-0.943	-0.936	-0.929	-0.921	-0.913	-0.905	-0.897
-10	9.125	-0.690	-0.685	-0.680	-0.674	-0.669	-0.663	-0.656	-0.650	-0.643	-0.636	-0.629	-0.621

Table A4 Enthalpy database of propylene, x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-5	9.295	-0.398	-0.395	-0.391	-0.386	-0.382	-0.377	-0.371	-0.366	-0.360	-0.354	-0.348	-0.341
0	9.469	9.191	-0.098	-0.095	-0.093	-0.089	-0.086	-0.082	-0.077	-0.073	-0.068	-0.062	-0.057
5	9.644	9.375	0.205	0.206	0.207	0.209	0.211	0.214	0.217	0.220	0.224	0.228	0.233
10	9.822	9.562	0.515	0.514	0.513	0.513	0.514	0.515	0.516	0.518	0.521	0.524	0.527
15	10.002	9.750	0.833	0.830	0.827	0.825	0.823	0.822	0.822	0.822	0.823	0.824	0.826
20	10.185	9.940	9.582	1.154	1.148	1.143	1.140	1.136	1.134	1.133	1.132	1.131	1.131
25	10.370	10.132	9.788	1.487	1.478	1.470	1.464	1.458	1.453	1.449	1.446	1.444	1.442
30	10.557	10.326	9.996	1.831	1.818	1.807	1.797	1.788	1.780	1.774	1.768	1.764	1.760
35	10.746	10.522	10.204	2.188	2.170	2.154	2.140	2.127	2.116	2.106	2.098	2.090	2.084
40	10.938	10.720	10.413	10.049	2.536	2.513	2.494	2.476	2.461	2.448	2.436	2.425	2.416
45	11.132	10.920	10.624	10.277	2.918	2.888	2.861	2.838	2.817	2.799	2.783	2.768	2.755
50	11.328	11.121	10.836	10.505	10.099	3.281	3.245	3.214	3.187	3.162	3.141	3.121	3.104
55	11.526	11.325	11.049	10.733	10.354	3.698	3.649	3.607	3.571	3.539	3.511	3.486	3.463
60	11.727	11.531	11.264	10.961	10.604	10.149	4.081	4.023	3.974	3.932	3.895	3.863	3.834
65	11.930	11.739	11.480	11.189	10.853	10.438	4.551	4.469	4.402	4.345	4.297	4.254	4.218
70	12.135	11.949	11.698	11.418	11.099	10.716	10.206	4.960	4.863	4.785	4.720	4.664	4.617
75	12.343	12.161	11.917	11.648	11.344	10.988	10.538	5.528	5.374	5.261	5.171	5.097	5.035
80	12.552	12.375	12.138	11.879	11.589	11.255	10.849	10.291	5.977	5.792	5.661	5.559	5.476
85	12.764	12.591	12.361	12.110	11.833	11.518	11.146	10.671	9.893	6.427	6.211	6.062	5.948
90	12.978	12.809	12.585	12.343	12.077	11.779	11.435	11.015	10.437	7.399	6.871	6.626	6.460
95	13.194	13.030	12.812	12.577	12.321	12.038	11.717	11.338	10.857	10.117	7.844	7.297	7.032
100	13.412	13.252	13.039	12.812	12.566	12.296	11.994	11.647	11.228	10.672	9.711	8.203	7.699
105	13.633	13.476	13.269	13.049	12.811	12.553	12.268	11.947	11.571	11.109	10.476	9.455	8.520
110	13.855	13.702	13.500	13.286	13.058	12.810	12.540	12.240	11.898	11.495	10.994	10.321	9.465

Table A4 Enthalpy database of propylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
115	14.080	13.930	13.734	13.526	13.305	13.067	12.810	12.528	12.213	11.852	11.427	10.906	10.262
120	14.307	14.160	13.968	13.767	13.553	13.324	13.079	12.812	12.519	12.191	11.817	11.381	10.870
125	14.535	14.392	14.205	14.009	13.802	13.582	13.347	13.094	12.819	12.517	12.180	11.801	11.372
130	14.766	14.626	14.444	14.253	14.052	13.840	13.615	13.374	13.115	12.834	12.526	12.187	11.813
135	14.999	14.862	14.684	14.498	14.303	14.098	13.882	13.652	13.407	13.144	12.860	12.552	12.218
140	15.234	15.100	14.926	14.745	14.556	14.358	14.149	13.930	13.697	13.449	13.184	12.901	12.598
145	15.471	15.340	15.170	14.993	14.810	14.618	14.417	14.206	13.984	13.750	13.501	13.238	12.960
150	15.710	15.581	15.415	15.243	15.065	14.879	14.685	14.483	14.270	14.048	13.813	13.567	13.309
155	15.951	15.825	15.663	15.495	15.321	15.141	14.954	14.759	14.556	14.343	14.121	13.890	13.648
160	16.194	16.071	15.912	15.748	15.579	15.405	15.223	15.035	14.840	14.637	14.426	14.207	13.980
165	16.439	16.318	16.163	16.003	15.839	15.669	15.493	15.312	15.124	14.930	14.729	14.521	14.306
170	16.686	16.568	16.416	16.260	16.100	15.935	15.764	15.589	15.408	15.221	15.029	14.831	14.628
175	16.935	16.819	16.671	16.518	16.362	16.201	16.036	15.867	15.692	15.513	15.328	15.139	14.946
180	17.186	17.072	16.927	16.778	16.626	16.469	16.309	16.145	15.976	15.803	15.626	15.445	15.261
185	17.439	17.327	17.185	17.040	16.891	16.739	16.583	16.424	16.261	16.094	15.924	15.750	15.573
190	17.694	17.584	17.445	17.303	17.158	17.010	16.858	16.704	16.546	16.385	16.221	16.054	15.884
195	17.950	17.843	17.707	17.568	17.426	17.282	17.134	16.984	16.831	16.676	16.517	16.356	16.194
200	18.209	18.104	17.971	17.835	17.696	17.555	17.412	17.266	17.118	16.967	16.814	16.659	16.502
205	18.470	18.367	18.236	18.103	17.968	17.830	17.691	17.549	17.405	17.258	17.111	16.961	16.810
210	18.732	18.631	18.503	18.373	18.241	18.107	17.971	17.832	17.692	17.551	17.407	17.263	17.117
215	18.997	18.898	18.772	18.645	18.515	18.385	18.252	18.117	17.981	17.844	17.705	17.565	17.424
220	19.263	19.166	19.043	18.918	18.792	18.664	18.534	18.403	18.271	18.137	18.003	17.867	17.731
225	19.531	19.436	19.315	19.193	19.070	18.945	18.818	18.691	18.562	18.432	18.301	18.170	18.038
230	19.801	19.708	19.589	19.470	19.349	19.227	19.104	18.979	18.854	18.727	18.600	18.473	18.345

Table A4 Enthalpy database of propylene, x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
235	20.073	19.981	19.865	19.748	19.630	19.511	19.390	19.269	19.147	19.024	18.900	18.776	18.652
240	20.347	20.257	20.143	20.028	19.913	19.796	19.678	19.560	19.441	19.321	19.201	19.080	18.960
245	20.623	20.534	20.423	20.310	20.197	20.083	19.968	19.852	19.736	19.619	19.502	19.385	19.268
250	20.900	20.813	20.704	20.594	20.483	20.371	20.259	20.146	20.033	19.919	19.805	19.691	19.577
255	21.180	21.094	20.987	20.879	20.770	20.661	20.551	20.441	20.330	20.219	20.108	19.997	19.886
260	21.461	21.377	21.272	21.166	21.060	20.953	20.845	20.737	20.629	20.521	20.413	20.305	20.197
265	21.744	21.662	21.558	21.455	21.350	21.246	21.141	21.035	20.930	20.824	20.718	20.613	20.508
270	22.029	21.948	21.847	21.745	21.643	21.540	21.437	21.334	21.231	21.128	21.025	20.922	20.820
275	22.315	22.236	22.137	22.037	21.937	21.836	21.736	21.635	21.534	21.433	21.333	21.233	21.133
280	22.604	22.526	22.428	22.330	22.232	22.134	22.035	21.937	21.838	21.740	21.642	21.544	21.446
285	22.894	22.818	22.722	22.626	22.530	22.433	22.337	22.240	22.144	22.048	21.952	21.856	21.761
290	23.186	23.111	23.017	22.923	22.828	22.734	22.640	22.545	22.451	22.357	22.263	22.170	22.077
295	23.480	23.406	23.314	23.221	23.129	23.036	22.944	22.851	22.759	22.667	22.576	22.485	22.394
300	23.775	23.703	23.612	23.522	23.431	23.340	23.250	23.159	23.069	22.979	22.889	22.800	22.712
305	24.073	24.002	23.913	23.824	23.735	23.646	23.557	23.468	23.380	23.292	23.205	23.117	23.031
310	24.372	24.302	24.215	24.127	24.040	23.953	23.866	23.779	23.693	23.606	23.521	23.436	23.351
315	24.673	24.604	24.518	24.433	24.347	24.261	24.176	24.091	24.007	23.922	23.838	23.755	23.672
320	24.975	24.908	24.824	24.740	24.656	24.572	24.488	24.405	24.322	24.239	24.157	24.076	23.995
325	25.280	25.213	25.131	25.048	24.966	24.883	24.801	24.720	24.639	24.558	24.478	24.398	24.319
330	25.586	25.521	25.439	25.358	25.277	25.197	25.116	25.036	24.957	24.878	24.799	24.721	24.644
335	25.894	25.830	25.750	25.670	25.591	25.512	25.433	25.354	25.276	25.199	25.122	25.046	24.970
340	26.203	26.140	26.062	25.984	25.906	25.828	25.751	25.674	25.597	25.521	25.446	25.371	25.297
345	26.514	26.452	26.375	26.299	26.222	26.146	26.070	25.995	25.920	25.845	25.772	25.698	25.626
350	26.827	26.766	26.691	26.615	26.540	26.465	26.391	26.317	26.244	26.171	26.098	26.027	25.956

Table A4 Enthalpy database of propylene, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
355	27.142	27.082	27.008	26.934	26.860	26.787	26.714	26.641	26.569	26.498	26.427	26.356	26.287
360	27.458	27.399	27.326	27.254	27.181	27.109	27.038	26.966	26.896	26.826	26.756	26.687	26.619
365	27.776	27.718	27.646	27.575	27.504	27.433	27.363	27.293	27.224	27.155	27.087	27.020	26.953
370	28.095	28.039	27.968	27.898	27.828	27.759	27.690	27.622	27.554	27.486	27.420	27.353	27.288
375	28.417	28.361	28.292	28.223	28.154	28.086	28.018	27.951	27.885	27.819	27.753	27.688	27.624
380	28.739	28.685	28.617	28.549	28.482	28.415	28.348	28.283	28.217	28.152	28.088	28.025	27.962
385	29.064	29.010	28.943	28.877	28.811	28.745	28.680	28.615	28.551	28.488	28.425	28.362	28.301
390	29.390	29.337	29.271	29.206	29.141	29.077	29.013	28.949	28.886	28.824	28.762	28.701	28.641
395	29.718	29.666	29.601	29.537	29.473	29.410	29.347	29.285	29.223	29.162	29.102	29.042	28.982
400	30.047	29.996	29.932	29.869	29.807	29.745	29.683	29.622	29.561	29.501	29.442	29.383	29.325

Table A5 Enthalpy database of r-12 (Dichlorodifluoromethane), x 10^6 [J/day] [kg/hr]$^{-1}$

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-250	-4.676	-4.671	-4.664	-4.657	-4.650	-4.644	-4.637	-4.630	-4.623	-4.617	-4.610	-4.603	-4.596
-245	-4.562	-4.557	-4.550	-4.543	-4.537	-4.530	-4.523	-4.516	-4.510	-4.503	-4.496	-4.489	-4.483
-240	-4.454	-4.449	-4.442	-4.435	-4.429	-4.422	-4.415	-4.408	-4.402	-4.395	-4.388	-4.381	-4.375
-235	-4.351	-4.346	-4.339	-4.332	-4.325	-4.319	-4.312	-4.305	-4.299	-4.292	-4.285	-4.278	-4.272
-230	-4.252	-4.246	-4.239	-4.233	-4.226	-4.219	-4.213	-4.206	-4.199	-4.192	-4.186	-4.179	-4.172
-225	-4.155	-4.150	-4.143	-4.136	-4.130	-4.123	-4.116	-4.109	-4.103	-4.096	-4.089	-4.083	-4.076
-220	-4.061	-4.056	-4.049	-4.042	-4.036	-4.029	-4.022	-4.016	-4.009	-4.002	-3.995	-3.989	-3.982
-215	-3.970	-3.964	-3.957	-3.951	-3.944	-3.937	-3.931	-3.924	-3.917	-3.911	-3.904	-3.897	-3.890
-210	-3.880	-3.874	-3.868	-3.861	-3.854	-3.848	-3.841	-3.834	-3.827	-3.821	-3.814	-3.807	-3.801
-205	-3.791	-3.786	-3.779	-3.773	-3.766	-3.759	-3.753	-3.746	-3.739	-3.733	-3.726	-3.719	-3.713
-200	-3.705	-3.699	-3.693	-3.686	-3.679	-3.673	-3.666	-3.659	-3.653	-3.646	-3.639	-3.633	-3.626
-195	-3.619	-3.614	-3.607	-3.600	-3.594	-3.587	-3.580	-3.574	-3.567	-3.560	-3.554	-3.547	-3.540
-190	-3.535	-3.529	-3.523	-3.516	-3.509	-3.503	-3.496	-3.489	-3.483	-3.476	-3.470	-3.463	-3.456
-185	-3.451	-3.446	-3.439	-3.433	-3.426	-3.419	-3.413	-3.406	-3.400	-3.393	-3.386	-3.380	-3.373
-180	-3.369	-3.363	-3.357	-3.350	-3.344	-3.337	-3.330	-3.324	-3.317	-3.310	-3.304	-3.297	-3.291
-175	-3.287	-3.282	-3.275	-3.269	-3.262	-3.255	-3.249	-3.242	-3.235	-3.229	-3.222	-3.216	-3.209
-170	-3.206	-3.201	-3.194	-3.187	-3.181	-3.174	-3.168	-3.161	-3.154	-3.148	-3.141	-3.135	-3.128
-165	-3.124	-3.119	-3.112	-3.106	-3.099	-3.093	-3.086	-3.080	-3.073	-3.067	-3.060	-3.053	-3.047
-160	-3.042	-3.037	-3.031	-3.024	-3.018	-3.011	-3.004	-2.998	-2.991	-2.985	-2.978	-2.972	-2.965
-155	-2.960	-2.955	-2.948	-2.942	-2.935	-2.929	-2.922	-2.916	-2.909	-2.903	-2.896	-2.889	-2.883
-150	-2.877	-2.872	-2.865	-2.859	-2.852	-2.846	-2.839	-2.833	-2.826	-2.820	-2.813	-2.807	-2.800
-145	-2.793	-2.788	-2.782	-2.775	-2.769	-2.762	-2.756	-2.749	-2.743	-2.736	-2.730	-2.723	-2.717
-140	-2.709	-2.704	-2.697	-2.691	-2.684	-2.678	-2.672	-2.665	-2.659	-2.652	-2.646	-2.639	-2.633
-135	-2.624	-2.619	-2.612	-2.606	-2.599	-2.593	-2.587	-2.580	-2.574	-2.567	-2.561	-2.555	-2.548
-130	-2.538	-2.533	-2.526	-2.520	-2.514	-2.507	-2.501	-2.495	-2.488	-2.482	-2.476	-2.469	-2.463

Table A5 Enthalpy database of r-12 (Dichlorodifluoromethane), x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-125	-2.451	-2.446	-2.440	-2.434	-2.427	-2.421	-2.415	-2.408	-2.402	-2.396	-2.389	-2.383	-2.377
-120	-2.364	-2.359	-2.353	-2.346	-2.340	-2.334	-2.328	-2.321	-2.315	-2.309	-2.302	-2.296	-2.290
-115	-2.276	-2.271	-2.265	-2.258	-2.252	-2.246	-2.240	-2.233	-2.227	-2.221	-2.215	-2.208	-2.202
-110	-2.187	-2.182	-2.176	-2.170	-2.163	-2.157	-2.151	-2.145	-2.139	-2.132	-2.126	-2.120	-2.114
-105	-2.097	-2.092	-2.086	-2.080	-2.074	-2.068	-2.062	-2.055	-2.049	-2.043	-2.037	-2.031	-2.025
-100	-2.006	-2.002	-1.996	-1.990	-1.983	-1.977	-1.971	-1.965	-1.959	-1.953	-1.947	-1.941	-1.935
-95	-1.915	-1.910	-1.904	-1.898	-1.892	-1.886	-1.880	-1.874	-1.868	-1.862	-1.856	-1.850	-1.844
-90	-1.823	-1.818	-1.812	-1.806	-1.800	-1.794	-1.788	-1.782	-1.776	-1.770	-1.764	-1.758	-1.752
-85	-1.729	-1.725	-1.719	-1.713	-1.707	-1.701	-1.695	-1.690	-1.684	-1.678	-1.672	-1.666	-1.660
-80	-1.635	-1.631	-1.625	-1.619	-1.613	-1.608	-1.602	-1.596	-1.590	-1.584	-1.578	-1.573	-1.567
-75	-1.540	-1.536	-1.530	-1.524	-1.519	-1.513	-1.507	-1.501	-1.496	-1.490	-1.484	-1.478	-1.473
-70	-1.444	-1.440	-1.434	-1.429	-1.423	-1.417	-1.412	-1.406	-1.400	-1.395	-1.389	-1.383	-1.378
-65	-1.347	-1.343	-1.337	-1.332	-1.326	-1.321	-1.315	-1.310	-1.304	-1.299	-1.293	-1.287	-1.282
-60	-1.249	-1.245	-1.240	-1.234	-1.229	-1.223	-1.218	-1.213	-1.207	-1.202	-1.196	-1.191	-1.185
-55	-1.150	-1.146	-1.141	-1.136	-1.130	-1.125	-1.120	-1.114	-1.109	-1.104	-1.098	-1.093	-1.088
-50	-1.050	-1.046	-1.041	-1.036	-1.031	-1.026	-1.021	-1.015	-1.010	-1.005	-1.000	-0.994	-0.989
-45	-0.949	-0.945	-0.940	-0.935	-0.930	-0.925	-0.920	-0.915	-0.910	-0.905	-0.900	-0.895	-0.890
-40	-0.847	-0.843	-0.838	-0.834	-0.829	-0.824	-0.819	-0.814	-0.809	-0.804	-0.799	-0.794	-0.789
-35	-0.744	-0.740	-0.735	-0.731	-0.726	-0.722	-0.717	-0.712	-0.707	-0.702	-0.698	-0.693	-0.688
-30	-0.639	-0.636	-0.631	-0.627	-0.622	-0.618	-0.613	-0.609	-0.604	-0.600	-0.595	-0.590	-0.585
-25	3.467	-0.530	-0.526	-0.522	-0.518	-0.513	-0.509	-0.505	-0.500	-0.496	-0.491	-0.487	-0.482
-20	3.534	-0.423	-0.419	-0.415	-0.411	-0.407	-0.403	-0.399	-0.395	-0.391	-0.386	-0.382	-0.378
-15	3.601	-0.315	-0.312	-0.308	-0.304	-0.300	-0.297	-0.293	-0.289	-0.285	-0.281	-0.276	-0.272
-10	3.669	-0.206	-0.202	-0.199	-0.196	-0.192	-0.188	-0.185	-0.181	-0.177	-0.173	-0.170	-0.166

Table A5 Enthalpy database of r-12 (Dichlorodifluoromethane), x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
-5	3.738	-0.095	-0.092	-0.089	-0.086	-0.082	-0.079	-0.076	-0.072	-0.069	-0.065	-0.062	-0.058
0	3.807	0.018	0.020	0.023	0.026	0.029	0.032	0.035	0.038	0.041	0.044	0.048	0.051
5	3.877	0.132	0.134	0.136	0.139	0.141	0.144	0.146	0.149	0.152	0.155	0.158	0.161
10	3.948	0.248	0.250	0.251	0.253	0.255	0.257	0.259	0.262	0.264	0.267	0.270	0.272
15	4.019	0.366	0.367	0.368	0.369	0.371	0.372	0.374	0.376	0.378	0.380	0.383	0.385
20	4.090	3.973	0.486	0.487	0.487	0.488	0.489	0.491	0.492	0.493	0.495	0.497	0.499
25	4.163	4.049	0.608	0.607	0.607	0.607	0.608	0.609	0.609	0.610	0.612	0.613	0.615
30	4.235	4.126	0.732	0.730	0.729	0.729	0.728	0.728	0.729	0.729	0.730	0.730	0.732
35	4.309	4.202	0.858	0.856	0.854	0.852	0.851	0.850	0.850	0.849	0.849	0.850	0.850
40	4.383	4.279	0.988	0.984	0.981	0.978	0.976	0.974	0.973	0.972	0.971	0.971	0.970
45	4.457	4.357	4.209	1.116	1.111	1.107	1.104	1.101	1.098	1.096	1.095	1.093	1.092
50	4.532	4.435	4.292	1.251	1.245	1.239	1.234	1.230	1.226	1.223	1.220	1.218	1.216
55	4.608	4.513	4.376	1.391	1.382	1.374	1.368	1.362	1.357	1.352	1.348	1.345	1.342
60	4.684	4.592	4.460	4.297	1.524	1.514	1.505	1.497	1.490	1.484	1.479	1.475	1.471
65	4.761	4.671	4.543	4.389	1.672	1.659	1.647	1.637	1.628	1.620	1.613	1.607	1.601
70	4.838	4.750	4.627	4.481	1.828	1.810	1.794	1.781	1.769	1.759	1.750	1.742	1.735
75	4.915	4.830	4.711	4.572	4.396	1.969	1.948	1.930	1.915	1.902	1.890	1.880	1.871
80	4.993	4.910	4.795	4.662	4.498	2.139	2.111	2.087	2.067	2.050	2.035	2.022	2.011
85	5.072	4.991	4.879	4.752	4.599	4.393	2.285	2.253	2.226	2.204	2.185	2.169	2.154
90	5.151	5.072	4.964	4.841	4.697	4.512	2.480	2.432	2.395	2.366	2.341	2.320	2.302
95	5.230	5.153	5.048	4.931	4.794	4.626	4.382	2.632	2.578	2.538	2.505	2.478	2.456
100	5.310	5.235	5.133	5.020	4.890	4.734	4.527	2.872	2.783	2.724	2.679	2.644	2.615
105	5.390	5.317	5.218	5.109	4.985	4.840	4.657	4.372	3.028	2.931	2.867	2.820	2.782
110	5.471	5.399	5.303	5.198	5.080	4.944	4.778	4.552	3.426	3.177	3.075	3.008	2.958

Table A5 Enthalpy database of r-12 (Dichlorodifluoromethane), x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
115	5.552	5.482	5.389	5.287	5.174	5.045	4.893	4.700	4.398	3.524	3.317	3.215	3.146
120	5.634	5.566	5.474	5.376	5.267	5.146	5.005	4.834	4.602	4.170	3.623	3.449	3.350
125	5.716	5.649	5.560	5.465	5.360	5.245	5.113	4.958	4.764	4.487	4.033	3.723	3.574
130	5.798	5.733	5.647	5.554	5.453	5.343	5.219	5.077	4.907	4.689	4.384	4.037	3.822
135	5.881	5.817	5.733	5.643	5.546	5.441	5.324	5.192	5.040	4.855	4.622	4.338	4.088
140	5.964	5.902	5.820	5.732	5.639	5.538	5.427	5.304	5.165	5.003	4.810	4.582	4.346
145	6.048	5.987	5.907	5.822	5.731	5.634	5.529	5.413	5.285	5.139	4.972	4.781	4.576
150	6.132	6.072	5.994	5.911	5.824	5.730	5.630	5.520	5.401	5.268	5.120	4.954	4.776
155	6.216	6.158	6.081	6.001	5.916	5.826	5.730	5.626	5.514	5.391	5.257	5.110	4.953
160	6.301	6.244	6.169	6.091	6.009	5.922	5.829	5.731	5.625	5.511	5.387	5.254	5.113
165	6.386	6.330	6.257	6.181	6.101	6.017	5.928	5.834	5.734	5.627	5.512	5.391	5.263
170	6.471	6.416	6.345	6.271	6.193	6.112	6.027	5.937	5.841	5.740	5.634	5.521	5.403
175	6.557	6.503	6.434	6.361	6.286	6.207	6.125	6.038	5.948	5.852	5.752	5.647	5.538
180	6.643	6.590	6.522	6.452	6.379	6.302	6.223	6.140	6.053	5.962	5.867	5.769	5.667
185	6.730	6.678	6.611	6.542	6.471	6.397	6.320	6.240	6.157	6.070	5.981	5.888	5.792
190	6.816	6.766	6.701	6.633	6.564	6.492	6.418	6.340	6.261	6.178	6.092	6.004	5.914
195	6.903	6.854	6.790	6.724	6.657	6.587	6.515	6.440	6.363	6.284	6.202	6.119	6.033
200	6.991	6.942	6.880	6.816	6.750	6.682	6.612	6.540	6.466	6.390	6.312	6.232	6.151
205	7.078	7.031	6.970	6.907	6.843	6.777	6.709	6.639	6.568	6.494	6.419	6.343	6.266
210	7.166	7.119	7.060	6.998	6.936	6.871	6.806	6.738	6.669	6.598	6.526	6.453	6.379
215	7.254	7.208	7.150	7.090	7.029	6.966	6.902	6.837	6.770	6.702	6.633	6.563	6.492
220	7.343	7.298	7.241	7.182	7.122	7.061	6.999	6.936	6.871	6.805	6.738	6.671	6.603
225	7.432	7.388	7.331	7.274	7.216	7.156	7.096	7.034	6.971	6.908	6.843	6.778	6.713
230	7.521	7.477	7.422	7.366	7.309	7.251	7.192	7.132	7.072	7.010	6.948	6.885	6.822

Table A5 Enthalpy database of r-12 (Dichlorodifluoromethane), x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	1	5	10	15	20	25	30	35	40	45	50	55	60
235	7.610	7.568	7.514	7.459	7.403	7.347	7.289	7.231	7.172	7.112	7.052	6.991	6.930
240	7.700	7.658	7.605	7.551	7.497	7.442	7.386	7.329	7.272	7.214	7.155	7.097	7.038
245	7.789	7.749	7.697	7.644	7.591	7.537	7.482	7.427	7.371	7.315	7.259	7.202	7.145
250	7.879	7.839	7.789	7.737	7.685	7.632	7.579	7.525	7.471	7.417	7.362	7.307	7.252
255	7.970	7.930	7.881	7.830	7.779	7.728	7.676	7.624	7.571	7.518	7.464	7.411	7.358
260	8.060	8.022	7.973	7.924	7.874	7.823	7.773	7.722	7.670	7.619	7.567	7.515	7.463
265	8.151	8.113	8.065	8.017	7.968	7.919	7.870	7.820	7.770	7.719	7.669	7.619	7.568
270	8.242	8.205	8.158	8.111	8.063	8.015	7.966	7.918	7.869	7.820	7.771	7.722	7.673
275	8.334	8.297	8.251	8.205	8.158	8.111	8.063	8.016	7.968	7.921	7.873	7.825	7.778
280	8.425	8.389	8.344	8.298	8.253	8.207	8.160	8.114	8.068	8.021	7.975	7.928	7.882
285	8.517	8.482	8.437	8.393	8.348	8.303	8.257	8.212	8.167	8.121	8.076	8.031	7.986
290	8.609	8.574	8.531	8.487	8.443	8.399	8.355	8.310	8.266	8.222	8.178	8.134	8.090
295	8.701	8.667	8.624	8.581	8.538	8.495	8.452	8.409	8.365	8.322	8.279	8.236	8.194
300	8.793	8.760	8.718	8.676	8.634	8.591	8.549	8.507	8.464	8.422	8.380	8.338	8.297
305	8.886	8.853	8.812	8.771	8.729	8.688	8.646	8.605	8.564	8.523	8.481	8.441	8.400
310	8.979	8.946	8.906	8.866	8.825	8.784	8.744	8.703	8.663	8.623	8.583	8.543	8.503
315	9.072	9.040	9.000	8.961	8.921	8.881	8.841	8.802	8.762	8.723	8.684	8.645	8.606
320	9.165	9.134	9.095	9.056	9.017	8.978	8.939	8.900	8.862	8.823	8.785	8.747	8.709
325	9.258	9.228	9.189	9.151	9.113	9.075	9.037	8.999	8.961	8.923	8.886	8.849	8.812
330	9.352	9.322	9.284	9.247	9.209	9.172	9.134	9.097	9.060	9.023	8.987	8.951	8.915
335	9.445	9.416	9.379	9.342	9.305	9.269	9.232	9.196	9.160	9.124	9.088	9.052	9.017
340	9.539	9.510	9.474	9.438	9.402	9.366	9.330	9.294	9.259	9.224	9.189	9.154	9.120
345	9.633	9.605	9.569	9.534	9.499	9.463	9.428	9.393	9.358	9.324	9.290	9.256	9.222
350	9.728	9.700	9.665	9.630	9.595	9.561	9.526	9.492	9.458	9.424	9.391	9.358	9.325

Table A5 Enthalpy database of r-12 (Dichlorodifluoromethane), x 10^6 [J/day] $[kg/hr]^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	1	5	10	15	20	25	30	35	40	45	50	55	60
355	9.822	9.795	9.760	9.726	9.692	9.658	9.624	9.591	9.557	9.524	9.492	9.459	9.427
360	9.917	9.890	9.856	9.822	9.789	9.756	9.723	9.690	9.657	9.625	9.593	9.561	9.530
365	10.011	9.985	9.952	9.919	9.886	9.853	9.821	9.789	9.757	9.725	9.694	9.663	9.632
370	10.106	10.080	10.048	10.015	9.983	9.951	9.919	9.888	9.856	9.825	9.795	9.764	9.734
375	10.201	10.176	10.144	10.112	10.080	10.049	10.018	9.987	9.956	9.926	9.896	9.866	9.836
380	10.297	10.271	10.240	10.209	10.178	10.147	10.116	10.086	10.056	10.026	9.997	9.967	9.939
385	10.392	10.367	10.336	10.306	10.275	10.245	10.215	10.185	10.156	10.126	10.098	10.069	10.041
390	10.488	10.463	10.433	10.403	10.373	10.343	10.314	10.285	10.256	10.227	10.199	10.171	10.143
395	10.583	10.559	10.530	10.500	10.471	10.441	10.413	10.384	10.356	10.327	10.300	10.272	10.245
400	10.679	10.656	10.626	10.597	10.568	10.540	10.511	10.483	10.456	10.428	10.401	10.374	10.347

Table A6 Enthalpy database of nitrogen, x 10^6 [J/day] [kg/hr]$^{-1}$

Temperature (°C)	Pressure (atm)											
	1	5	10	15	20	25	30	35	40	45	50	55
-200	-10.846	-10.839	-10.830	-10.822	-10.813	-10.804	-10.795	-10.786	-10.777	-10.768	-10.759	-10.750
-190	-5.635	-10.343	-10.337	-10.330	-10.324	-10.317	-10.310	-10.303	-10.295	-10.288	-10.281	-10.273
-180	-5.379	-9.813	-9.811	-9.809	-9.806	-9.803	-9.799	-9.796	-9.791	-9.787	-9.782	-9.777
-170	-5.123	-5.283	-9.222	-9.230	-9.236	-9.241	-9.244	-9.247	-9.249	-9.250	-9.251	-9.251
-160	-4.869	-5.005	-5.200	-5.444	-8.538	-8.570	-8.596	-8.617	-8.635	-8.649	-8.662	-8.672
-150	-4.616	-4.734	-4.895	-5.080	-5.302	-5.597	-7.564	-7.741	-7.837	-7.904	-7.954	-7.993
-140	-4.364	-4.467	-4.604	-4.755	-4.922	-5.112	-5.337	-5.619	-6.015	-6.547	-6.891	-7.075
-130	-4.112	-4.203	-4.322	-4.449	-4.585	-4.731	-4.890	-5.064	-5.256	-5.469	-5.699	-5.935
-120	-3.860	-3.941	-4.046	-4.156	-4.271	-4.390	-4.516	-4.648	-4.786	-4.931	-5.080	-5.233
-110	-3.609	-3.682	-3.775	-3.871	-3.970	-4.072	-4.176	-4.284	-4.394	-4.506	-4.621	-4.736
-100	-3.358	-3.423	-3.507	-3.592	-3.679	-3.767	-3.856	-3.947	-4.039	-4.132	-4.226	-4.319
-90	-3.107	-3.166	-3.241	-3.317	-3.394	-3.472	-3.550	-3.629	-3.708	-3.787	-3.866	-3.944
-80	-2.856	-2.910	-2.978	-3.046	-3.115	-3.184	-3.253	-3.322	-3.391	-3.460	-3.528	-3.596
-70	-2.606	-2.655	-2.716	-2.778	-2.840	-2.901	-2.963	-3.024	-3.085	-3.146	-3.206	-3.265
-60	-2.355	-2.400	-2.456	-2.512	-2.568	-2.623	-2.678	-2.733	-2.788	-2.842	-2.895	-2.948
-50	-2.105	-2.146	-2.197	-2.248	-2.298	-2.349	-2.398	-2.448	-2.497	-2.545	-2.593	-2.640
-40	-1.855	-1.892	-1.939	-1.985	-2.031	-2.077	-2.122	-2.166	-2.211	-2.254	-2.297	-2.339
-30	-1.605	-1.639	-1.682	-1.724	-1.766	-1.807	-1.848	-1.889	-1.929	-1.968	-2.007	-2.045
-20	-1.354	-1.386	-1.425	-1.464	-1.502	-1.540	-1.577	-1.614	-1.650	-1.686	-1.721	-1.756
-10	-1.104	-1.133	-1.169	-1.205	-1.240	-1.274	-1.308	-1.342	-1.375	-1.407	-1.439	-1.471
0	-0.854	-0.881	-0.914	-0.946	-0.978	-1.010	-1.041	-1.072	-1.102	-1.131	-1.161	-1.189
10	-0.604	-0.629	-0.659	-0.689	-0.718	-0.747	-0.775	-0.803	-0.831	-0.858	-0.884	-0.910
20	-0.354	-0.377	-0.405	-0.432	-0.459	-0.485	-0.511	-0.537	-0.562	-0.586	-0.611	-0.634
30	-0.104	-0.125	-0.150	-0.175	-0.200	-0.224	-0.248	-0.271	-0.294	-0.317	-0.339	-0.361

Table A6 Enthalpy database of nitrogen, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)											
	1	5	10	15	20	25	30	35	40	45	50	55
40	0.146	0.127	0.103	0.080	0.058	0.036	0.014	-0.007	-0.028	-0.049	-0.069	-0.089
50	0.396	0.378	0.357	0.336	0.315	0.295	0.275	0.256	0.237	0.218	0.200	0.182
60	0.646	0.630	0.610	0.591	0.572	0.554	0.536	0.518	0.500	0.483	0.467	0.450
70	0.896	0.881	0.863	0.846	0.829	0.812	0.795	0.779	0.763	0.748	0.733	0.718
80	1.146	1.133	1.116	1.100	1.085	1.070	1.054	1.040	1.025	1.011	0.998	0.984
90	1.396	1.384	1.369	1.355	1.341	1.327	1.313	1.300	1.287	1.274	1.262	1.250
100	1.647	1.636	1.622	1.609	1.596	1.584	1.571	1.559	1.548	1.536	1.525	1.514
110	1.897	1.887	1.875	1.863	1.852	1.840	1.829	1.818	1.808	1.797	1.787	1.778
120	2.148	2.139	2.128	2.117	2.107	2.097	2.087	2.077	2.067	2.058	2.049	2.041
130	2.399	2.391	2.381	2.371	2.362	2.353	2.344	2.335	2.327	2.319	2.311	2.303
140	2.650	2.642	2.634	2.625	2.617	2.609	2.601	2.593	2.586	2.579	2.572	2.565
150	2.901	2.895	2.887	2.879	2.872	2.865	2.858	2.851	2.845	2.838	2.832	2.826
160	3.152	3.147	3.140	3.133	3.127	3.121	3.115	3.109	3.103	3.098	3.092	3.087
170	3.404	3.399	3.393	3.387	3.382	3.376	3.371	3.366	3.361	3.357	3.352	3.348
180	3.656	3.652	3.647	3.642	3.637	3.632	3.628	3.624	3.620	3.616	3.612	3.609
190	3.908	3.904	3.900	3.896	3.892	3.888	3.885	3.881	3.878	3.875	3.872	3.869
200	4.161	4.158	4.154	4.151	4.147	4.144	4.141	4.139	4.136	4.134	4.131	4.129

Table A6 Enthalpy database of nitrogen, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	**Pressure (atm)**												
	60	65	70	75	80	85	90	95	100	105	110	115	120
-200	-10.741	-10.732	-10.722	-10.713	-10.704	-10.694	-10.685	-10.675	-10.666	-10.656	-10.647	-10.637	-10.628
-190	-10.265	-10.258	-10.250	-10.242	-10.234	-10.226	-10.217	-10.209	-10.201	-10.192	-10.184	-10.175	-10.167
-180	-9.772	-9.767	-9.761	-9.755	-9.749	-9.743	-9.737	-9.730	-9.724	-9.717	-9.710	-9.703	-9.696
-170	-9.250	-9.249	-9.247	-9.245	-9.243	-9.240	-9.237	-9.233	-9.230	-9.226	-9.221	-9.217	-9.212
-160	-8.681	-8.688	-8.694	-8.699	-8.702	-8.705	-8.708	-8.709	-8.710	-8.710	-8.710	-8.710	-8.708
-150	-8.025	-8.052	-8.075	-8.094	-8.110	-8.125	-8.137	-8.147	-8.156	-8.164	-8.170	-8.175	-8.180
-140	-7.193	-7.278	-7.344	-7.397	-7.440	-7.476	-7.507	-7.533	-7.556	-7.576	-7.593	-7.608	-7.621
-130	-6.151	-6.331	-6.473	-6.586	-6.676	-6.750	-6.811	-6.863	-6.907	-6.946	-6.979	-7.008	-7.033
-120	-5.387	-5.535	-5.675	-5.802	-5.915	-6.014	-6.100	-6.174	-6.240	-6.297	-6.347	-6.391	-6.430
-110	-4.851	-4.965	-5.075	-5.182	-5.282	-5.376	-5.463	-5.542	-5.614	-5.680	-5.739	-5.792	-5.841
-100	-4.412	-4.503	-4.593	-4.681	-4.766	-4.847	-4.924	-4.997	-5.065	-5.129	-5.188	-5.243	-5.294
-90	-4.022	-4.099	-4.175	-4.249	-4.320	-4.390	-4.457	-4.521	-4.583	-4.641	-4.696	-4.748	-4.797
-80	-3.663	-3.729	-3.794	-3.858	-3.920	-3.980	-4.039	-4.095	-4.149	-4.202	-4.252	-4.300	-4.345
-70	-3.324	-3.382	-3.438	-3.494	-3.548	-3.601	-3.653	-3.703	-3.751	-3.798	-3.843	-3.886	-3.928
-60	-3.000	-3.051	-3.101	-3.150	-3.198	-3.245	-3.291	-3.335	-3.378	-3.420	-3.460	-3.499	-3.537
-50	-2.686	-2.732	-2.776	-2.820	-2.863	-2.905	-2.946	-2.985	-3.024	-3.062	-3.098	-3.133	-3.167
-40	-2.381	-2.422	-2.462	-2.501	-2.540	-2.577	-2.614	-2.650	-2.684	-2.718	-2.751	-2.783	-2.814
-30	-2.083	-2.119	-2.156	-2.191	-2.226	-2.259	-2.293	-2.325	-2.356	-2.387	-2.417	-2.446	-2.474
-20	-1.790	-1.823	-1.856	-1.888	-1.919	-1.950	-1.980	-2.009	-2.037	-2.065	-2.092	-2.118	-2.144
-10	-1.502	-1.532	-1.561	-1.590	-1.619	-1.647	-1.674	-1.700	-1.726	-1.751	-1.776	-1.800	-1.823
0	-1.217	-1.245	-1.272	-1.298	-1.324	-1.349	-1.374	-1.398	-1.421	-1.444	-1.466	-1.488	-1.509
10	-0.936	-0.961	-0.985	-1.009	-1.033	-1.056	-1.078	-1.100	-1.121	-1.142	-1.162	-1.182	-1.201
20	-0.658	-0.680	-0.703	-0.724	-0.746	-0.767	-0.787	-0.807	-0.826	-0.845	-0.864	-0.881	-0.899
30	-0.382	-0.402	-0.423	-0.443	-0.462	-0.481	-0.499	-0.517	-0.535	-0.552	-0.569	-0.585	-0.601

Table A6 Enthalpy database of nitrogen, x 10^6 [J/day] [kg/hr]$^{-1}$ (cont'd)

Temperature (°C)	Pressure (atm)												
	60	65	70	75	80	85	90	95	100	105	110	115	120
40	-0.108	-0.127	-0.145	-0.163	-0.181	-0.198	-0.215	-0.231	-0.247	-0.263	-0.278	-0.293	-0.307
50	0.164	0.147	0.130	0.114	0.098	0.082	0.067	0.052	0.038	0.023	0.010	-0.004	-0.017
60	0.435	0.419	0.404	0.389	0.374	0.360	0.346	0.333	0.320	0.307	0.295	0.282	0.271
70	0.703	0.689	0.676	0.662	0.649	0.636	0.624	0.611	0.600	0.588	0.577	0.566	0.555
80	0.971	0.958	0.946	0.934	0.922	0.910	0.899	0.888	0.877	0.867	0.857	0.847	0.838
90	1.238	1.226	1.215	1.204	1.193	1.183	1.173	1.163	1.154	1.144	1.135	1.127	1.118
100	1.503	1.493	1.483	1.473	1.464	1.454	1.445	1.437	1.428	1.420	1.412	1.404	1.397
110	1.768	1.759	1.750	1.741	1.733	1.724	1.716	1.709	1.701	1.694	1.687	1.680	1.673
120	2.032	2.024	2.016	2.008	2.001	1.993	1.986	1.979	1.973	1.966	1.960	1.954	1.949
130	2.295	2.288	2.281	2.274	2.268	2.261	2.255	2.249	2.244	2.238	2.233	2.227	2.223
140	2.558	2.552	2.546	2.540	2.534	2.529	2.523	2.518	2.513	2.508	2.504	2.500	2.495
150	2.821	2.815	2.810	2.805	2.800	2.795	2.790	2.786	2.782	2.778	2.774	2.771	2.767
160	3.082	3.078	3.073	3.069	3.065	3.061	3.057	3.053	3.050	3.047	3.044	3.041	3.038
170	3.344	3.340	3.336	3.333	3.329	3.326	3.323	3.320	3.317	3.315	3.312	3.310	3.308
180	3.605	3.602	3.599	3.596	3.593	3.591	3.588	3.586	3.584	3.582	3.580	3.579	3.577
190	3.866	3.864	3.861	3.859	3.857	3.855	3.853	3.852	3.850	3.849	3.848	3.847	3.846
200	4.127	4.125	4.124	4.122	4.121	4.119	4.118	4.117	4.116	4.115	4.115	4.114	4.114

Appendix B Properties of Refrigerants from Pro/II V 9.4

Table B1 Saturated properties of ethane, H_L x 10^6 [J/day] [kg/hr]$^{-1}$, H_V x 10^6 [J/day] [kg/hr]$^{-1}$

Property	**Pressure (atm)**												
	1.000	2.412	3.354	4.296	5.237	6.179	7.121	8.062	9.004	10.416	11.358	12.299	13.241
Tsat (°C)	-88.276	-70.379	-62.667	-56.448	-51.177	-46.570	-42.455	-38.722	-35.296	-30.616	-27.747	-25.046	-22.490
H_L	-6.339	-5.239	-4.749	-4.344	-3.994	-3.681	-3.397	-3.134	-2.888	-2.545	-2.330	-2.124	-1.925
H_V	5.603	6.101	6.297	6.445	6.564	6.662	6.745	6.816	6.876	6.952	6.994	7.031	7.062
Property	**Pressure (atm)**												
	14.183	15.124	16.066	17.008	18.420	19.362	20.303	21.245	22.186	23.128	24.070	25.011	25.953
Tsat (°C)	-20.062	-17.747	-15.533	-13.411	-10.380	-8.450	-6.586	-4.783	-3.035	-1.340	0.307	1.909	3.469
H_L	-1.734	-1.549	-1.368	-1.192	-0.936	-0.769	-0.606	-0.444	-0.285	-0.128	0.027	0.181	0.334
H_V	7.090	7.113	7.132	7.147	7.165	7.173	7.178	7.180	7.180	7.177	7.171	7.163	7.152
Property	**Pressure (atm)**												
	26.895	27.836	28.307	29.249	30.190	31.132	32.073	33.015	34.428	35.369	36.311	37.252	38.194
Tsat (°C)	4.989	6.472	7.201	8.632	10.031	11.399	12.739	14.051	15.971	17.221	18.447	19.651	20.834
H_L	0.486	0.637	0.712	0.863	1.014	1.164	1.315	1.467	1.697	1.851	2.008	2.167	2.329
H_V	7.139	7.123	7.114	7.094	7.071	7.046	7.018	6.986	6.933	6.893	6.849	6.800	6.747
Property	**Pressure (atm)**												
	39.136	40.077	41.019	42.431	43.373	44.315	45.256	46.198	47.139	48.081			
Tsat (°C)	21.996	23.139	24.264	25.917	26.998	28.062	29.111	30.144	31.163	32.168			
H_L	2.495	2.665	2.840	3.117	3.314	3.525	3.756	4.019	4.345	5.028			
H_V	6.689	6.624	6.552	6.428	6.331	6.219	6.085	5.917	5.686	5.096			

Table B2 Saturated properties of ethylene, H_L x 10^6 [J/day] [kg/hr]$^{-1}$, H_V x 10^6 [J/day] [kg/hr]$^{-1}$

Property	**Pressure (atm)**												
	1.000	2.462	3.437	4.411	5.386	6.360	7.335	8.310	9.284	10.259	11.233	12.208	13.183
Tsat (°C)	-103.61	-86.690	-79.450	-73.625	-68.693	-64.385	-60.538	-57.050	-53.849	-50.884	-48.116	-45.518	-43.065
H_L	-7.460	-6.481	-6.047	-5.689	-5.379	-5.103	-4.851	-4.619	-4.402	-4.197	-4.002	-3.816	-3.637
H_V	4.226	4.615	4.762	4.870	4.955	5.022	5.076	5.121	5.158	5.188	5.212	5.231	5.246
Property	**Pressure (atm)**												
	14.157	15.132	16.106	17.081	18.056	19.030	20.005	21.467	22.441	23.416	24.390	25.365	26.340
Tsat (°C)	-40.739	-38.526	-36.412	-34.389	-32.446	-30.577	-28.774	-26.184	-24.527	-22.919	-21.358	-19.841	-18.365
H_L	-3.464	-3.297	-3.135	-2.977	-2.822	-2.671	-2.522	-2.304	-2.161	-2.020	-1.880	-1.741	-1.604
H_V	5.257	5.265	5.269	5.270	5.269	5.265	5.258	5.243	5.231	5.216	5.199	5.179	5.158
Property	**Pressure (atm)**												
	27.314	28.289	29.263	30.238	31.213	32.187	33.162	34.136	35.111	36.086	37.060	38.035	39.009
Tsat (°C)	-16.926	-15.524	-14.155	-12.817	-11.510	-10.231	-8.980	-7.753	-6.551	-5.373	-4.216	-3.081	-1.966
H_L	-1.467	-1.331	-1.195	-1.059	-0.923	-0.786	-0.649	-0.512	-0.373	-0.232	-0.090	0.054	0.201
H_V	5.134	5.107	5.079	5.048	5.015	4.979	4.940	4.898	4.854	4.806	4.755	4.699	4.640
Property	**Pressure (atm)**												
	40.471	41.446	42.421	43.395	44.370	45.344	46.319	47.294	48.268	49.243	49.730		
Tsat (°C)	-0.329	0.740	1.791	2.825	3.843	4.845	5.833	6.806	7.766	8.711	9.180		
H_L	0.429	0.585	0.748	0.917	1.095	1.285	1.491	1.722	1.995	2.370	2.789		
H_V	4.541	4.468	4.388	4.300	4.202	4.090	3.962	3.808	3.610	3.308	2.928		

Table B3 Saturated properties of propane, H_L x 10^6 [J/day] [kg/hr]$^{-1}$, H_V x 10^6 [J/day] [kg/hr]$^{-1}$

Property	**Pressure (atm)**												
	1.000	2.228	3.046	4.274	5.092	6.320	7.138	8.366	9.184	10.002	11.230	12.048	13.276
Tsat (°C)	-41.882	-22.129	-13.355	-3.074	2.598	9.948	14.278	20.133	23.693	27.028	31.676	34.573	38.661
H_L	-2.413	-1.318	-0.809	-0.192	0.159	0.626	0.908	1.298	1.540	1.771	2.100	2.309	2.609
H_V	7.947	8.525	8.777	9.065	9.221	9.418	9.530	9.678	9.766	9.845	9.952	10.017	10.104

Property	**Pressure (atm)**												
	14.094	15.322	16.140	17.368	18.186	19.005	20.232	21.051	22.278	23.097	24.324	25.143	26.370
Tsat (°C)	41.237	44.905	47.233	50.572	52.705	54.769	57.750	59.666	62.442	64.232	66.835	68.518	70.971
H_L	2.803	3.083	3.264	3.529	3.702	3.872	4.122	4.286	4.528	4.688	4.925	5.082	5.317
H_V	10.156	10.227	10.270	10.328	10.362	10.393	10.435	10.459	10.490	10.507	10.527	10.537	10.548

Property	**Pressure (atm)**												
	27.189	28.007	29.235	30.053	31.281	32.099	33.327	34.145	35.373	36.191	37.010	38.237	39.056
Tsat (°C)	72.562	74.118	76.394	77.874	80.040	81.451	83.521	84.871	86.853	88.147	89.421	91.296	92.521
H_L	5.473	5.628	5.862	6.019	6.256	6.415	6.659	6.824	7.079	7.255	7.438	7.729	7.939
H_V	10.551	10.551	10.546	10.538	10.521	10.504	10.471	10.443	10.390	10.346	10.294	10.195	10.111

Property	**Pressure (atm)**		
	40.283	41.102	41.920
Tsat (°C)	94.326	95.508	96.674
H_L	8.299	8.600	9.201
H_V	9.937	9.758	9.283

Table B4 Saturated properties of propylene, H_L x 10^6 [J/day] [kg/hr]$^{-1}$, H_V x 10^6 [J/day] [kg/hr]$^{-1}$

Property	**Pressure (atm)**												
	1.000	2.351	3.252	4.152	5.053	6.404	7.304	8.205	9.105	10.006	11.357	12.258	13.158
Tsat (°C)	-47.581	-26.953	-17.988	-10.746	-4.603	3.232	7.796	11.961	15.804	19.377	24.319	27.381	30.284
H_L	-2.735	-1.644	-1.147	-0.734	-0.375	0.097	0.378	0.640	0.886	1.119	1.448	1.656	1.857
H_V	7.910	8.456	8.686	8.868	9.018	9.203	9.307	9.400	9.482	9.556	9.653	9.711	9.763

Property	**Pressure (atm)**												
	14.059	15.410	16.310	17.211	18.111	19.012	20.363	21.264	22.164	23.065	24.416	25.316	26.217
Tsat (°C)	33.046	36.958	39.430	41.806	44.094	46.302	49.477	51.510	53.483	55.400	58.176	59.967	61.713
H_L	2.050	2.330	2.511	2.687	2.859	3.028	3.275	3.437	3.597	3.755	3.988	4.142	4.294
H_V	9.811	9.874	9.911	9.945	9.975	10.002	10.037	10.057	10.074	10.088	10.105	10.112	10.117

Property	**Pressure (atm)**												
	27.117	28.018	29.369	30.270	31.170	32.071	33.422	34.322	35.223	36.123	37.024	38.375	39.276
Tsat (°C)	63.417	65.080	67.506	69.080	70.620	72.130	74.338	75.776	77.187	78.572	79.934	81.932	83.237
H_L	4.446	4.597	4.823	4.974	5.124	5.275	5.503	5.657	5.812	5.969	6.129	6.375	6.545
H_V	10.119	10.119	10.113	10.106	10.096	10.082	10.056	10.034	10.008	9.978	9.944	9.882	9.832

Property	**Pressure (atm)**						
	40.176	41.077	42.428	43.328	44.229	45.129	46.030
Tsat (°C)	84.521	85.785	87.645	88.861	90.060	91.242	92.407
H_L	6.720	6.904	7.199	7.417	7.663	7.964	8.542
H_V	9.775	9.709	9.586	9.481	9.346	9.155	8.657

Table B5 Saturated properties of r-12 (Dichlorodifluoromethane), $H_L \times 10^6$ [J/day] [kg/hr]$^{-1}$, $H_V \times 10^6$ [J/day] [kg/hr]$^{-1}$

Property	**Pressure (atm)**												
	1.000	2.191	3.383	4.177	5.368	6.162	7.354	8.148	9.339	10.133	11.325	12.119	13.310
Tsat (°C)	-29.573	-9.547	3.203	9.899	18.337	23.211	29.713	33.626	38.999	42.307	46.930	49.818	53.902
H_L	-0.630	-0.197	0.090	0.246	0.446	0.564	0.725	0.824	0.962	1.049	1.172	1.250	1.363
H_V	3.406	3.636	3.777	3.849	3.936	3.985	4.047	4.083	4.131	4.159	4.196	4.218	4.248
Property	**Pressure (atm)**												
	14.104	15.296	16.090	17.281	18.075	19.267	20.061	21.252	22.046	23.238	24.032	25.223	26.017
Tsat (°C)	56.480	60.155	62.491	65.844	67.987	71.079	73.064	75.938	77.791	80.481	82.221	84.754	86.395
H_L	1.435	1.540	1.607	1.706	1.771	1.866	1.928	2.019	2.079	2.168	2.227	2.315	2.373
H_V	4.265	4.289	4.302	4.321	4.331	4.345	4.352	4.362	4.366	4.372	4.374	4.375	4.375
Property	**Pressure (atm)**												
	27.209	28.003	29.194	30.385	31.180	32.371	33.165	34.356	35.151	36.342	37.136	38.327	39.122
Tsat (°C)	88.792	90.348	92.624	94.835	96.275	98.386	99.763	101.785	103.105	105.047	106.316	108.184	109.406
H_L	2.461	2.519	2.606	2.695	2.754	2.845	2.907	3.003	3.069	3.172	3.246	3.368	3.462
H_V	4.372	4.368	4.361	4.350	4.341	4.324	4.311	4.287	4.268	4.232	4.203	4.147	4.096

Property	**Pressure (atm)**	
	39.916	40.710
Tsat (°C)	110.611	111.862
H_L	3.576	3.653
H_V	4.024	3.969

Table B6 Saturated properties of nitrogen, $H_L \times 10^6$ [J/day] [kg/hr]$^{-1}$, $H_V \times 10^6$ [J/day] [kg/hr]$^{-1}$

Property	**Pressure (atm)**										
	1.000	2.302	3.278	4.254	5.230	6.206	7.183	8.159	9.135	10.111	11.087
Tsat (°C)	-195.684	-187.915	-184.097	-181.046	-178.472	-176.226	-174.223	-172.407	-170.740	-169.196	-167.75
H_L	-10.634	-10.239	-10.038	-9.872	-9.728	-9.599	-9.481	-9.371	-9.268	-9.170	-9.076
H_V	-5.782	-5.649	-5.596	-5.561	-5.538	-5.522	-5.513	-5.508	-5.506	-5.509	-5.513
Property	**Pressure (atm)**										
	12.064	13.040	14.016	14.992	15.318	16.294	17.270	18.246	19.222	20.199	21.175
Tsat (°C)	-166.401	-165.122	-163.909	-162.754	-162.381	-161.294	-160.252	-159.250	-158.285	-157.353	-156.45
H_L	-8.985	-8.898	-8.812	-8.729	-8.701	-8.619	-8.539	-8.459	-8.379	-8.300	-8.220
H_V	-5.521	-5.531	-5.543	-5.557	-5.562	-5.579	-5.598	-5.619	-5.642	-5.667	-5.694
Property	**Pressure (atm)**										
	22.151	23.127	24.103	25.080	26.056	27.032	28.008	28.984	29.961	30.286	31.262
Tsat (°C)	-155.580	-154.734	-153.913	-153.114	-152.337	-151.580	-150.841	-150.120	-149.415	-149.184	-148.50
H_L	-8.140	-8.059	-7.977	-7.893	-7.807	-7.717	-7.624	-7.526	-7.420	-7.382	-7.259
H_V	-5.724	-5.756	-5.791	-5.830	-5.872	-5.918	-5.970	-6.028	-6.095	-6.119	-6.204
Property	**Pressure (atm)**										
	32.238	33.215	33.540								
Tsat (°C)	-147.831	-147.176	-146.960								
H_L	-7.112	-6.897	-6.738								
H_V	-6.314	-6.493	-6.658								

Table B7 Properties for indicating gas region above critical point of nitrogen

Pressure (atm)	**Temperature (°C)**	**Enthalpy x 10^6 [J/day] [kg/hr]$^{-1}$**
35	-146.0	-6.661
40	-142.9	-6.608
45	-140.1	-6.566
50	-137.5	-6.522
55	-135.1	-6.481
60	-132.8	-6.435
65	-130.5	-6.378
70	-128.4	-6.332
75	-126.4	-6.288
80	-124.5	-6.246
85	-122.6	-6.199
90	-120.8	-6.155
95	-119.1	-6.114
100	-117.4	-6.071
105	-115.8	-6.031
110	-114.2	-5.988
115	-112.6	-5.944
120	-111.1	-5.904

Appendix C Exergy Analysis on LNG Production

Especially, LNG production or cryogenic process operates under below ambient condition that required a lot of work or utility to meet the suitable operating condition. Hence exergy analysis is interested in sub-ambient process in order to define energy loss or exergy destruction such as energy loss from hot and cold streams in heat exchanger which these streams transferred each other. This research was concerned mainly in the thermo-mechanical exergy in terms of change of temperature in heat exchanger and change of pressure in turbo-machine. Applying the exergy analysis to LNG production, a simplified design using pure nitrogen as working fluid is shown in Figure C1.

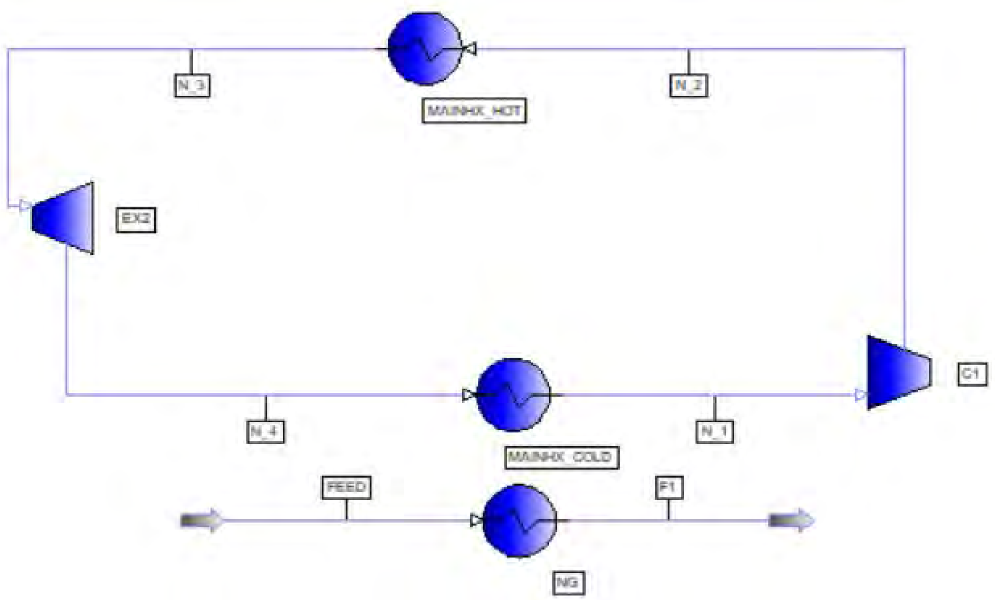

Figure C1 Flow sheet of simplified cooling system with nitrogen gas.

First, the simplified design is used for cooling the natural gas which has the same compositions shown in Table 4.2 but different operating temperature which is 25 °C to -76.11 °C in liquefaction process. Before analysis, the data of these streams are shown in Table C1 and used for conducting the traditional composite curves and exergetic composite curves (ECCs) with streams passing though turbo-machine (expander or compressor) by using ΔT = 3 °C. When streams pass though expender, they will act as hot stream due to decrease of temperature. Besides that, the streams pass though compressor, they will act as cold stream due to increase of temperature.

Table C1 Stream data for simplified cooling system with nitrogen gas

Hot Stream	T_{in} (K)	T_{out} (K)	P_{in} (atm)	P_{out} (atm)	H_{in} (kW)	H_{out} (kW)	mc_p (kW/K)
Main HX. Hot	453.26	301.15	50.66	50.66	161.84	-176.60	1.18
NG	298.15	197.04	48.26	46.19	52.23	-63.94	1.15
Exp.	301.15	194.04	50.66	11.41	-17.60	-133.04	1.08
Cold Stream	**T_{in} (K)**	**T_{out} (K)**	**P_{in} (atm)**	**P_{out} (atm)**	**H_{in} (kW)**	**H_{out} (kW)**	**mc_p (kW/K)**
Main HX. Cold	194.04	295.15	11.41	11.41	-133.0	-16.14	1.16
Com.	295.15	453.26	11.41	50.66	-16.14	161.84	1.13

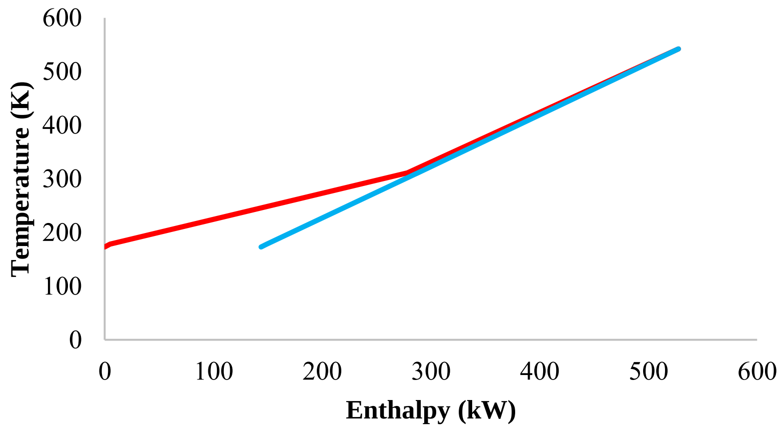

Figure C2 (a) Composite curves of simplified cooling system with nitrogen gas.

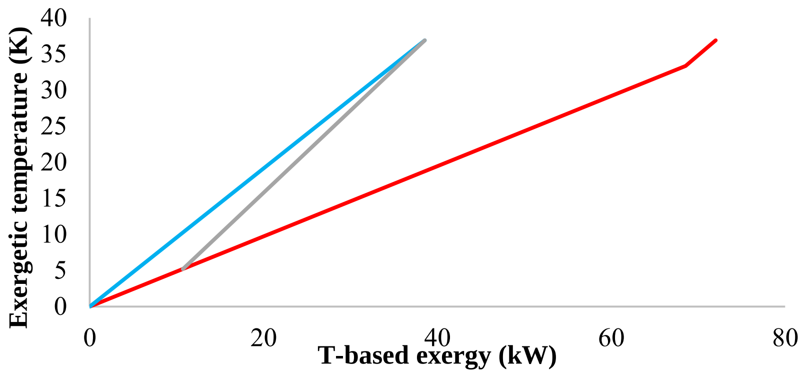

Figure C2 (b) Exergetic composite curves of below ambient simplified cooling system with nitrogen gas.

According to Figure C2 (b), the exergy requirement in below ambient condition is 40.83 kW while exergy deficit and exergy destruction are 16.99 kW and 23.84 kW, respectively. In terms of work, the work required by compressor is 177.98 kW while work produced by expander is 115.44 kW. Furthermore, the exergy destruction is defined by the end of temperature of cold streams at below ambient used to identify the temperature of hot stream that has the same enthalpy in CCs or Figure C2 (a). After that, the exergy destruction will be decreased when temperature of the end of cold stream is raised to reach the temperature of hot stream or heat capacity flow rate of cold stream is decreased. Besides that, temperature of the end of hot stream is reduced to reach the temperature of cold stream or heat capacity flow rate of hot stream is increased.

Table C2 Stream data for modified pressure of cooling system with nitrogen gas

Hot Stream	T_{in} (K)	T_{out} (K)	P_{in} (atm)	P_{out} (atm)	H_{in} (kW)	H_{out} (kW)	mc_p (kW/K)
Main HX. Hot	456.09	301.15	4.65	4.65	172.31	-8.01	1.16
NG	298.15	197.04	48.26	46.19	52.23	-63.94	1.15
Exp.	301.15	194.04	4.65	1.01	-8.01	-131.03	1.15
Cold Stream	**T_{in} (K)**	**T_{out} (K)**	**P_{in} (atm)**	**P_{out} (atm)**	**H_{in} (kW)**	**H_{out} (kW)**	**mc_p (kW/K)**
Main HX. Cold	194.04	295.15	1.01	1.01	-131.0	-14.08	1.16
Com.	295.15	456.09	1.01	4.65	-14.08	172.31	1.16

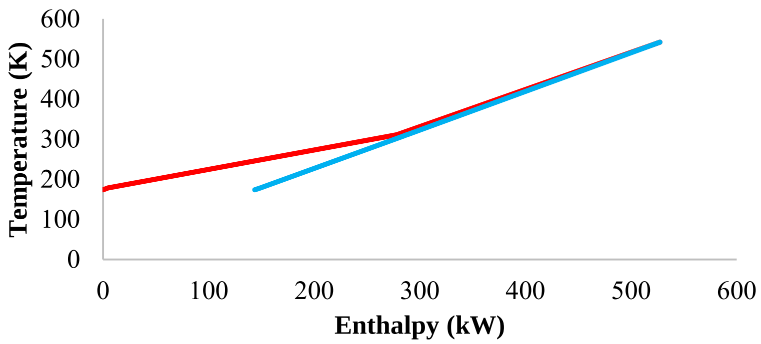

Figure C3 (a) Composite curves of modified pressure of cooling system with nitrogen gas.

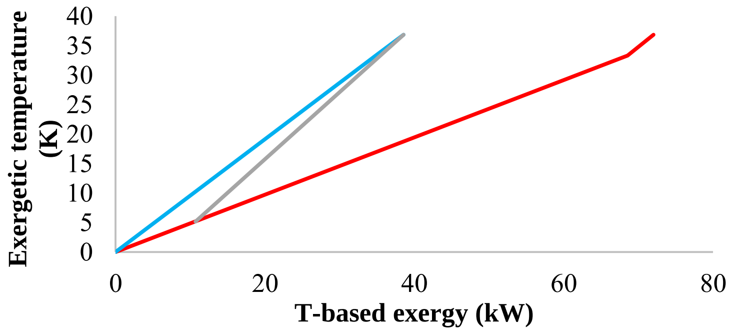

Figure C3 (b) Exergetic composite curves of below ambient modified pressure of cooling system with nitrogen gas.

In order to manipulate operating pressure, the mass flow rate of working fluid will be changed with the constant heat duty required by natural gas. Hence the operating conditions of second design will be changed shown in Table C2. From exergetic diagram or Figure C3 (b), the exergy destruction decreases from 16.99 kW to15.87 kW while exergy deficit increases from 23.84 kW to 25.52 kW. Therefore, the exergy requirement is 41.39 kW. Consequently, the work requirement of cooling system will be increased as well. The work required by compressor is 186.38 kW while work produced by expander is 123.02 kW. In addition, when concerning in the below ambient process, it should be added more the heat capacity flow rate of hot stream.

Last design, in order to increase heat capacity flow rate of hot stream, the simplified design shown in Figure C4 will be added the pre-cooler to cold coolant to reach the ambient condition before entering the main heat exchanger (T_{N_3}) to heat coolant when the heat duty at cooler (Main Hx. cold) has the heat duty more than the heat duty required by natural gas ($Q_{\text{Main Hx. cold}} > Q_{NG}$). After that, the inlet temperature at main heat exchanger (Main Hx. hot) is lower than ambient condition, which means the heat capacity flow rate of hot stream in below ambient is increased. Besides that, mass flow rate of coolant is required more than the case which has the equal of heat duty between natural gas and refrigerant ($Q_{NG} = Q_{\text{Main Hx. cold}}$). The operating conditions are listed in Table C3. From Figure C5 (b), the exergy requirement is 41.27 kW when exergy deficit and exergy destruction are 20.70 kW and 20.57 kW, respectively. Even if the exergy requirement is higher, the work requirement of this design can be decrease by work required as 155.94 kW and work produced as 95.54 kW. The inlet temperature from expander decrease when adding the pre-cooler, so the outlet pressure at expander is increased to effect on the shaft work at compressor that should be reduced.

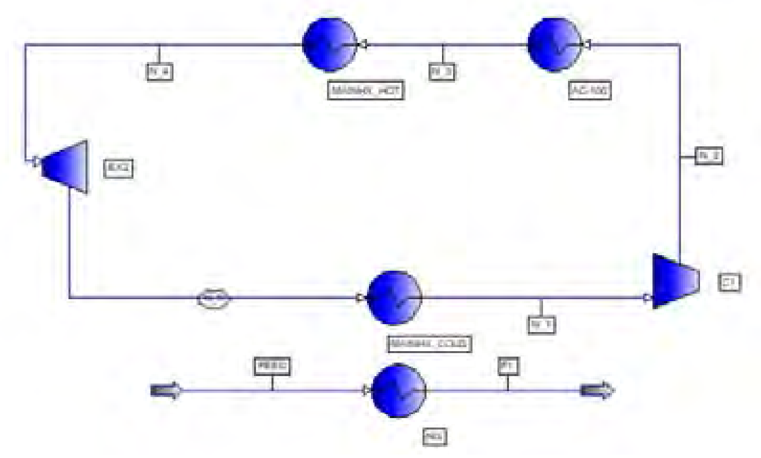

Figure C4 Flow sheet of modified cooling system with nitrogen gas.

Table C3 Stream data for modified cooling system with nitrogen gas

Hot Stream	T_{in} (K)	T_{out} (K)	P_{in} (atm)	P_{out} (atm)	H_{in} (kW)	H_{out} (kW)	mc_p (kW/K)
Main HX. Hot	295.15	281.88	120.00	120.00	-84.59	-103.91	1.46
NG	298.15	197.04	48.26	46.19	52.23	-63.94	1.15
Exp.	281.88	194.04	120.00	34.34	-103.9	-199.45	1.09
AC-100	424.58	295.15	120.00	120.00	91.98	-84.59	1.36
Cold Stream	**T_{in} (K)**	**T_{out} (K)**	**P_{in} (atm)**	**P_{out} (atm)**	**H_{in} (kW)**	**H_{out} (kW)**	**mc_p (kW/K)**
Main HX. Cold	194.04	295.15	34.34	34.34	-199.4	-63.97	1.34
Com.	295.15	424.58	34.34	120.00	-63.97	91.98	1.20

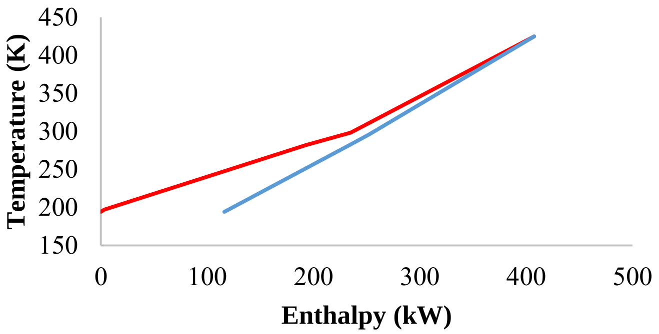

Figure C5 (a) Composite curves of modified cooling system with nitrogen gas.

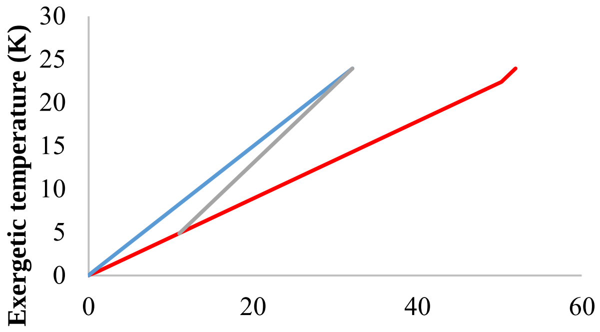

Figure C5 (b) Exergetic composite curves of below ambient for modified cooling system with nitrogen gas.

Table C4 Summary of energy usage and energy saving for analysis of LNG Productions

Case	W_c (kW)	W_e (kW)	Hot Utility (kW)	Cold Utility (kW)	Overall Saving (kW)
Simplified Cooling System	178.0	-115.4	0	115.5	0
Modified pressure of Cooling System	186.4	-123.0	0	179.6	-64.9
Modified Cooling System	155.9	-95.55	0	60.5	57.25

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Proceedings:

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