The comparison between CO_2/NH_3 and CO_2/R1234yf for optimal condensing temperature in cascade refrigeration systems

By

Norhazini bt. Awang

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

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Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

Prof Dr. Vijay R.Raghavan
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION OF ORIGINALITY

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

NORHAZINI BT AWANG

ABSTRACT

Nowadays industries use CO_2/NH_3 cascade refrigeration systems for deep cooling, down to – 50ºC. Even though it is compatible with the environment, it has an adverse impact on human beings. In this work, an alternative combination of refrigerants, namely CO_2/R123yf, is investigated for a cascade refrigeration system which has no adverse effects, either on health or environment. This study performs a thermodynamic analysis and compares two refrigerant pairs CO_2/NH_3 and CO_2/R1234yf, to determine the optimal condensing temperature of the cascade-condenser using various design parameters which are evaporating temperature, condensing temperature and intermediate temperature difference in order to maximize the COP. Theoretically, the optimal condensing temperature of the cascade-condenser increases with the condensing temperature, the evaporating temperature and the temperature difference. On the other hand, the maximum COP increases with the evaporating temperature but decreases as the condensing temperature or difference temperature increases. The comparison between CO_2/NH_3 and CO_2/R1234yf for thermodynamic analysis of optimal condensing temperature in cascade refrigeration system will give broad understanding of the safer refrigeration system.

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Nomenclature

COP	Coefficient of Performance
h	specific enthalpy (kJ/kg)
P	Pressure (MPa)
s	specific entropy (kJ/kg.K)
LTC	Low temperature circuit
HTC	High temperature circuit
T	Temperature (°C)

Subscripts

be	Bottom evaporator
CO_2	Carbon Dioxide
NH_3	Ammonia
mc	middle condenser
me	middle evaporator
max	maximum
htc	high temperature circuit
R1234yf	2,3,3,3-tetrafluoropropene/HFO-1234yf
tc	top condenser

CHAPTER 1
INTRODUCTION

1.1 Project Background

It is impractical to get maximum COP in low temperature applications by using single vapor compression refrigeration cycles with large temperature and pressure difference. The use of a single-cycle vapour compression refrigeration system can only achieve effective cooling of about -40^{0}C, and the efficiency begins to deteriorate under -35^{0}C due to the vast difference between the evaporating and condensing temperatures. Thus, in order to reach a lower temperature, a cascade refrigeration system is utilized [1]. Cascade refrigeration systems consist of at least two refrigeration systems that work independently. The two refrigeration systems is are connected by a cascade heat exchanger where heat is released in the condenser low-temperature circuit (LTC) and is absorbed from the evaporator high temperature circuit (HTC)[2].

The high and low temperature circuits in a cascade system are filled separately with appropriate refrigerants. On the other hand, the high and low pressure sides of a two stage refrigeration system are charged with the same refrigerant. With respect to global environment protection, the use of natural refrigerant in refrigeration systems has been demonstrated to be a complete solution for alternative fluorocarbon based refrigerant. Therefore, using environmental friendly refrigerants in both two stage and cascade refrigeration system helps to satisfy the obligations of environmental treaties [3].

The significant parameters in the design of cascade refrigeration system are evaporating temperature, condensing temperature and intermediate temperature difference. Nowadays, in a large capacity industrial cascade refrigeration system, CO_2/NH_3 or NH_3/NH_3 are commonly used. Since no other refrigerant had been used in cascade refrigeration system yet except for CO_2 and NH_3, the authors have chosen to compare CO_2/NH_3 and CO_2/R1234yf for optimal condensing temperature in such systems. R1234yf which is known as HFO contains hydrogen, fluorine and carbon like the HFCs, but they are distinctly different. They are olefins, which means they have very short atmospheric lifetimes of a few days, leading to distinct environmental benefits [4].

1.2 Problem Statement

Even though NH_3 is compatible with the environment and CO_2 / NH_3 combination in a cascade system performs better and at a lower cost, both initial and operating, than the conventional two-stage NH_3 system [5], it still has adverse impact on human beings, flora and fauna [6]. The immediate effect of NH_3 exposure arises from inhalation, skin or eye contact and ingestion [7]. Meanwhile the moisture or leakage of NH_3 in the equipment will cause equipment damage which will lead to high maintenance cost [8]. Furthermore, the evaporating temperature of an ammonia system is below -35^{0}C, causing air to leak into refrigeration system, leading to short term inefficiency and long term unreliability of the system. On the other hand, CO_2 needs to be maintained because it is already environmentally friendly and compatible for use at the lower temperature of the cascade refrigeration system [9].

1.3 Objectives

i. To determine the maximum COP of CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system.
ii. To compare the optimal condensing temperature of the cascade condenser between CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system.
iii. To monitor and record the effect of various design parameter towards COP in cascade refrigeration system

1.4 Scope of Study

This project is a study and research based which emphasizes the energy and environment sustainability issues as the top priority regardless the investment cost, the practicality of the system and the size of the plant's elements. Ammonia is widely used in the industry but it has an integrity problem with the plant equipment where by the moisture in the equipment will cause the short term equipment damage as well as high maintenance cost.

The significance of this study is for considering alternative refrigerants instead of presently used CO_2/NH_3 or NH_3/NH_3 in cascade refrigerant systems. The comparison of the optimal condensing temperature of both systems will give clear picture of their trend.

In order to do the comparison between CO_2/NH_3 and CO_2/R1234yf for optimal condensing temperature in cascade refrigeration systems, the author will use the various design parameters include the evaporating temperature, condensing temperature and temperature difference in the cascade condenser.

The comparison will base on thermodynamic analysis but the author will only deal with the ideal case without considering sub-cooling and superheating. This research expected to become a kick start for people to know that there is an alternative cascade refrigeration system besides CO_2/NH_3 cascade refrigeration system.

Apart from determining the maximum COP of CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system and comparing the optimal condensing temperature of the cascade condenser between CO_2/NH_3 and CO_2/R1234yf combinations, this study also reports the effect of various design parameters towards COP in a cascade refrigeration system.

CHAPTER 2
LITERATURE REVIEW

2.1 The Significance of Cascade Refrigeration System

In low-temperature applications, including rapid freezing and the storage of frozen food, the required evaporating temperature of the refrigeration system ranges from -40^{0}C to -55^{0}C, so a single-stage vapor-compression refrigeration system is insufficient. Instead, two-stage or cascade refrigeration systems are used for low-temperature applications. The high- and low-pressure sides of a two-stage refrigeration system are charged with the same refrigerant, whereas the high and low-temperature circuits in a cascade system are filled separately with appropriate refrigerants [3].

In the design phase of a CO_2/NH_3 cascade refrigeration system, an important issue is the means of determining the optimal condensing temperature of a cascade-condenser under particular design conditions, such as condensing temperature, evaporating temperature and the temperature difference between the high and low circuits in cascade condenser. Studies that seek to find the optimal condensing temperature of the CO_2/NH_3 cascade refrigeration system are lacking. Lee et al. found that the optimal condensing temperature of a cascade-condenser is -18^{0}C at a condensing temperature of 35^{0}C and an evaporating temperature of -50^{0}C. However, they reported only one specific condition and did not evaluate the effects of varying the design conditions, such as the condensing and evaporating temperatures, on the optimal condensing temperature of the cascade-condenser and its corresponding maximum COP [3].

2.1.1 Mitigation of Risk of New Refrigerant

Since 1987 refrigerants are experiencing new constraints due to global environment. The protection of stratospheric ozone under the Montreal Protocol has led to the phase down and then the phase-out of chlorinated substances such as CFC-12 and HCFC-22 which were the two most used refrigerants. All along those years, changes have been made, a number of new refrigerant blends have been proposed, tested, commercialized, and used in millions of equipment, but still a new revolution is under way in order to use low GWP and zero ODP refrigerants. Certain possible options are known: hydrocarbons (HC-290, HC-1270, HC-600a), ammonia (R-717), CO2 (R-744); all those refrigerants have deserved a lot of attention, applications have been found adapted to those fluids, but still none is seen as capable to replace HCFC-22 in all its current applications [10].

2.1.2 R1234yf Become the Alternative Refrigerant

Refrigerant HFC R134a is soon to be replaced in automotive applications. The phase-out of R134a is to begin in 2011 in Europe with a total ban due by 2017. In the US, the 2017 target date is desired, but the Automotive Industry is pushing for accelerated progress, as environmental concerns over climate change escalate. The leading MAC (Mobile Air Conditioning) replacement candidate is HFO R1234yf. It is behaviorally very similar to R134a, which allows component manufacturers as well as automotive designers the luxury of not having to make drastic changes to current products.

In fact, data suggests the possibility that R1234yf could be used as a direct replacement, with only minimal efficiency loss when used in existing R134a systems, allowing for swift global adoption. Studies of the effects of mixing R1234yf with R134a show only minor pressure increases resulting from their blending. R1234yf also has the potential to be used in direct expansion systems which are more efficient and smaller than secondary loop systems. This will help meet Coefficient of Performance requirements for overall A/C system efficiency [11].

R1234yf has the following positive characteristics:

- Global Warming Potential of 4 in 100 years versus 1410 of R134a (the EU's new limit is 150).
- Ozone Depletion scores of 0.
- Lowest LCCP of other known alternatives.
- Flammability listed as "mild" or "manageable" compared to the higher flammability of R152-a.
- Much lower operating pressure versus CO2 (R744) [11].

2.1.3 The Characteristic Comparison between R134a and R1234yf

The cooling characteristic of R1234yf is similar to R134a such as boiling point of R134a is -26^{0}C and boiling point for R1234yf is -29^{0}C [12].

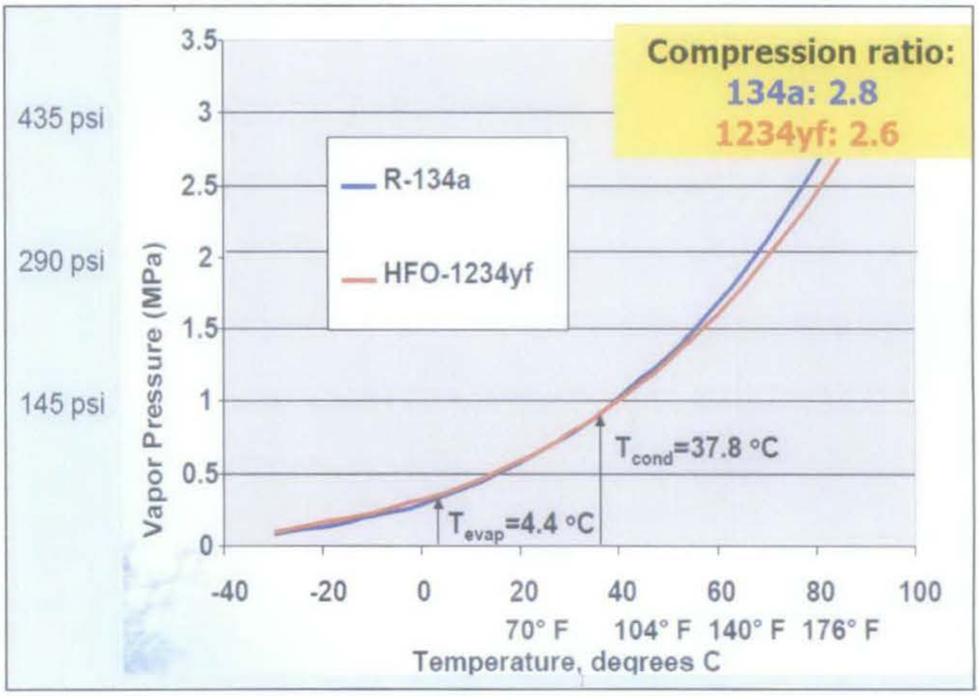


Figure 2.1: Cooling characteristic comparison between R1234yf and R134a.[12]

2.1.4 R1234yf Will Have No Adverse Impact To The Ecosystem.

Atmospheric oxidation of HFO-1234yf gives $CF_3C(O)OH$(TFA) in 100% molar yield. Trifluoroacetic acid is a ubiquitous natural component of the hydrosphere. Trifluoroacetic acid is biodegradable and does not bioaccumulate in animals or lower aquatic life forms. For emission of <50 kt HFO 1234yf per year uniform mixing, and 4.9E17L annual global precipitation, the global average TFA concentration in precipitation will be <100 ng/L.

Majority of emissions will be in N.Hemisphere, so lie in range 3-2400 ng.L. HFO 1234yf degradation is not expected to have significant impact on environmental loadings of TFA. Tang et a. (1998) conclude "no significant risk is anticipated from TFA produced by atmospheric degradation of the present and future production of the HFCs and HCFCs as there is 1000-folf difference between the PNEC(Predicted No Effect Concentration) and the PEC(Predicted Environmental Concentration)".

Benesch et al. (2002) studied impact of 10-10000 ug/L TFA on vernal pool and wetland plant species, no effect was observed, conclusion was "predicted TFA concentrations will not adversely affect the development of sol 50000 times higher than N.Hemispheric average estimate above for HFO-1234yf degradation.

WMO(2007) conclude "..trifluoroacetic acid from the degradation of HCFCs and HFCs will not result in environment concentrations capable of significant ecosystem damage". Hurley et a.(2008) conclude that "the products of the atmospheric oxidation of HFO-1234yf have negligible environmental impact", Trifluoroacetic acid formation from HFO-1234yf will not impact ecosystems [13].

2.1.5 R1234yf Development

EU Mac Directive 40/2006, refrigerant with GWP >150 will be phased out progressively between 2011 and 2017. US GHG Regulation EPA-420-F-09-047a implemented 1-Apr-10 OEM tailpipe CO2 and CAFE mpg credits available for adopting advanced technologies including LGWP refrigerants [14].

Figure 2.2: The phase out of refrigerant with GWP > 150[14]

2.1.6 The Environmental Performance

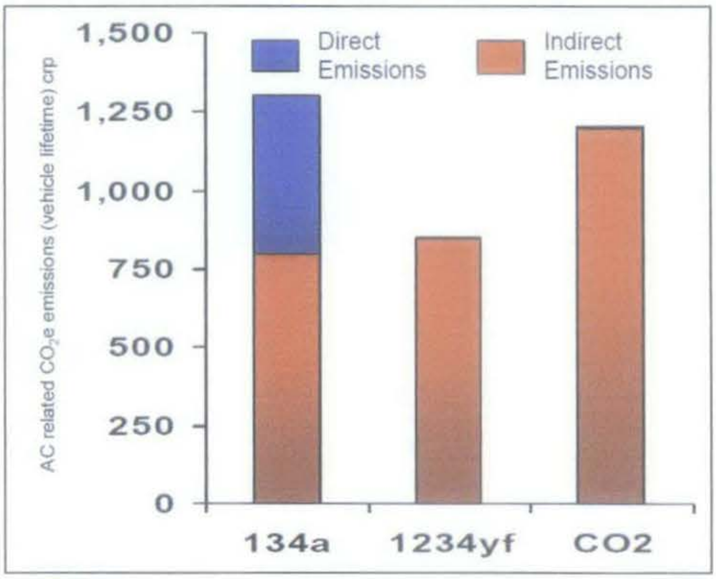


Figure 2.3: Environmental performance[14]

Table 2.1: Physical and Flammability properties of flammable refrigerants[14].

Refrigerant	Molar mass (g/mol)	LFL (% v/v)	UFL (% v/v)	RCL (kg/m^3)	RF number (kJ/mole)	BV (cm/s)	MIE (mJ)	HOC (MJ/kg)
R-290	44.1	2.5	10	0.009	56.7	46	0.25	46.3
R-717	17.0	15	18	0.00035	6.82	7.2	100	18.6
R-32	52.0	14.4	29.3	0.0614	4.6	6.7	30	9.4
R-152a	66.0	4.65	16.9	0.025	16.6	23	0.38	17.4
R-1234yf	114	6.2	12.3	0.058	3.6	1.5	5000	10.7

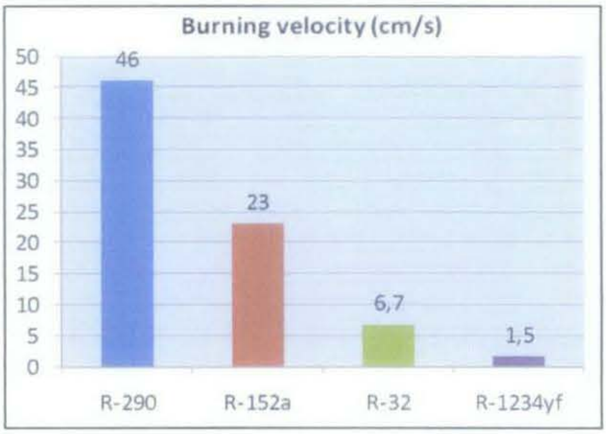


Figure 2.4: Classification of flammable refrigerants as a function of the inverse of minimum ignition energy (MIE)[14].

Table 2.2: Comparison of Flammability numbers [14].

Refrigerant	R(dimension less)	F (dimensionless)	RF(kJ/mole)	RF2 (kJ/mole)(m/s)
R-290	1.99	0.55	56.7	37.2
R-152a	1.78	0.5	16.6	17.9
R-32	1.31	0.33	4.6	2.3
R-1234yf	0.97	0.27	3.6	0.6

The key evolution during those last 20 years is related to the revisit of essential physical properties, such as burning velocity and Minimum Ignition Energy, in order to provide measured values to substantiate risk assessment of new refrigerants capable to fulfill environmental criteria, energy efficiency, and safety[10].

Please refer Appendix A for major Milestones in the Development of HFO-1234yf [15].

2.2 Theoretical Background

2.2.1 Working Principle

Figure 2.5 schematically represents a CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system, respectively. Figure 2.6 represents the corresponding temperature-entropy and pressure-enthalpy diagrams. This refrigeration system includes two separate refrigeration circuits, the high temperature circuit (HTC) and the low temperature circuit (LTC). Ammonia and R1234yf are the refrigerants in HTC, respectively in two different cascade refrigeration systems with both systems having carbon dioxide as the refrigerant in LTC.

The circuits are thermally connected to each other through the cascade-condenser, which acts as evaporator for the HTC and a condenser for the LTC. Figure 2.6 shows that the condensing and evaporating pressures in the NH_3 and R1234yf respectively are both lower than those in the CO_2 circuit. Therefore, the NH_3 and R1234yf respectively are called the high temperature circuit (HTC) rather than the high-pressure circuit, and the CO_2 circuit is called the low temperature circuit (LTC) rather than the low-pressure circuit.

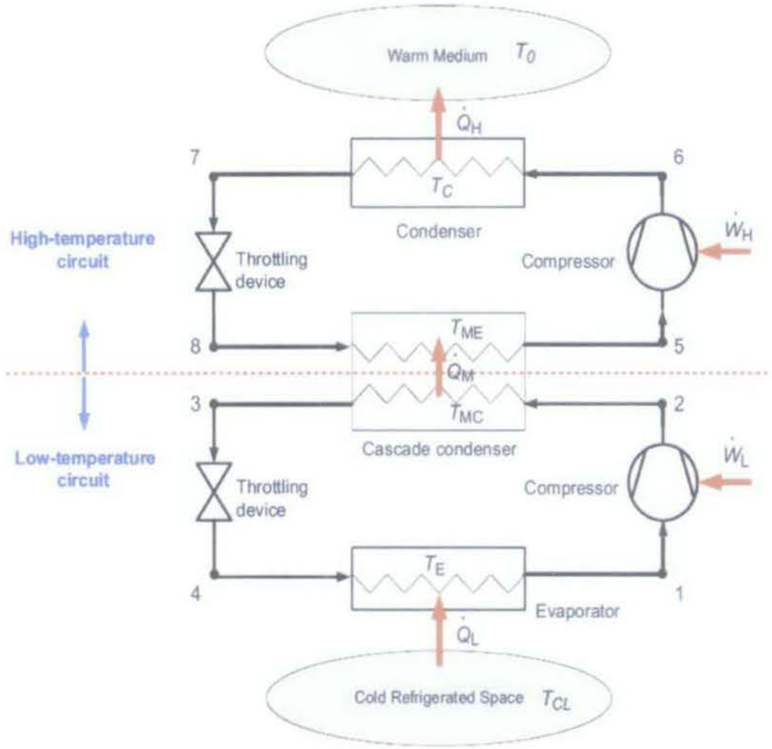
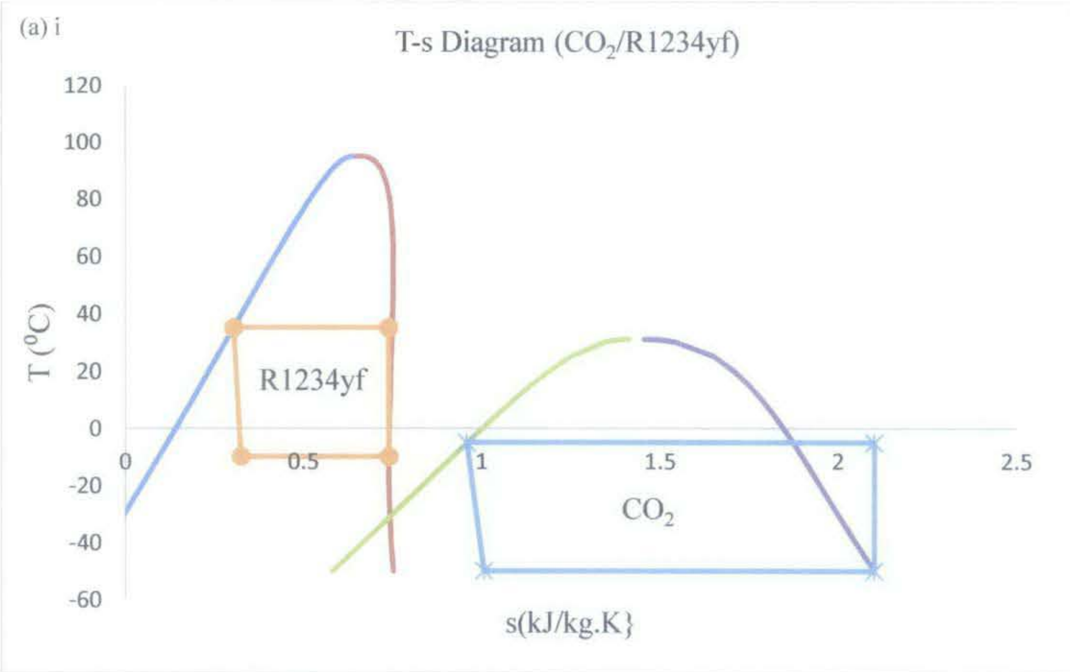
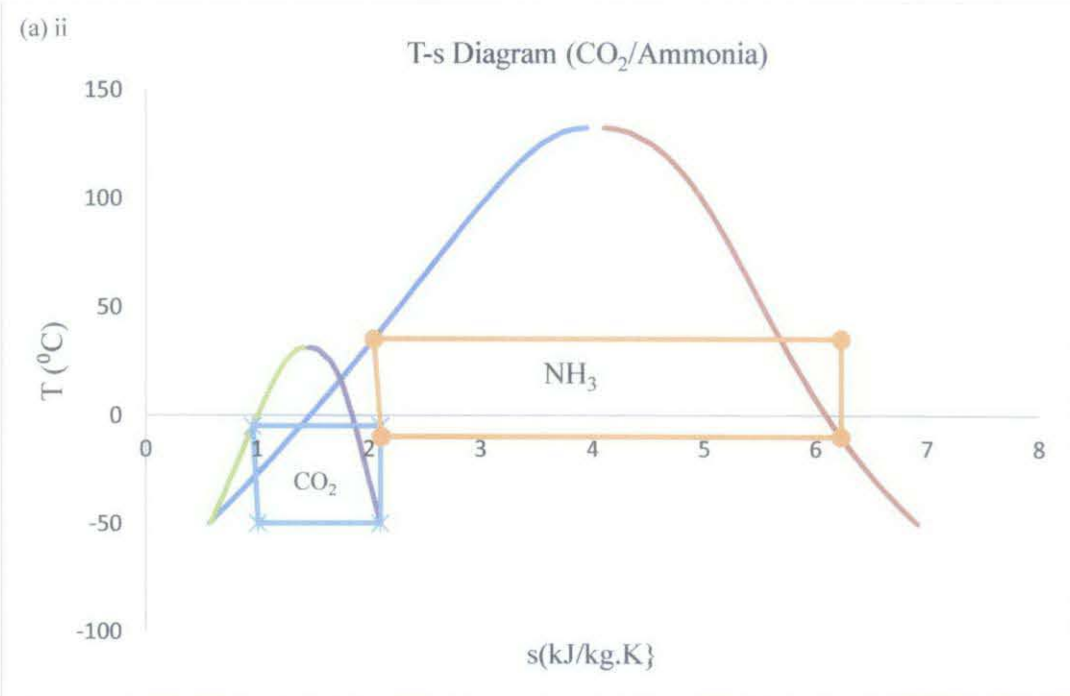


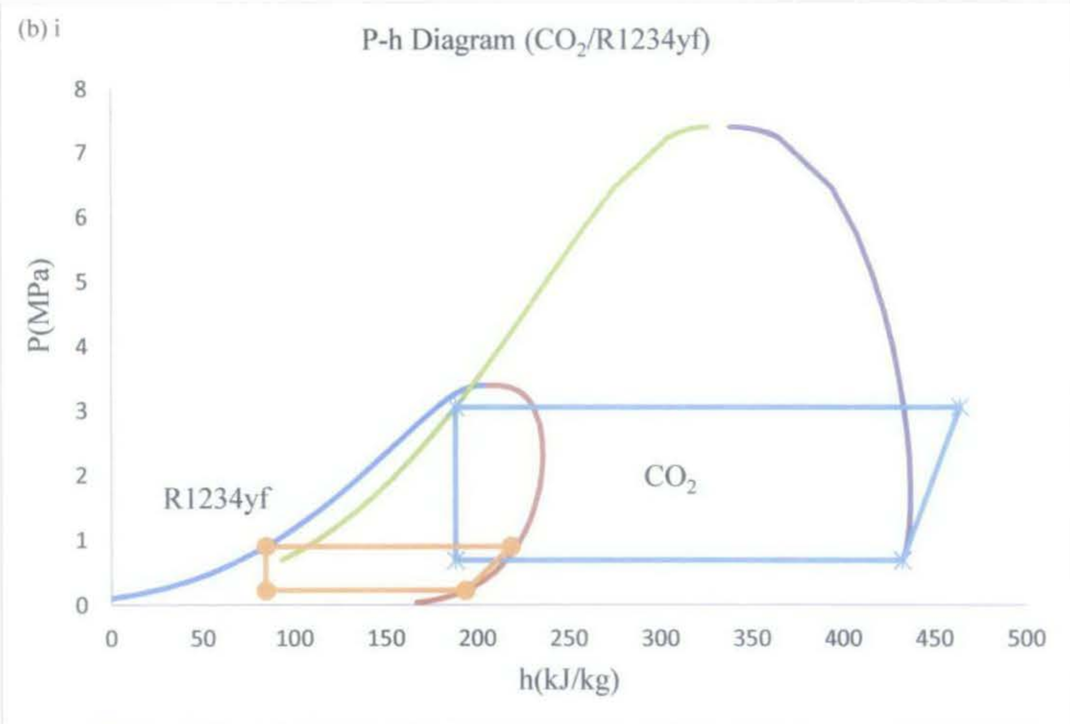
Figure 2.5: Schematic diagram of cascade refrigeration system. [3]

Fig. 2.1 shows that the condenser in this cascade refrigeration system rejects heat of $\dot{Q}_H$ at a condensing temperature T_c, to its warm coolant or environment at temperature T_0. The evaporator of this cascade system absorbs a refrigerated load $\dot{Q}_L$ from the refrigerated space at T_{CL} to the evaporating temperature T_E. The heat absorbed by the evaporator of the LTC plus the work input to the LTC compressor equals the heat absorbed by the evaporator of the HTC.

T_{MC} and T_{ME} represent the condensing and evaporating temperatures of the cascade condenser. The evaporating temperature T_E, the condensing temperature T_C, and the temperature difference in the cascade-condenser are three important design parameters of a CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system. The main components of the test CO_2/NH_3 cascade refrigeration system are compressor, evaporator condenser, expansion valve and cascade condenser [3].


(a) i
T-s Diagram (CO2/R1234yf)
120
100
80
60
40
20
0
-20
-40
-60
T (0C)
0
0.5
1
1.5
2
2.5
R1234yf
CO2
s(kJ/kg.K}


(a) ii
T-s Diagram (CO2/Ammonia)
150
100
50
0
-50
-100
T (0C)
0
1
2
3
4
5
6
7
8
NH3
CO2
s(kJ/kg.K}



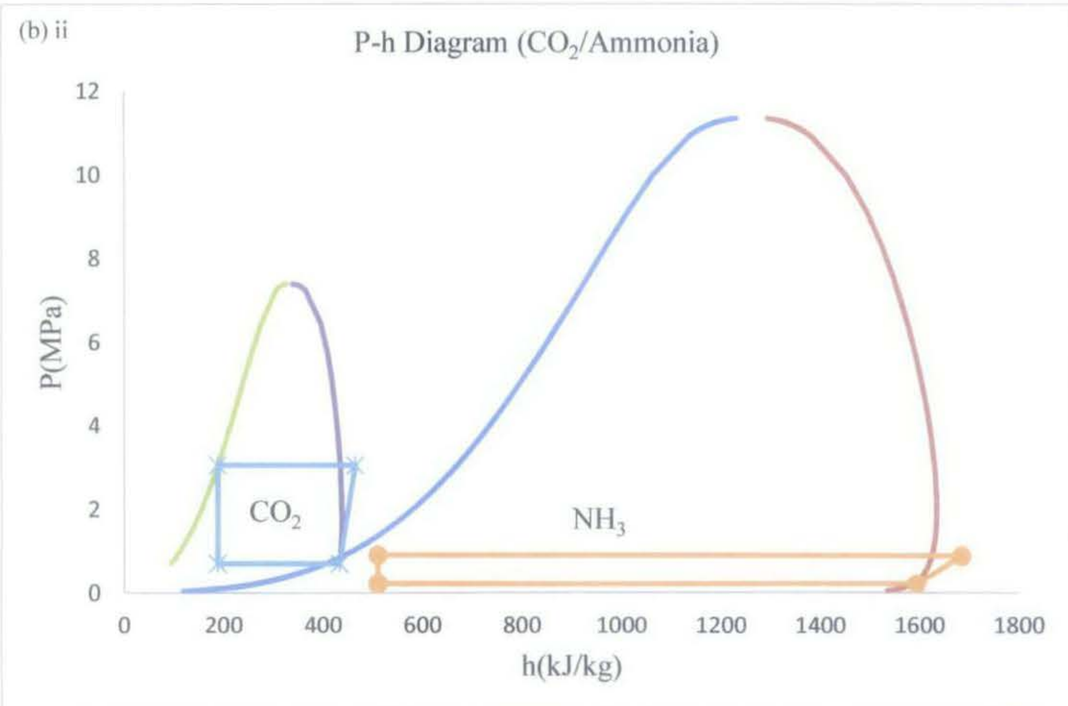


Figure 2.6: (a) i,ii The temperature-entropy and (b)i,ii Pressure-enthalpy diagram of CO_2/R1234yf and CO_2/NH_3 cascade refrigeration system

2.2.2 Thermodynamic Analysis of a Cascade Refrigeration System

In order to compare the optimal condensing temperature between CO_2/NH_3 and CO_2/R1234yf in cascade refrigeration systems, a parametric study must be conducted using various design parameters used for both cascade refrigeration systems that include condensing temperature, evaporating temperature and temperature difference. The top condensing temperatures used in the parametric study are 35^0C, 45^0C and 55^0C. The bottom evaporating temperatures are -40^0C, -45^0C and -50^0C. The temperature differences in the cascade condenser are 2^0C, 3^0C, 4^0C and 5^0C. Each component in the cascade refrigeration system, shown in Figure 2.1, can be treated as a control volume. In order to simplify the thermodynamic analysis, the following assumption had been made.

1. No superheating and sub-cooling in the cascade refrigeration system.
2. All components are assumed to be at steady state and steady flow process. Negligible changes in kinetic and potential energy.
3. Negligible pressure and heat losses/gains in the pipe networks or system components.
4. Isenthalpic expansion across expansion valves.
5. The outlet states of the condenser and the cascade condenser are at saturated liquid states and that of the evaporator is at saturated vapor state.
6. The dead state temperature of the cascade refrigeration system is at ambient temperature, 25^0C and atmospheric pressure, 101.3 kPa.[3]

CHAPTER 3

METHODOLODY

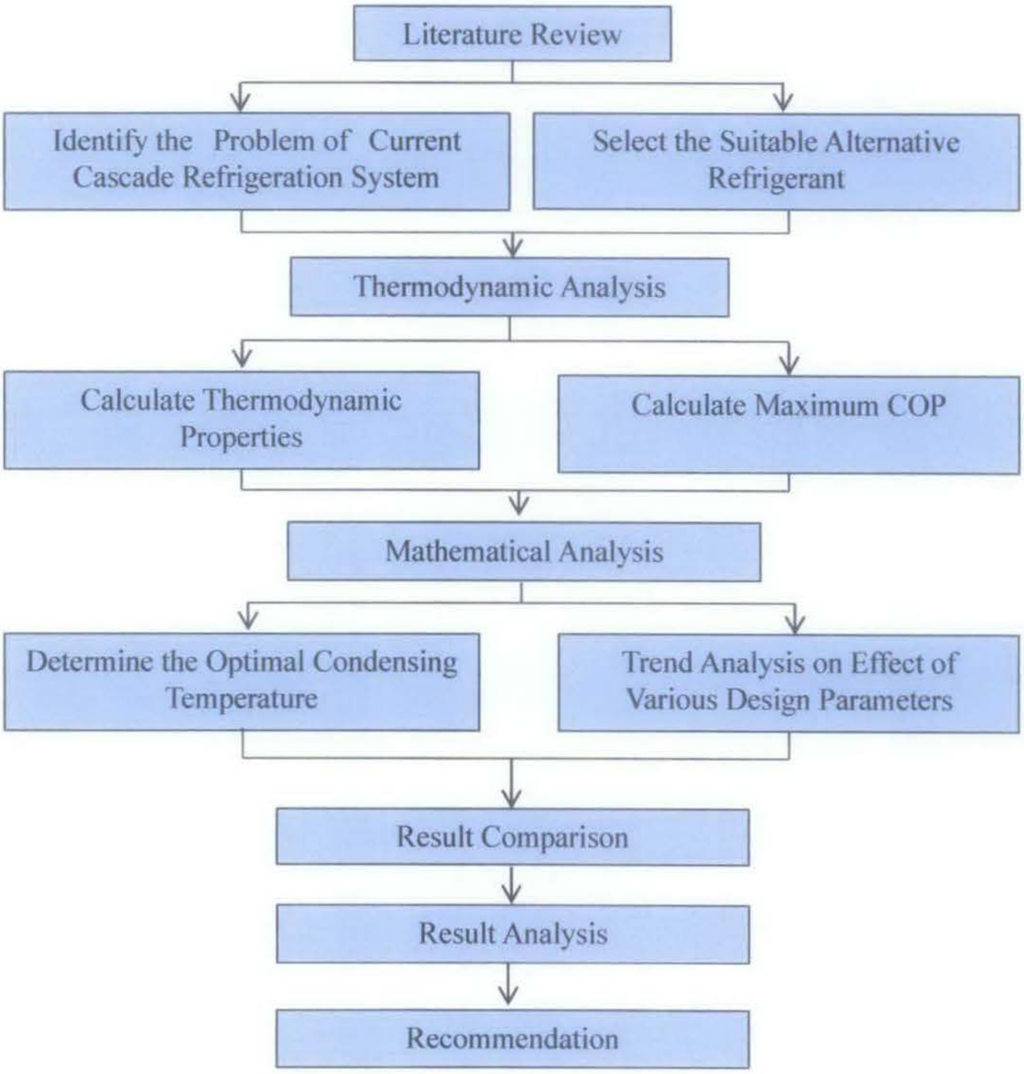


Figure 3.1: The methodology of the project

3.1 Project Work

This project is a research and study base project. Since in the current industry, they use carbon dioxide and ammonia as the refrigerants in the cascade refrigeration system, so the author starts the project with problem analysis of the current cascade refrigeration system. After identify the constraint of the current refrigerants used in the cascade refrigeration system which is the current refrigerants used will give adverse impact to the ecosystem, the author decide to use R1234yf as an alternative refrigerant which will not give impact on the ecosystem base on fundamental studies from references and journal.

The author will proceed with thermodynamic analysis once literature review completed. The thermodynamic analysis will include the analysis of the related thermodynamic cycle, as well as calculate the thermodynamic properties in order to determine the maximum COP of CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system. Then, the author will proceed with mathematical analysis, the author will varies the various design parameters which are evaporating temperature, condensing temperature and intermediate temperature difference in order to determine the optimal condensing temperature of the cascade condenser between CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system. Besides, the trend monitoring and recording will be done in order to see the effect of the various design parameters to the COP.

Lastly, the author will do the comparison between CO_2/NH_3 and CO_2/R1234yf for optimal condensing temperature in cascade refrigeration systems by means as a kick start for people to consider the R1234yf as the replacement for ammonia. Besides, the author will explain the constraints as well as recommendation of this work in order to ensure the continuity between this work and the work in the future. All the project work will documented in the final report.

3.2 Research Methodology

Research is a method taken in order to gain information regarding the major scope of the project. The sources of the research cover the handbook of air conditioning and refrigeration, e-journal, e-thesis and several trusted link.

3.2.1 The Steps of Research:

1. Do the research on current cascade refrigeration system used in the industries.
2. Gain the information of environmental friendly refrigerants.
3. Choose the most suitable refrigerant which is better than ammonia.
4. Study on working principle of cascade refrigeration system
5. Do the thermodynamic analysis of the cascade refrigeration system.
6. Calculate the thermodynamic properties.
7. Determine the maximum COP of CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system.
8. Do the mathematical analysis of cascade refrigeration system.
9. Determine the optimal condensing temperature of the cascade condenser between CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system.
10. Record the trend on effect of various design parameters to COP
11. Report on comparison between CO_2/NH_3 and CO_2/R1234yf for optimal condensing temperature in cascade refrigeration systems.
12. State the restrictions.
13. Do the recommendations.

3.3 Software Required

1. Microsoft Excel
2. Software REFPROP7
3. Software SPSS Statistics 17.0

CHAPTER 4
RESULT AND DISCUSSION

4.1 The Maximum COP Comparison

Table 4.1shows the comparison between CO_2/NH_3 and CO_2/R1234yf for maximum COP. For both CO_2/NH_3 and CO_2/R1234yf, the maximum COP increases with T_{be} but decrease with increasing ΔT provided T_{tc} is fixed. The lower the ΔT, the higher the maximum COP whereas maximum COP increase linearly with T_{be}. Significant difference exists between CO_2/NH_3 and CO_2/R1234yf for maximum COP.

With the same T_{tc}, T_{be} and ΔT condition, maximum COP for CO_2/R1234yf is higher than CO_2/NH_3. Figure 4.1 clearly shows the relationship between the various parameters as well as maximum COP comparison. Maximum COP is determined by variation in T_{mc} and ΔT but fixed T_{tc} and T_{be}, since it is more significant to get the maximum COP for each ΔT first before evaluating the relationship between maximum COP with other design parameters which are ΔT, T_{be} and T_{tc}.

Based on thermodynamic properties, for CO_2/NH_3 the maximum COP decreases as T_{mc} decreases but for CO_2/R1234yf, the maximum COP increases as T_{mc} decreases. Even though the thermodynamic properties are different, at the same condition of ΔT, T_{be} and T_{tc}, the maximum COP for CO_2/R1234yf still is higher than maximum COP for CO_2/NH_3.

Table 4.1: COP_{max} comparison between CO_2/NH_3 and CO_2/R1234yf

Design Parameters			COP_{max}	
T_{tc} (^{0}C)	T_{be} (^{0}C)	ΔT	CO_2/NH_3	CO_2/R1234yf
35	-40	2	2.44	6.40
		3	2.39	6.32
		4	2.33	6.22
		5	2.27	6.12
	-45	2	2.32	5.94
		3	2.27	5.87
		4	2.22	5.78
		5	2.17	5.70
	-50	2	2.20	5.52
		3	2.16	5.47
		4	2.11	5.39
		5	2.06	5.31

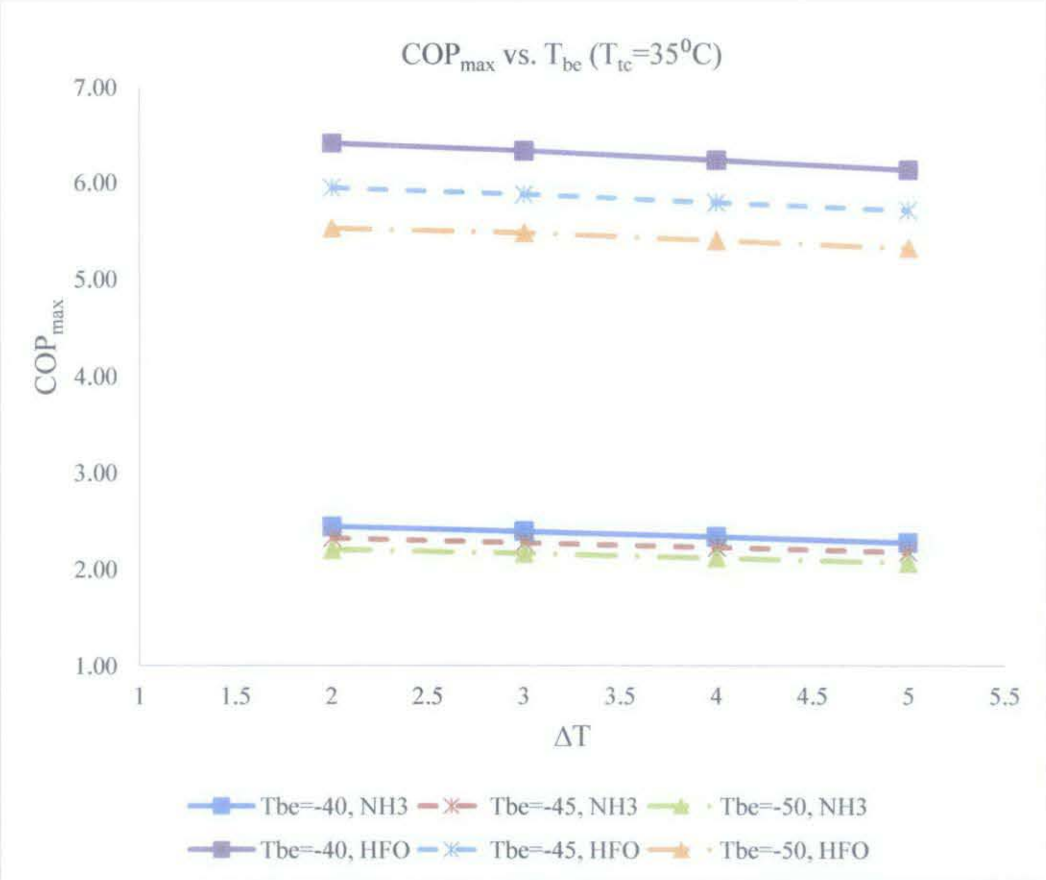


Figure 4.1: COP_{max} vs. T_{be} for CO_2/NH_3 and CO_2/R1234yf

4.2 The Optimal Intermediate Condensing Temperature Comparison

Based on the mathematical analysis, the optimal condensing temperatures for CO_2/R1234yf is lower than CO_2/NH_3. Actually, the various design parameters will affect the optimal condensing temperature for both CO_2/R1234yf and CO_2/NH_3 but there is a limitation of temperature range covered in this study. It is concluded that the optimal condensing temperature does not occur in the range studied, though it might occur in cycles that cool to -80°C or lower for biological systems.

Theoretically, the optimal condensing temperature of the cascade-condenser rises with increase in condensing temperature, evaporating temperature and temperature difference.

4.3 Effect of T_{tc}, T_{be} and ΔT On COP_{max}

Using SPSS software, by considering all the design parameters, a linear regression yields the following correlation.

The goodness of fit (R^2) is 0.991 and the maximum COP of CO_2/R1234yf cascade refrigeration system:

$$COP_{max} = 10.8 - 0.041T_{tc} + 0.073T_{be} - 0.075\,\Delta T$$

The goodness of fit (R^2) is 0.985 and the maximum COP of CO_2/NH_3 cascade refrigeration system:

$$COP_{max} = 4.272 - 0.033\,T_{tc} + 0.017\,T_{be} - 0.037\,\Delta T$$

Table 4.2 Comparison between CO_2/NH_3 and CO_2/R1234yf for effect of T_{tc}, T_{be} and ΔT on COP_{max}

Condition	CO_2/NH_3	CO_2/R1234yf
COP_{max} vs. ΔT Fixed parameters: T_{be} and T_{tc}	COP_{max} inversely proportional with ΔT	COP_{max} inversely proportional with ΔT
COP_{max} vs. T_{tc} Fixed parameters: T_{be}	COP_{max} inversely proportional with T_{tc}	COP_{max} inversely proportional with T_{tc}
COP_{max} vs. T_{be} Fixed parameters: T_{tc}	COP_{max} directly proportional with T_{be}	COP_{max} directly proportional with T_{be}
COP_{max} vs. T_{mc} Fixed parameters: T_{be} and T_{tc}	COP_{max} directly proportional with T_{mc}	COP_{max} inversely proportional with T_{mc}

4.3.1 Condition 1

COP_{max} Vs. ΔT, fixed T_{be} and T_{tc}

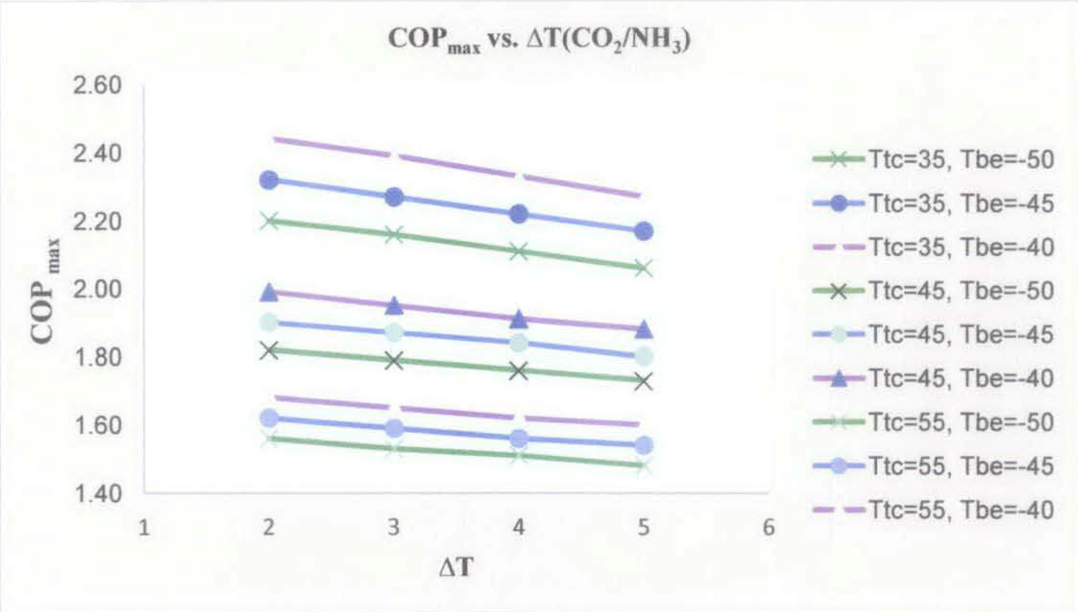


Figure 4.2: COP_{max} vs. ΔT for CO_2/NH_3

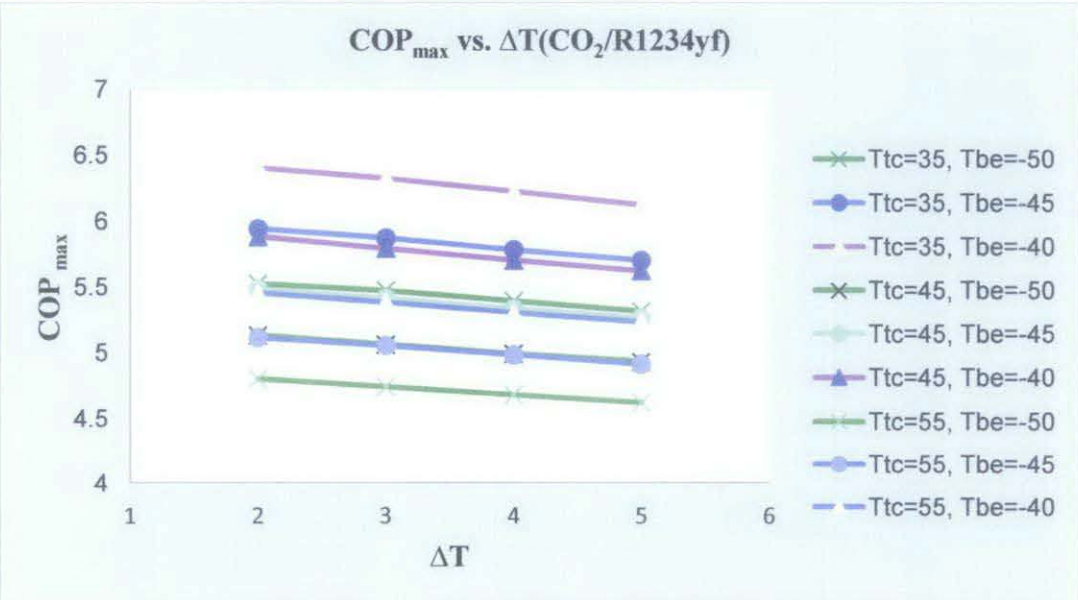


Figure 4.3: COP_{max} vs. ΔT for CO_2/R1234yf

4.3.2 Condition 2

COP_{max} vs. T_{tc}, fixed T_{be}

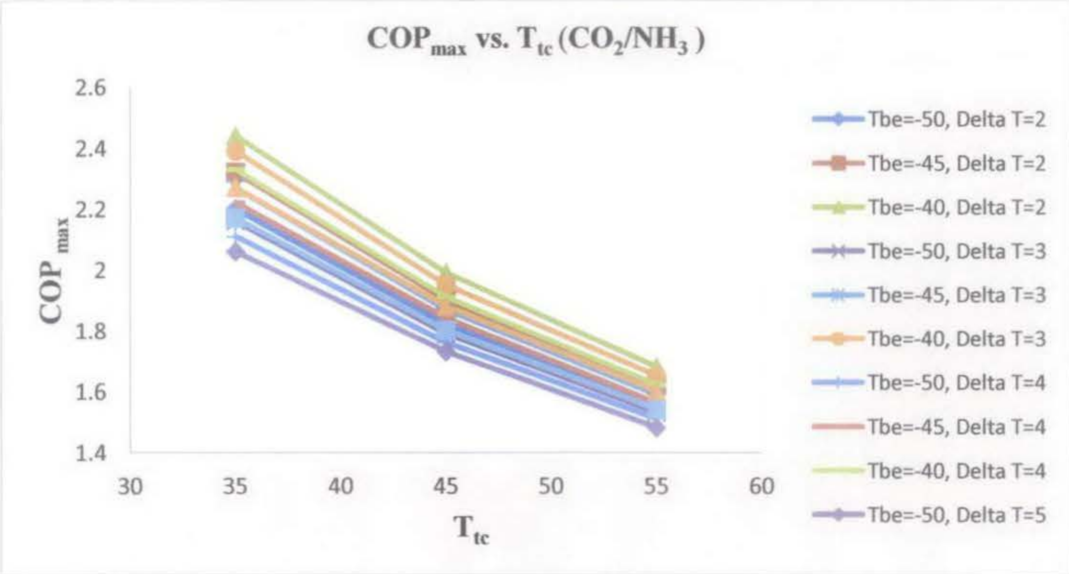


Figure 4.4: COP_{max} vs. T_{tc} for CO_2/NH_3

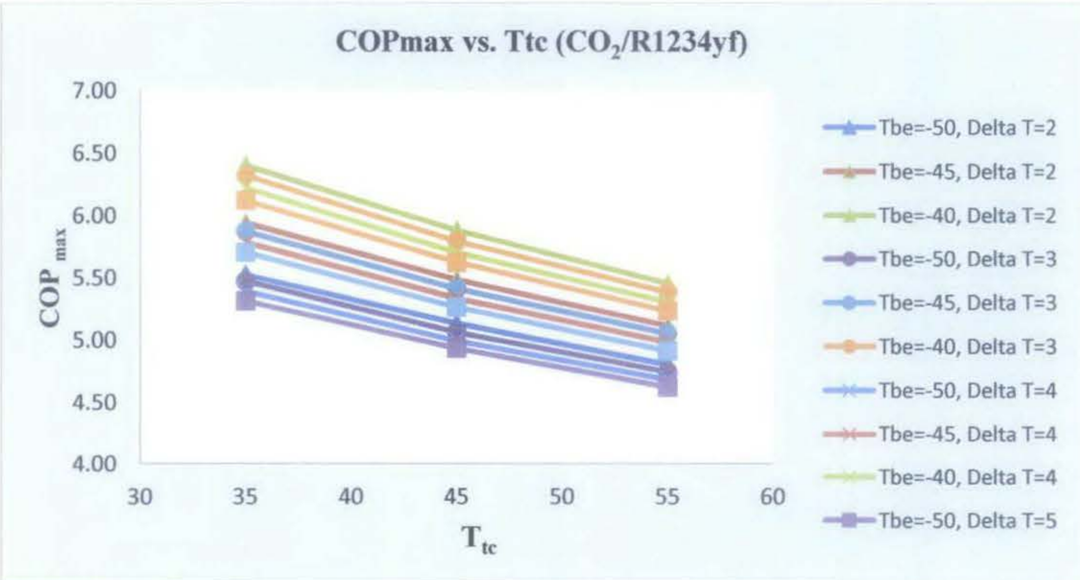


Figure 4.5: COP_{max} vs. T_{be} for CO_2/R1234yf

4.3.3 Condition 3

COP_{max} vs. T_{be} fixed T_{tc}

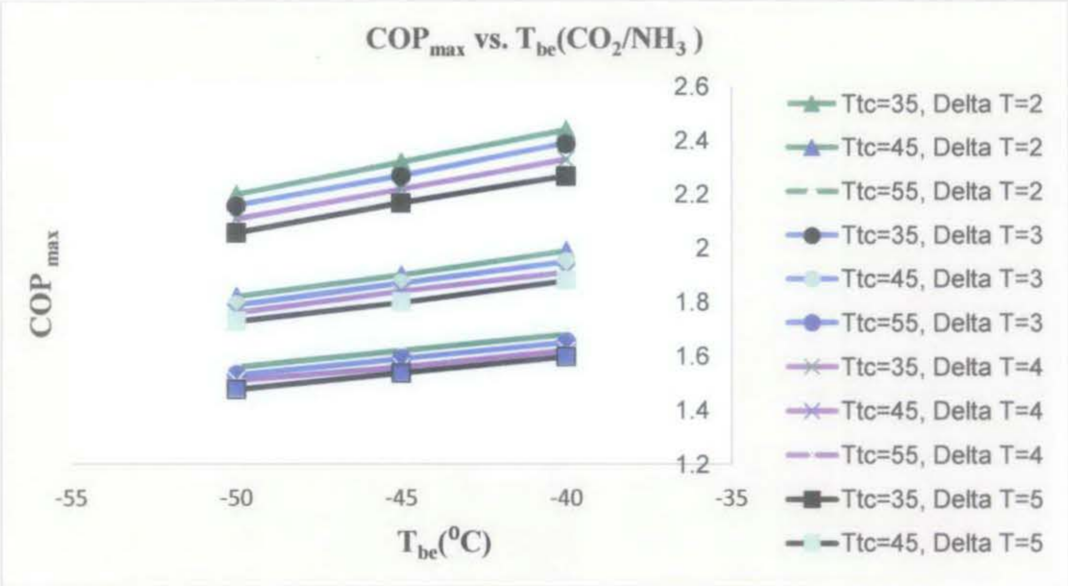


Figure 4.6: COP_{max} vs. T_{be} for CO_2/NH_3

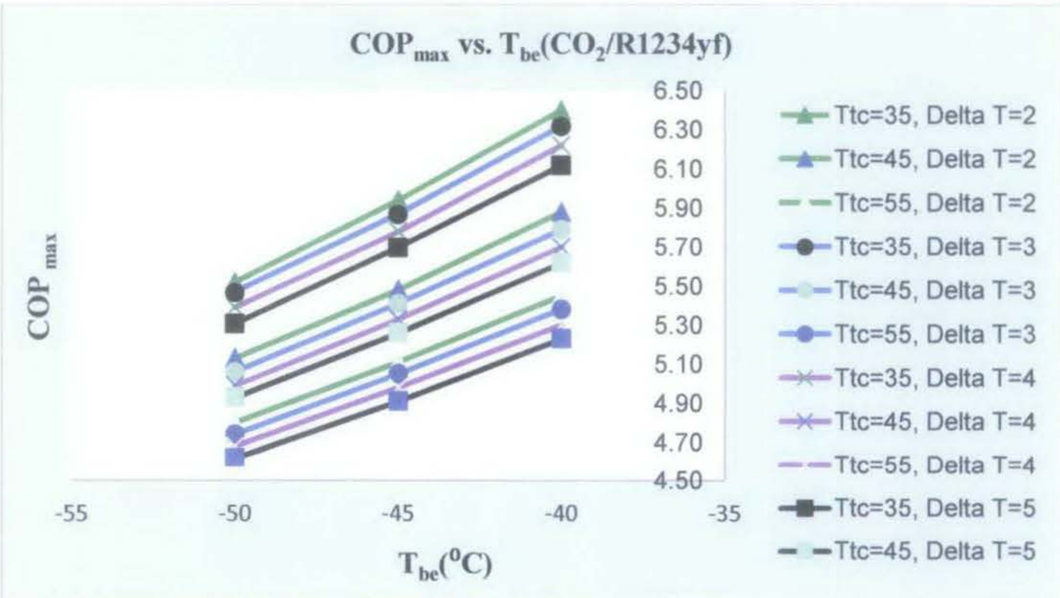


Figure 4.7: COP_{max} vs. T_{be} for CO_2/R1234yf

4.3.4 Condition 4

COP vs. T_{mc} fixed T_{be} and T_{tc}

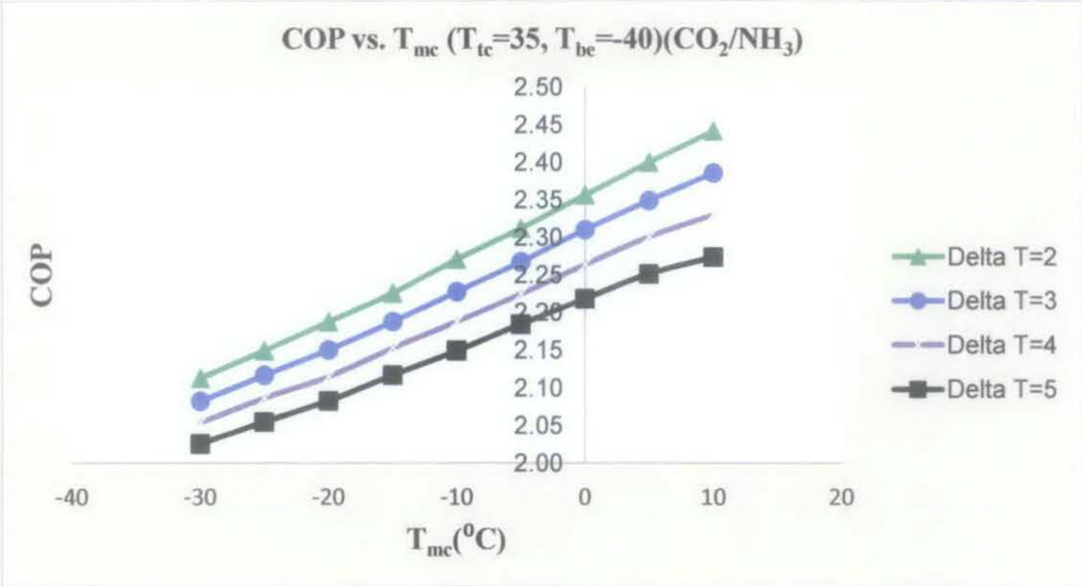


Figure 4.8: COP vs. T_{mc} for CO_2/NH_3

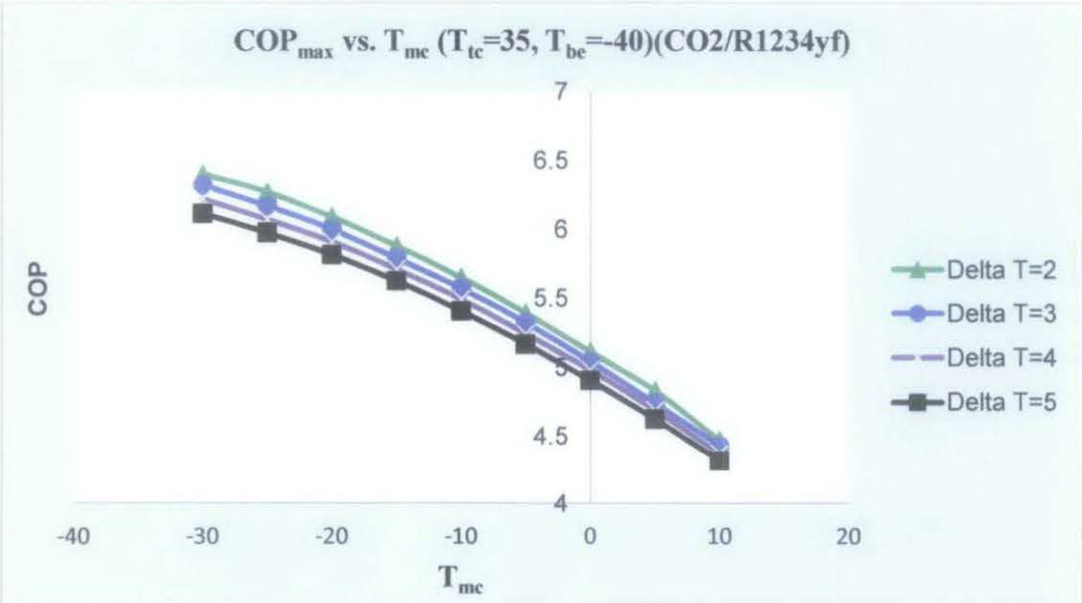


Figure 4.9: COP vs. T_{mc} for CO_2/R1234yf

4.4 Restrictions

1. The maximum COP will increase as T_{be} is increases. Lower T_{be} will lead to longer cooling time but the COP will decrease. High T_{be} will result high COP and it causes shorter cooling time. Thus, T_{be} greatly depends on the demand of the company's operation.

2. The optimal condensing temperature also depends on plant efficiency and system performance but these were not included in the scope of this study. This is basically a fundamental study of thermodynamic analysis to compare CO_2/NH_3 and CO_2/R1234yf in order to serve as an impetus for designers to consider the other alternative refrigerants to replace ammonia.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Recommendations

1. Use the correlation to determine the optimal condensing temperature of a cascade condenser and the corresponding maximum COP based on three design parameters which are T_{be}, T_{tc} and ΔT.

2. Use other alternative refrigerants in the thermodynamic analysis in order to find the most suitable refrigerant which is compatible with the ecosystem and equipment as well as high COP at optimal condensing temperature.

3. Consider the superheating and sub-cooling in the cascade refrigeration system for thermodynamic and mathematical analysis.

5.2 Conclusion

The fundamental study of thermodynamic analysis deals with three design parameters which are top condensing temperature Tt_c, bottom evaporating temperature T_{be} and temperature difference ΔT in order to compare the physical thermodynamic properties of CO_2/R1234yf and CO_2/NH_3. Based on the thermodynamic and mathematical analysis, the conclusions of both CO_2/R1234yf and CO_2/NH_3 cascade refrigeration systems are as follows.

1. The optimal condensing temperature of the cascade depends on T_{tc}, T_{be} and ΔT. The optimal condensing temperature for CO_2/R1234yf lower than CO_2/NH_3.
2. For both CO_2/R1234yf and CO_2/NH_3, the maximum COP increases with T_{be} but decreases as T_{tc} or ΔT decreases.
3. For CO_2/NH_3, COP increases with T_{mc}, but for CO_2/R1234yf, COP decreases with T_{mc}.

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APPENDIX A

Gantt chart and Key Milestone for FYP 1

No	Detail/Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14	15
1	Selection of Project Topic																
2	Literature Review																
3	Project work																
	3.1 Study on the current cascade refrigeration system																
	3.2 Find the weakness of the current refrigerants used																
	3.3 Analyze the related thermodynamic cycle																
	3.4 Obtaining the thermodynamic properties																
4	Results / Analysis																
	4.1 Choose the alternative refrigerant to replace ammonia																
	4.2 Comparison of the available refrigerants																
5	Reporting																
	5.1 Preliminary Report																
	5.2 Progress Report																
	5.3 Seminar																
	5.4 Interim Report																
6	Oral Presentation																

APPENDIX B

Gantt chart and Key Milestone for FYP 2

No	Detail/Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14	15
1	Literature Review																
2	Project work																
	2.1 Determine the maximum COP of CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system																
	2.2 Determine the optimal condensing temperature of the cascade condenser between CO_2/NH_3 and CO2/R1234yf cascade refrigeration system																
	2.3 Plot the graph of various design parameters vs. COP																
3	Results / Analysis																
	3.1 Comparison between CO_2/NH_3 and CO2/R1234yf for optimal condensing temperature in cascade refrigeration systems																
	3.2 Record the trend on effect of various design parameters to COP																
4	Reporting																
	4.1 Preliminary Report																
	4.2 Progress Report																
	4.3 Seminar																
	4.4 Interim Report																
5	Oral Presentation																

APPENDIX C

Major Milestones in the Development of HFO-1234yf from the Kyoto-Protokoll to the MAC-directive – the development of HFO-1234yf is tied closely to the history of climate protection:

Date	Milestones
16 September 1987	The signatory states of the UN sign the "Montreal Protocol". It aims to prevent emissions that harm the earth's ozone layer.
1 January 1989	The "Montreal Protocol" comes into effect.
11 December 1997	The signatory states of the UN adopt the "Kyoto-Protocol". The industrial nations commit themselves to reduce emissions of greenhouse gases until 2012 by 5.2 percent below 1990's level.
8 March 2000	The EU-Commission's European Climate Change Program intensifies the efforts to implement the "Kyoto-Protocol". Working groups discuss options, motor vehicle air conditioning comes into focus.
10 October 2000	The EU Environment Council requests from the EU-Commission to consider measures to reduce emissions of F-Gases (fluorinated greenhouse gases) in motor vehicle air conditioning.
2003	The European Commission approves HFC-152a, R744 and other refrigerants as possible new refrigerants for motor vehicle air conditioning.
16 February 2006	Honeywell presents new, climate-friendly refrigerants.
17 May 2006	The EU-directive on air conditioning systems in motor vehicles (2006/40/EG, "MAC-directive") imposes strict requirements on refrigerants applied. Only refrigerants with a Global Warming Potential (GWP) of less than 150 will be approved for use in mobile systems.
4 July 2006	The EU F-Gas regulation (EU regulation no. 842/2006) and the MAC-directive of the European Parliament and Council on emissions of F-Gases in motor vehicle air conditioning and on

	amending directive 70/156/EWG come into effect.
14 February 2007	Honeywell and DuPont introduce new refrigerants with low GWP at the annual "Alternative Refrigerant Winter Meeting" of the German Association of the Automotive Industry (VDA).
13 February 2008	Honeywell and DuPont present the new and market-ready HFO-1234yf at the annual VDA "Alternative Refrigerant Winter Meeting".
1 December 2008	The registration process of HFO-1234yf for REACH begins. REACH, the new EU chemicals regulation, requires that chemical substances on their own and in preparations have to be registered to the European Chemicals Agency (ECHA).
8 December 2008	Honeywell's low-global-warming-potential refrigerant HFO-1234yf is endorsed by the renowned SAE's (International Society of Automobile Engineers) International Cooperative Research Program for use in vehicles: "HFO-1234yf offers greatest potential to meet environmental and consumer needs"
1 January 2009	After intensive testing of R744, SAE's International Cooperative Research Program prioritizes HFO-1234yf over R744 as refrigerant for practical use in vehicles.
28 May 2009	The German Association of the Automotive Industry (VDA) demands a global standard for refrigerants.
4 August 2009	HFO-1234yf is intensively tested by the Japanese Ministries of Health, Labour and Welfare, Economy, Trade and Industry and of the Environment and approved for practical use.
13 October 2009	The US-Environmental Protection Agency (EPA) accepts HFO-1234yf in its SNAP-program for use as low GWP-refrigerant in motor vehicle air conditioning.
5 January 2010	The European Patent Office grants Honeywell the patent for the new low-GWP refrigerant HFO-1234yf for motor vehicle air conditioning.

20 May 2010	Honeywell and Dupont announce a Joint Venture to manufacture the new low-GWP refrigerant HFO-1234yf.
23 July 2010	GM chooses to use HFO-1234yf in cars of its U.S. brands Cadillac, Chevrolet, Buick and GMC from 2013 on.
28 February 2011	EPA approves HFO-1234yf for use in motor vehicle air conditioning. EPA's SNAP report criticizes the tests conducted by the German Bundesanstalt für Materialforschung und -prüfung BAM (Federal Institute for Materials Research and Testing) for not fully revealing the test set-up. Thus, tests cannot really be judged scientifically, EPA notes.

APPENDIX D

Thermodynamics Properties of Carbon Dioxide (CO_2)

Temperature (°C)	Pressure (MPa)	Liquid density (kg/m³)	Vapour density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg.K)	Vapor Entropy (kJ/kg.K)
-50	0.6823	1154.60	17.925	92.94	432.68	0.5794	2.1018
-45	0.8318	1135.80	21.717	102.87	434.13	0.6228	2.0747
-40	1.0045	1116.40	26.121	112.90	435.32	0.6656	2.0485
-35	1.2024	1096.40	31.216	123.05	436.23	0.7079	2.0230
-30	1.4278	1075.70	37.098	133.34	436.82	0.7498	1.9980
-25	1.6827	1054.20	43.880	143.79	437.06	0.7914	1.9732
-20	1.9696	1031.70	51.700	154.45	436.89	0.8328	1.9485
-15	2.2908	1008.00	60.728	165.34	436.27	0.8742	1.9237
-10	2.6487	982.93	71.185	176.52	435.14	0.9157	1.8985
-5	3.0459	956.21	83.359	188.05	433.38	0.9576	1.8725
0	3.4851	927.43	97.647	200.00	430.89	1.0000	1.8453
5	3.9695	896.03	114.620	212.50	427.48	1.0434	1.8163
10	4.5022	861.12	135.160	225.73	422.88	1.0884	1.7847
15	5.0871	821.21	160.730	239.99	416.64	1.1359	1.7489
20	5.7291	773.39	194.200	255.87	407.87	1.1877	1.7062
25	6.4342	710.50	242.730	274.78	394.43	1.2485	1.6498
30	7.2137	593.31	345.100	304.55	365.13	1.3435	1.5433
30.01	7.2153	592.85	345.530	304.66	365.01	1.3438	1.5429
30.02	7.2170	592.39	345.960	304.76	364.88	1.3441	1.5424
30.03	7.2186	591.93	346.400	304.87	364.76	1.3445	1.5420
30.04	7.2203	591.46	346.840	304.97	364.63	1.3448	1.5416
30.05	7.2219	590.99	347.280	305.08	364.51	1.3452	1.5412
30.06	7.2236	590.52	347.720	305.19	364.38	1.3455	1.5407
30.07	7.2252	590.04	348.170	305.30	364.25	1.3458	1.5403
30.08	7.2269	589.56	348.620	305.41	364.12	1.3462	1.5398
30.09	7.2285	589.08	349.070	305.52	363.99	1.3465	1.5394
30.1	7.2302	588.59	349.530	305.63	363.86	1.3469	1.5390
30.11	7.2318	588.10	349.990	305.74	363.73	1.3473	1.5385
30.12	7.2335	587.61	350.460	305.85	363.6	1.3476	1.5380
30.13	7.2352	587.11	350.930	305.96	363.47	1.3480	1.5376
30.14	7.2368	586.61	351.400	306.07	363.33	1.3483	1.5371
30.15	7.2385	586.10	351.870	306.19	363.2	1.3487	1.5367
30.16	7.2401	585.59	352.350	306.30	363.06	1.3491	1.5362
30.17	7.2418	585.08	352.840	306.42	362.92	1.3494	1.5357

30.18	7.2434	584.57	353.320	306.53	362.78	1.3498	1.5353
30.19	7.2451	584.04	353.820	306.65	362.64	1.3502	1.5348
30.2	7.2467	583.52	354.310	306.77	362.5	1.3506	1.5343
30.21	7.2484	582.99	354.810	306.89	362.36	1.3510	1.5338
30.22	7.2501	582.46	355.320	307.01	362.22	1.3513	1.5333
30.23	7.2517	581.92	355.830	307.13	362.07	1.3517	1.5328
30.24	7.2534	581.38	356.340	307.25	361.92	1.3521	1.5323
30.25	7.2550	580.83	356.860	307.37	361.78	1.3525	1.5318
30.26	7.2567	580.28	357.380	307.49	361.63	1.3529	1.5313
30.27	7.2584	579.72	357.910	307.62	361.48	1.3533	1.5308
30.28	7.2600	579.16	358.440	307.74	361.33	1.3537	1.5303
30.29	7.2617	578.60	358.980	307.87	361.17	1.3541	1.5298
30.3	7.2633	578.02	359.520	308.00	361.02	1.3545	1.5293
30.31	7.2650	577.45	360.070	308.13	360.86	1.3549	1.5287
30.32	7.2667	576.87	360.630	308.26	360.71	1.3554	1.5282
30.33	7.2683	576.28	361.190	308.39	360.55	1.3558	1.5277
30.34	7.2700	575.69	361.750	308.52	360.39	1.3562	1.5271
30.35	7.2717	575.09	362.320	308.65	360.23	1.3566	1.5266
30.36	7.2733	574.48	362.900	308.78	360.06	1.3571	1.5260
30.37	7.2750	573.87	363.480	308.92	359.9	1.3575	1.5255
30.38	7.2766	573.25	364.070	309.06	359.73	1.3579	1.5249
30.39	7.2783	572.63	364.670	309.19	359.56	1.3584	1.5243
30.4	7.2800	572.00	365.270	309.33	359.39	1.3588	1.5237
30.41	7.2816	571.36	365.880	309.47	359.22	1.3593	1.5232
30.42	7.2833	570.72	366.500	309.62	359.04	1.3598	1.5226
30.43	7.2850	570.07	367.130	309.76	358.87	1.3602	1.5220
30.44	7.2867	569.41	367.760	309.90	358.69	1.3607	1.5214
30.45	7.2883	568.74	368.400	310.05	358.51	1.3612	1.5208
30.46	7.2900	568.07	369.050	310.20	358.32	1.3616	1.5201
30.47	7.2917	567.39	369.700	310.35	358.14	1.3621	1.5195
30.48	7.2933	566.70	370.370	310.50	357.95	1.3626	1.5189
30.49	7.2950	566.00	371.040	310.65	357.76	1.3631	1.5182
30.5	7.2967	565.29	371.730	310.81	357.57	1.3636	1.5176
30.51	7.2983	564.58	372.420	310.97	357.37	1.3641	1.5169
30.52	7.3000	563.85	373.120	311.12	357.17	1.3646	1.5163
30.53	7.3017	563.11	373.830	311.28	356.97	1.3651	1.5156
30.54	7.3034	562.37	374.560	311.45	356.77	1.3657	1.5149
30.55	7.3050	561.61	375.290	311.61	356.56	1.3662	1.5142
30.56	7.3067	560.84	376.030	311.78	356.35	1.3667	1.5135
30.57	7.3084	560.07	376.790	311.95	356.14	1.3673	1.5128
30.58	7.3101	559.28	377.560	312.12	355.93	1.3678	1.5121

30.59	7.3117	558.47	378.340	312.30	355.71	1.3684	1.5113
30.6	7.3134	557.66	379.140	312.47	355.48	1.3690	1.5106
30.61	7.3151	556.83	379.950	312.65	355.26	1.3696	1.5098
30.62	7.3168	555.99	380.770	312.84	355.03	1.3702	1.5090
30.63	7.3184	555.13	381.610	313.02	354.79	1.3708	1.5083
30.64	7.3201	554.26	382.460	313.21	354.55	1.3714	1.5075
30.65	7.3218	553.37	383.330	313.40	354.31	1.3720	1.5066
30.66	7.3235	552.47	384.220	313.60	354.06	1.3726	1.5058
30.67	7.3252	551.55	385.130	313.80	353.81	1.3733	1.5050
30.68	7.3268	550.61	386.060	314.00	353.55	1.3739	1.5041
30.69	7.3285	549.65	387.000	314.21	353.29	1.3746	1.5032
30.7	7.3302	548.67	387.970	314.42	353.02	1.3753	1.5023
30.71	7.3319	547.67	388.960	314.63	352.74	1.3760	1.5014
30.72	7.3336	546.65	389.980	314.86	352.46	1.3767	1.5005
30.73	7.3353	545.60	391.020	315.08	352.17	1.3774	1.4995
30.74	7.3369	544.53	392.090	315.31	351.88	1.3782	1.4985
30.75	7.3386	543.42	393.180	315.55	351.57	1.3790	1.4975
30.76	7.3403	542.29	394.310	315.79	351.26	1.3797	1.4965
30.77	7.3420	541.13	395.480	316.04	350.94	1.3806	1.4954
30.78	7.3437	539.94	396.680	316.30	350.61	1.3814	1.4943
30.79	7.3454	538.70	397.920	316.56	350.27	1.3823	1.4931
30.8	7.3471	537.43	399.200	316.84	349.91	1.3831	1.4920
30.81	7.3488	536.11	400.530	317.12	349.55	1.3841	1.4908
30.82	7.3505	534.75	401.910	317.41	349.17	1.3850	1.4895
30.83	7.3521	533.33	403.350	317.72	348.78	1.3860	1.4882
30.84	7.3538	531.85	404.850	318.03	348.37	1.3870	1.4868
30.85	7.3555	530.30	406.420	318.36	347.94	1.3881	1.4854
30.86	7.3572	528.68	408.080	318.71	347.49	1.3892	1.4839
30.87	7.3589	526.97	409.830	319.08	347.02	1.3904	1.4823
30.88	7.3606	525.17	411.680	319.46	346.51	1.3917	1.4807
30.89	7.3623	523.24	413.660	319.88	345.98	1.3931	1.4789
30.9	7.3640	521.18	415.790	320.32	345.41	1.3945	1.4770
30.91	7.3657	518.94	418.110	320.80	344.79	1.3961	1.4750
30.92	7.3674	516.48	420.650	321.33	344.11	1.3978	1.4727
30.93	7.3691	513.74	423.500	321.92	343.35	1.3997	1.4702
30.94	7.3708	510.60	426.760	322.60	342.49	1.4019	1.4674
30.95	7.3725	506.86	430.640	323.41	341.48	1.4046	1.4640
30.96	7.3742	502.09	435.570	324.44	340.2	1.4080	1.4598
30.97	7.3759	494.91	442.890	326.02	338.32	1.4132	1.4536

APPENDIX E

Thermodynamics Properties of Ammonia (NH_3)

Temperature (°C)	Pressure (MPa)	Liquid density (kg/m³)	Vapour density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg.K)	Vapor Entropy (kJ/kg.K)
-50	0.0408	702.09	0.381	118.43	1534.3	0.5661	6.9112
-45	0.0545	696.17	0.498	140.31	1542.7	0.6630	6.8100
-40	0.0717	690.15	0.644	162.32	1550.9	0.7583	6.7141
-35	0.0931	684.04	0.822	184.48	1558.8	0.8522	6.6232
-30	0.1194	677.83	1.037	206.76	1566.5	0.9446	6.5367
-25	0.1515	671.53	1.296	229.17	1573.8	1.0357	6.4543
-20	0.1901	665.14	1.603	251.71	1580.8	1.1253	6.3757
-15	0.2362	658.65	1.966	274.37	1587.5	1.2137	6.3005
-10	0.2907	652.06	2.391	297.16	1593.9	1.3009	6.2285
-5	0.3548	645.37	2.885	320.09	1599.8	1.3868	6.1592
0	0.4294	638.57	3.457	343.15	1605.4	1.4716	6.0926
5	0.5158	631.66	4.115	366.36	1610.5	1.5553	6.0284
10	0.6151	624.64	4.868	389.72	1615.3	1.6380	5.9662
15	0.7285	617.49	5.727	413.24	1619.5	1.7197	5.9060
20	0.8575	610.20	6.703	436.94	1623.3	1.8005	5.8475
25	1.0032	602.76	7.807	460.82	1626.6	1.8804	5.7904
30	1.1672	595.17	9.053	484.91	1629.3	1.9597	5.7347
35	1.3508	587.40	10.457	509.23	1631.5	2.0382	5.6801
40	1.5554	579.44	12.034	533.79	1633.1	2.1161	5.6265
45	1.7827	571.27	13.803	558.63	1634.0	2.1936	5.5736
50	2.0340	562.86	15.785	583.77	1634.2	2.2706	5.5213
55	2.3111	554.20	18.006	609.26	1633.7	2.3473	5.4693
60	2.6156	545.24	20.493	635.12	1632.4	2.4239	5.4174
65	2.9491	535.96	23.280	661.42	1630.2	2.5004	5.3655
70	3.3135	526.31	26.407	688.20	1627.1	2.5770	5.3131
75	3.7105	516.23	29.923	715.53	1622.9	2.6539	5.2601
80	4.1420	505.67	33.888	743.50	1617.5	2.7312	5.2060
85	4.6100	494.54	38.376	772.20	1610.7	2.8093	5.1504
90	5.1167	482.75	43.484	801.76	1602.3	2.8884	5.0929
95	5.6643	470.17	49.340	832.34	1592.2	2.9689	5.0327
100	6.2553	456.63	56.117	864.16	1579.8	3.0513	4.9691
105	6.8923	441.90	64.063	897.51	1564.7	3.1363	4.9007
110	7.5783	425.61	73.550	932.84	1546.2	3.2249	4.8258

115	8.3170	407.18	85.182	970.89	1523.1	3.3190	4.7418
120	9.1125	385.49	100.070	1013.10	1493.4	3.4218	4.6435
125	9.9702	357.80	120.730	1062.80	1452.3	3.5417	4.5199
130	10.8980	312.29	156.770	1135.20	1382.5	3.7153	4.3287
130.01	10.9000	312.15	156.880	1135.40	1382.3	3.7158	4.3282
130.02	10.9020	312.01	156.990	1135.60	1382.0	3.7163	4.3276
130.03	10.9030	311.87	157.100	1135.80	1381.8	3.7168	4.3270
130.04	10.9050	311.72	157.220	1136.00	1381.6	3.7173	4.3265
130.05	10.9070	311.58	157.330	1136.20	1381.4	3.7179	4.3259
130.06	10.9090	311.43	157.440	1136.40	1381.2	3.7184	4.3254
130.07	10.9110	311.29	157.560	1136.70	1381.0	3.7189	4.3248
130.08	10.9130	311.14	157.670	1136.90	1380.8	3.7194	4.3242
130.09	10.9150	311.00	157.790	1137.10	1380.5	3.7199	4.3237
130.1	10.9170	310.85	157.900	1137.30	1380.3	3.7204	4.3231
130.11	10.9190	310.70	158.020	1137.50	1380.1	3.7210	4.3225
130.12	10.9210	310.56	158.140	1137.70	1379.9	3.7215	4.3219
130.13	10.9230	310.41	158.250	1138.00	1379.7	3.7220	4.3214
130.14	10.9250	310.26	158.370	1138.20	1379.4	3.7225	4.3208
130.15	10.9270	310.11	158.490	1138.40	1379.2	3.7231	4.3202
130.16	10.9290	309.96	158.600	1138.60	1379.0	3.7236	4.3196
130.17	10.9310	309.81	158.720	1138.80	1378.8	3.7241	4.3190
130.18	10.9320	309.66	158.840	1139.10	1378.6	3.7247	4.3185
130.19	10.9340	309.51	158.960	1139.30	1378.3	3.7252	4.3179
130.2	10.9360	309.36	159.080	1139.50	1378.1	3.7257	4.3173
130.21	10.9380	309.21	159.200	1139.70	1377.9	3.7263	4.3167
130.22	10.9400	309.05	159.320	1139.90	1377.7	3.7268	4.3161
130.23	10.9420	308.90	159.440	1140.20	1377.4	3.7274	4.3155
130.24	10.9440	308.75	159.560	1140.40	1377.2	3.7279	4.3149
130.25	10.9460	308.59	159.680	1140.60	1377.0	3.7284	4.3143
130.26	10.9480	308.44	159.800	1140.90	1376.7	3.7290	4.3137
130.27	10.9500	308.28	159.920	1141.10	1376.5	3.7295	4.3131
130.28	10.9520	308.13	160.040	1141.30	1376.3	3.7301	4.3125
130.29	10.9540	307.97	160.170	1141.50	1376.1	3.7306	4.3119
130.3	10.9560	307.82	160.290	1141.80	1375.8	3.7312	4.3113
130.31	10.9580	307.66	160.410	1142.00	1375.6	3.7317	4.3107
130.32	10.9600	307.50	160.540	1142.20	1375.4	3.7323	4.3101
130.33	10.9620	307.34	160.660	1142.50	1375.1	3.7329	4.3095
130.34	10.9640	307.18	160.780	1142.70	1374.9	3.7334	4.3089
130.35	10.9650	307.02	160.910	1142.90	1374.7	3.7340	4.3083
130.36	10.9670	306.86	161.040	1143.20	1374.4	3.7346	4.3077

130.37	10.9690	306.70	161.160	1143.40	1374.2	3.7351	4.3071
130.38	10.9710	306.54	161.290	1143.60	1374.0	3.7357	4.3065
130.39	10.9730	306.38	161.410	1143.90	1373.7	3.7363	4.3058
130.4	10.9750	306.22	161.540	1144.10	1373.5	3.7368	4.3052
130.41	10.9770	306.05	161.670	1144.30	1373.2	3.7374	4.3046
130.42	10.9790	305.89	161.800	1144.60	1373.0	3.7380	4.3040
130.43	10.9810	305.72	161.930	1144.80	1372.8	3.7386	4.3033
130.44	10.9830	305.56	162.050	1145.10	1372.5	3.7391	4.3027
130.45	10.9850	305.39	162.180	1145.30	1372.3	3.7397	4.3021
130.46	10.9870	305.23	162.310	1145.50	1372.0	3.7403	4.3015
130.47	10.9890	305.06	162.440	1145.80	1371.8	3.7409	4.3008
130.48	10.9910	304.89	162.570	1146.00	1371.5	3.7415	4.3002
130.49	10.9930	304.72	162.710	1146.30	1371.3	3.7421	4.2995
130.5	10.9950	304.55	162.840	1146.50	1371.0	3.7427	4.2989
130.51	10.9970	304.38	162.970	1146.80	1370.8	3.7433	4.2983
130.52	10.9990	304.21	163.100	1147.00	1370.6	3.7439	4.2976
130.53	11.0000	304.04	163.240	1147.30	1370.3	3.7445	4.2970
130.54	11.0020	303.87	163.370	1147.50	1370.1	3.7451	4.2963
130.55	11.0040	303.70	163.500	1147.80	1369.8	3.7457	4.2957
130.56	11.0060	303.53	163.640	1148.00	1369.6	3.7463	4.2950
130.57	11.0080	303.35	163.770	1148.30	1369.3	3.7469	4.2944
130.58	11.0100	303.18	163.910	1148.50	1369.0	3.7475	4.2937
130.59	11.0120	303.00	164.040	1148.80	1368.8	3.7481	4.2930
130.6	11.0140	302.83	164.180	1149.00	1368.5	3.7487	4.2924
130.61	11.0160	302.65	164.320	1149.30	1368.3	3.7493	4.2917
130.62	11.0180	302.47	164.460	1149.50	1368.0	3.7500	4.2911
130.63	11.0200	302.29	164.600	1149.80	1367.8	3.7506	4.2904
130.64	11.0220	302.11	164.730	1150.10	1367.5	3.7512	4.2897
130.65	11.0240	301.93	164.870	1150.30	1367.2	3.7518	4.2890
130.66	11.0260	301.75	165.010	1150.60	1367.0	3.7525	4.2884
130.67	11.0280	301.57	165.150	1150.80	1366.7	3.7531	4.2877
130.68	11.0300	301.39	165.290	1151.10	1366.5	3.7537	4.2870
130.69	11.0320	301.21	165.440	1151.40	1366.2	3.7544	4.2863
130.7	11.0340	301.02	165.580	1151.60	1365.9	3.7550	4.2856
130.71	11.0360	300.84	165.720	1151.90	1365.7	3.7557	4.2849
130.72	11.0380	300.65	165.870	1152.20	1365.4	3.7563	4.2843
130.73	11.0390	300.46	166.010	1152.40	1365.1	3.7570	4.2836
130.74	11.0410	300.28	166.150	1152.70	1364.9	3.7576	4.2829
130.75	11.0430	300.09	166.300	1153.00	1364.6	3.7583	4.2822
130.76	11.0450	299.90	166.440	1153.30	1364.3	3.7589	4.2815

130.77	11.0470	299.71	166.590	1153.50	1364.0	3.7596	4.2808
130.78	11.0490	299.52	166.740	1153.80	1363.8	3.7603	4.2801
130.79	11.0510	299.33	166.890	1154.10	1363.5	3.7609	4.2794
130.8	11.0530	299.13	167.030	1154.40	1363.2	3.7616	4.2786
130.81	11.0550	298.94	167.180	1154.60	1362.9	3.7623	4.2779
130.82	11.0570	298.75	167.330	1154.90	1362.7	3.7629	4.2772
130.83	11.0590	298.55	167.480	1155.20	1362.4	3.7636	4.2765
130.84	11.0610	298.35	167.630	1155.50	1362.1	3.7643	4.2758
130.85	11.0630	298.16	167.790	1155.80	1361.8	3.7650	4.2750
130.86	11.0650	297.96	167.940	1156.10	1361.5	3.7657	4.2743
130.87	11.0670	297.76	168.090	1156.30	1361.3	3.7664	4.2736
130.88	11.0690	297.56	168.240	1156.60	1361.0	3.7671	4.2729
130.89	11.0710	297.36	168.400	1156.90	1360.7	3.7678	4.2721
130.9	11.0730	297.15	168.550	1157.20	1360.4	3.7685	4.2714
130.91	11.0750	296.95	168.710	1157.50	1360.1	3.7692	4.2706
130.92	11.0770	296.75	168.870	1157.80	1359.8	3.7699	4.2699
130.93	11.0790	296.54	169.020	1158.10	1359.5	3.7706	4.2691
130.94	11.0810	296.33	169.180	1158.40	1359.2	3.7713	4.2684
130.95	11.0830	296.13	169.340	1158.70	1358.9	3.7720	4.2676
130.96	11.0840	295.92	169.500	1159.00	1358.7	3.7728	4.2669
130.97	11.0860	295.71	169.660	1159.30	1358.4	3.7735	4.2661
130.98	11.0880	295.50	169.820	1159.60	1358.1	3.7742	4.2653
130.99	11.0900	295.28	169.980	1159.90	1357.8	3.7750	4.2646
131	11.0920	295.07	170.150	1160.20	1357.5	3.7757	4.2638
131.01	11.0940	294.86	170.310	1160.50	1357.2	3.7764	4.2630
131.02	11.0960	294.64	170.470	1160.80	1356.9	3.7772	4.2622
131.03	11.0980	294.42	170.640	1161.10	1356.5	3.7779	4.2615
131.04	11.1000	294.20	170.810	1161.40	1356.2	3.7787	4.2607
131.05	11.1020	293.98	170.970	1161.70	1355.9	3.7794	4.2599
131.06	11.1040	293.76	171.140	1162.10	1355.6	3.7802	4.2591
131.07	11.1060	293.54	171.310	1162.40	1355.3	3.7810	4.2583
131.08	11.1080	293.32	171.480	1162.70	1355.0	3.7818	4.2575
131.09	11.1100	293.09	171.650	1163.00	1354.7	3.7825	4.2567
131.1	11.1120	292.87	171.820	1163.30	1354.4	3.7833	4.2559
131.11	11.1140	292.64	171.990	1163.70	1354.1	3.7841	4.2551
131.12	11.1160	292.41	172.160	1164.00	1353.7	3.7849	4.2543
131.13	11.1180	292.18	172.340	1164.30	1353.4	3.7857	4.2534
131.14	11.1200	291.95	172.510	1164.60	1353.1	3.7865	4.2526
131.15	11.1220	291.72	172.690	1165.00	1352.8	3.7873	4.2518
131.16	11.1240	291.48	172.870	1165.30	1352.4	3.7881	4.2510

131.17	11.1260	291.25	173.040	1165.60	1352.1	3.7889	4.2501
131.18	11.1280	291.01	173.220	1166.00	1351.8	3.7897	4.2493
131.19	11.1300	290.77	173.400	1166.30	1351.5	3.7905	4.2484
131.2	11.1320	290.53	173.580	1166.70	1351.1	3.7914	4.2476
131.21	11.1340	290.29	173.770	1167.00	1350.8	3.7922	4.2467
131.22	11.1360	290.05	173.950	1167.40	1350.5	3.7930	4.2459
131.23	11.1380	289.80	174.130	1167.70	1350.1	3.7939	4.2450
131.24	11.1390	289.55	174.320	1168.10	1349.8	3.7947	4.2441
131.25	11.1410	289.31	174.500	1168.40	1349.4	3.7956	4.2433
131.26	11.1430	289.06	174.690	1168.80	1349.1	3.7965	4.2424
131.27	11.1450	288.80	174.880	1169.10	1348.8	3.7973	4.2415
131.28	11.1470	288.55	175.070	1169.50	1348.4	3.7982	4.2406
131.29	11.1490	288.29	175.260	1169.80	1348.1	3.7991	4.2397
131.3	11.1510	288.04	175.450	1170.20	1347.7	3.8000	4.2388
131.31	11.1530	287.78	175.650	1170.60	1347.4	3.8009	4.2379
131.32	11.1550	287.52	175.840	1170.90	1347.0	3.8017	4.2370
131.33	11.1570	287.26	176.040	1171.30	1346.6	3.8027	4.2361
131.34	11.1590	286.99	176.230	1171.70	1346.3	3.8036	4.2352
131.35	11.1610	286.73	176.430	1172.10	1345.9	3.8045	4.2343
131.36	11.1630	286.46	176.630	1172.40	1345.6	3.8054	4.2334
131.37	11.1650	286.19	176.830	1172.80	1345.2	3.8063	4.2324
131.38	11.1670	285.91	177.040	1173.20	1344.8	3.8073	4.2315
131.39	11.1690	285.64	177.240	1173.60	1344.5	3.8082	4.2306
131.4	11.1710	285.36	177.440	1174.00	1344.1	3.8092	4.2296
131.41	11.1730	285.09	177.650	1174.40	1343.7	3.8101	4.2286
131.42	11.1750	284.80	177.860	1174.80	1343.3	3.8111	4.2277
131.43	11.1770	284.52	178.070	1175.20	1342.9	3.8121	4.2267
131.44	11.1790	284.24	178.280	1175.60	1342.6	3.8130	4.2257
131.45	11.1810	283.95	178.490	1176.00	1342.2	3.8140	4.2248
131.46	11.1830	283.66	178.710	1176.40	1341.8	3.8150	4.2238
131.47	11.1850	283.37	178.920	1176.80	1341.4	3.8160	4.2228
131.48	11.1870	283.07	179.140	1177.20	1341.0	3.8170	4.2218
131.49	11.1890	282.78	179.360	1177.70	1340.6	3.8181	4.2208
131.5	11.1910	282.48	179.580	1178.10	1340.2	3.8191	4.2198
131.51	11.1930	282.17	179.800	1178.50	1339.8	3.8201	4.2187
131.52	11.1950	281.87	180.020	1178.90	1339.4	3.8212	4.2177
131.53	11.1970	281.56	180.250	1179.40	1339.0	3.8222	4.2167
131.54	11.1990	281.25	180.480	1179.80	1338.6	3.8233	4.2156
131.55	11.2010	280.94	180.710	1180.30	1338.2	3.8244	4.2146
131.56	11.2030	280.62	180.940	1180.70	1337.8	3.8255	4.2135

131.57	11.2050	280.31	181.170	1181.20	1337.3	3.8266	4.2125
131.58	11.2070	279.98	181.410	1181.60	1336.9	3.8277	4.2114
131.59	11.2090	279.66	181.640	1182.10	1336.5	3.8288	4.2103
131.6	11.2110	279.33	181.880	1182.50	1336.0	3.8299	4.2092
131.61	11.2120	279.00	182.120	1183.00	1335.6	3.8310	4.2081
131.62	11.2140	278.67	182.370	1183.50	1335.2	3.8322	4.2070
131.63	11.2160	278.33	182.610	1183.90	1334.7	3.8334	4.2059
131.64	11.2180	277.99	182.860	1184.40	1334.3	3.8345	4.2048
131.65	11.2200	277.65	183.110	1184.90	1333.8	3.8357	4.2036
131.66	11.2220	277.30	183.360	1185.40	1333.4	3.8369	4.2025
131.67	11.2240	276.95	183.620	1185.90	1332.9	3.8381	4.2013
131.68	11.2260	276.60	183.870	1186.40	1332.5	3.8393	4.2001
131.69	11.2280	276.24	184.130	1186.90	1332.0	3.8406	4.1990
131.7	11.2300	275.88	184.400	1187.40	1331.5	3.8418	4.1978
131.71	11.2320	275.51	184.660	1187.90	1331.1	3.8431	4.1966
131.72	11.2340	275.14	184.930	1188.50	1330.6	3.8443	4.1954
131.73	11.2360	274.77	185.200	1189.00	1330.1	3.8456	4.1942
131.74	11.2380	274.39	185.470	1189.50	1329.6	3.8469	4.1929
131.75	11.2400	274.01	185.750	1190.10	1329.1	3.8483	4.1917
131.76	11.2420	273.63	186.030	1190.60	1328.6	3.8496	4.1904
131.77	11.2440	273.24	186.310	1191.20	1328.1	3.8509	4.1892
131.78	11.2460	272.84	186.590	1191.70	1327.6	3.8523	4.1879
131.79	11.2480	272.44	186.880	1192.30	1327.1	3.8537	4.1866
131.8	11.2500	272.04	187.170	1192.90	1326.6	3.8551	4.1853
131.81	11.2520	271.63	187.470	1193.40	1326.1	3.8565	4.1840
131.82	11.2540	271.21	187.770	1194.00	1325.5	3.8579	4.1826
131.83	11.2560	270.79	188.070	1194.60	1325.0	3.8594	4.1813
131.84	11.2580	270.37	188.370	1195.20	1324.5	3.8609	4.1799
131.85	11.2600	269.94	188.680	1195.80	1323.9	3.8623	4.1785
131.86	11.2620	269.50	189.000	1196.50	1323.3	3.8639	4.1772
131.87	11.2640	269.06	189.310	1197.10	1322.8	3.8654	4.1757
131.88	11.2660	268.61	189.630	1197.70	1322.2	3.8669	4.1743
131.89	11.2680	268.16	189.960	1198.40	1321.6	3.8685	4.1729
131.9	11.2700	267.70	190.290	1199.00	1321.1	3.8701	4.1714
131.91	11.2720	267.23	190.630	1199.70	1320.5	3.8717	4.1699
131.92	11.2740	266.76	190.970	1200.40	1319.9	3.8734	4.1684
131.93	11.2760	266.28	191.310	1201.10	1319.3	3.8751	4.1669
131.94	11.2780	265.79	191.660	1201.70	1318.6	3.8768	4.1653
131.95	11.2800	265.30	192.020	1202.50	1318.0	3.8785	4.1638
131.96	11.2820	264.80	192.380	1203.20	1317.4	3.8802	4.1622

131.97	11.2840	264.29	192.740	1203.90	1316.7	3.8820	4.1606
131.98	11.2860	263.77	193.120	1204.60	1316.1	3.8838	4.1589
131.99	11.2880	263.24	193.500	1205.40	1315.4	3.8857	4.1573
132	11.2900	262.70	193.880	1206.20	1314.8	3.8876	4.1556
132.01	11.2920	262.16	194.270	1207.00	1314.1	3.8895	4.1539
132.02	11.2940	261.60	194.670	1207.80	1313.4	3.8914	4.1521
132.03	11.2960	261.04	195.080	1208.60	1312.7	3.8934	4.1504
132.04	11.2980	260.47	195.490	1209.40	1311.9	3.8954	4.1486
132.05	11.3000	259.88	195.920	1210.20	1311.2	3.8975	4.1467
132.06	11.3020	259.28	196.350	1211.10	1310.5	3.8996	4.1448
132.07	11.3040	258.68	196.790	1212.00	1309.7	3.9018	4.1429
132.08	11.3060	258.06	197.240	1212.90	1308.9	3.9040	4.1410
132.09	11.3080	257.42	197.700	1213.80	1308.1	3.9062	4.1390
132.1	11.3100	256.78	198.170	1214.70	1307.3	3.9085	4.1370
132.11	11.3120	256.11	198.650	1215.70	1306.5	3.9108	4.1349
132.12	11.3140	255.44	199.150	1216.70	1305.6	3.9132	4.1327
132.13	11.3160	254.75	199.660	1217.70	1304.7	3.9157	4.1306
132.14	11.3180	254.04	200.180	1218.70	1303.9	3.9182	4.1283
132.15	11.3200	253.31	200.720	1219.80	1302.9	3.9208	4.1260
132.16	11.3210	252.57	201.270	1220.90	1302.0	3.9235	4.1237
132.17	11.3230	251.80	201.840	1222.00	1301.0	3.9263	4.1212
132.18	11.3250	251.01	202.430	1223.10	1300.0	3.9291	4.1187
132.19	11.3270	250.20	203.040	1224.30	1299.0	3.9320	4.1161
132.2	11.3290	249.36	203.670	1225.60	1297.9	3.9351	4.1135
132.21	11.3310	248.49	204.330	1226.90	1296.8	3.9382	4.1107
132.22	11.3330	247.60	205.020	1228.20	1295.6	3.9415	4.1078
132.23	11.3350	246.67	205.730	1229.60	1294.4	3.9449	4.1048
132.24	11.3370	245.70	206.490	1231.00	1293.1	3.9484	4.1016

APPENDIX F

Thermodynamics Properties of 2,3,3,3-tetrafluoropropene (R1234yf)

Temperature (^{0}C)	Pressure (MPa)	Liquid density (kg/m³)	Vapour density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg.K)	Vapor Entropy (kJ/kg.K)
-50	0.0374	1318.4	2.3545	-23.791	166.43	-0.1017	0.7507
-45	0.0486	1305.2	3.0067	-18.110	169.79	-0.0766	0.7470
-40	0.0624	1291.9	3.7945	-12.355	173.15	-0.0517	0.7440
-35	0.0790	1278.3	4.7372	-6.523	176.53	-0.0270	0.7416
-30	0.0991	1264.5	5.8553	-0.613	179.90	-0.0025	0.7399
-25	0.1229	1250.5	7.1712	5.377	183.27	0.0218	0.7387
-20	0.1509	1236.3	8.7093	11.447	186.63	0.0459	0.7379
-15	0.1837	1221.8	10.4960	17.601	189.97	0.0699	0.7376
-10	0.2218	1207.0	12.5590	23.839	193.30	0.0937	0.7377
-5	0.2656	1191.8	14.9310	30.163	196.60	0.1174	0.7381
0	0.3158	1176.3	17.6470	36.576	199.87	0.1409	0.7387
5	0.3729	1160.4	20.7440	43.081	203.10	0.1643	0.7396
10	0.4375	1144.0	24.2670	49.679	206.28	0.1876	0.7407
15	0.5103	1127.2	28.2660	56.376	209.41	0.2109	0.7419
20	0.5917	1109.9	32.7960	63.173	212.47	0.2340	0.7433
25	0.6826	1091.9	37.9250	70.076	215.44	0.2571	0.7446
30	0.7835	1073.3	43.7290	77.090	218.33	0.2801	0.7460
35	0.8952	1054.0	50.3010	84.221	221.10	0.3031	0.7473
40	1.0184	1033.8	57.7530	91.478	223.75	0.3261	0.7484
45	1.1538	1012.6	66.2230	98.875	226.24	0.3491	0.7494
50	1.3023	990.4	75.8840	106.430	228.56	0.3722	0.7501
55	1.4647	966.7	86.9610	114.160	230.66	0.3954	0.7504
60	1.6419	941.3	99.7540	122.100	232.51	0.4189	0.7503
65	1.8348	913.7	114.6800	130.300	234.03	0.4427	0.7494
70	2.0445	883.2	132.3300	138.800	235.15	0.4669	0.7477
75	2.2723	848.9	153.6700	147.690	235.71	0.4919	0.7447
80	2.5194	809.0	180.3300	157.120	235.48	0.5179	0.7398
85	2.7879	760.5	215.6700	167.390	233.98	0.5458	0.7318
90	3.0803	694.1	269.1000	179.370	229.90	0.5779	0.7171
90.1	3.0865	692.4	270.5200	179.640	229.77	0.5787	0.7167
90.2	3.0926	690.7	271.9700	179.920	229.63	0.5794	0.7162
90.3	3.0987	689.0	273.4400	180.190	229.49	0.5801	0.7158
90.4	3.1049	687.2	274.9300	180.470	229.35	0.5809	0.7153

90.5	3.1111	685.5	276.4500	180.750	229.21	0.5816	0.7149
90.6	3.1172	683.7	278.0000	181.040	229.06	0.5824	0.7144
90.7	3.1234	681.8	279.5700	181.320	228.91	0.5831	0.7139
90.8	3.1296	680.0	281.1700	181.610	228.75	0.5839	0.7134
90.9	3.1358	678.1	282.7900	181.900	228.59	0.5847	0.7129
91	3.1421	676.2	284.4500	182.200	228.43	0.5855	0.7124
91.1	3.1483	674.3	286.1400	182.500	228.26	0.5863	0.7119
91.2	3.1546	672.3	287.8600	182.800	228.09	0.5871	0.7114
91.3	3.1608	670.3	289.6200	183.100	227.91	0.5879	0.7108
91.4	3.1671	668.2	291.4100	183.410	227.73	0.5887	0.7103
91.5	3.1734	666.1	293.2400	183.720	227.54	0.5895	0.7097
91.6	3.1797	664.0	295.1100	184.030	227.35	0.5904	0.7091
91.7	3.1860	661.9	297.0200	184.350	227.15	0.5912	0.7085
91.8	3.1923	659.6	298.9800	184.680	226.95	0.5921	0.7079
91.9	3.1987	657.4	300.9900	185.000	226.73	0.5929	0.7072
92	3.2050	655.1	303.0400	185.340	226.52	0.5938	0.7066
92.1	3.2114	652.7	305.1500	185.670	226.29	0.5947	0.7059
92.2	3.2178	650.3	307.3200	186.010	226.06	0.5956	0.7052
92.3	3.2242	647.8	309.5400	186.360	225.82	0.5965	0.7045
92.4	3.2306	645.3	311.8400	186.720	225.57	0.5975	0.7038
92.5	3.2370	642.7	314.2000	187.080	225.31	0.5984	0.7030
92.6	3.2434	640.0	316.6300	187.450	225.04	0.5994	0.7022
92.7	3.2499	637.2	319.1500	187.820	224.76	0.6004	0.7014
92.8	3.2563	634.4	321.7600	188.210	224.46	0.6014	0.7005
92.9	3.2628	631.4	324.4600	188.600	224.16	0.6025	0.6996
93	3.2693	628.4	327.2700	189.000	223.84	0.6036	0.6987
93.1	3.2758	625.2	330.1900	189.420	223.51	0.6047	0.6977
93.2	3.2823	621.9	333.2500	189.840	223.15	0.6058	0.6967
93.3	3.2889	618.5	336.4400	190.280	222.78	0.6070	0.6957
93.4	3.2954	614.8	339.8000	190.740	222.39	0.6082	0.6945
93.5	3.3020	611.1	343.3500	191.210	221.97	0.6094	0.6934
93.6	3.3086	607.1	347.1000	191.700	221.53	0.6108	0.6921
93.7	3.3152	602.8	351.1000	192.220	221.05	0.6121	0.6907
93.8	3.3218	598.3	355.3900	192.770	220.54	0.6136	0.6893
93.9	3.3284	593.4	360.0200	193.340	219.98	0.6151	0.6877
94	3.3351	588.1	365.0800	193.960	219.37	0.6168	0.6860
94.1	3.3417	582.2	370.6800	194.640	218.69	0.6186	0.6841
94.2	3.3484	575.7	376.9800	195.380	217.92	0.6206	0.6819
94.3	3.3551	568.2	384.2500	196.210	217.02	0.6228	0.6795
94.4	3.3619	559.2	392.9600	197.200	215.95	0.6255	0.6765

94.5	3.3686	547.8	404.0900	198.420	214.58	0.6288	0.6727
94.6	3.3754	531.1	420.4200	200.180	212.58	0.6335	0.6672
94.7	3.3822	475.6	475.5500	206.130	206.13	0.6497	0.6497

APPENDIX G

Maximum COP comparison between CO_2/NH_3 and CO_2/R1234yf cascade refrigeration system

Design Parameters			COPmax	
T_{tc} (^0C)	T_{be} (^0C)	ΔT	CO_2/NH_3	CO_2/R1234yf
35	-40	2	2.44	6.40
		3	2.39	6.32
		4	2.33	6.22
		5	2.27	6.12
	-45	2	2.32	5.94
		3	2.27	5.87
		4	2.22	5.78
		5	2.17	5.70
	-50	2	2.20	5.52
		3	2.16	5.47
		4	2.11	5.39
		5	2.06	5.31
45	-40	2	1.99	5.88
		3	1.95	5.79
		4	1.91	5.70
		5	1.88	5.62
	-45	2	1.90	5.48
		3	1.87	5.41
		4	1.84	5.33
		5	1.80	5.26
	-50	2	1.82	5.13
		3	1.79	5.06
		4	1.76	4.99
		5	1.73	4.93
55	-40	2	1.68	5.45
		3	1.65	5.38
		4	1.62	5.30
		5	1.60	5.23
	-45	2	1.62	5.11
		3	1.59	5.05
		4	1.56	4.98
		5	1.54	4.91
	-50	2	1.56	4.80
		3	1.53	4.74
		4	1.51	4.68
		5	1.48	4.62

APPENDIX H

Maximum COP comparison between CO_2/R1234yf and CO_2/NH_3 cascade refrigeration system

CO_2/R1234yf

T_{tc}	Tbe	ΔT	COP_{max}
35	-40	2	6.40
45			5.88
55			5.45
35		3	6.32
45			5.79
55			5.38
35		4	6.22
45			5.70
55			5.30
35		5	6.12
45			5.62
55			5.23
35	-45	2	5.94
45			5.48
55			5.11
35		3	5.87
45			5.41
55			5.05
35		4	5.78
45			5.33
55			4.98
35		5	5.70
45			5.26
55			4.91
35	-50	2	5.52
45			5.13
55			4.80
35		3	5.47
45			5.06
55			4.74
35		4	5.39
45			4.99
55			4.68
35		5	5.31
45			4.93
55			4.62

CO_2/NH_3

T_{tc}	T_{be}	Δ T	COP_{max}
35	-40	2	2.44
45			1.99
55			1.68
35		3	2.39
45			1.95
55			1.65
35		4	2.33
45			1.91
55			1.62
35		5	2.27
45			1.88
55			1.6
35	-45	2	2.32
45			1.9
55			1.62
35		3	2.27
45			1.87
55			1.59
35		4	2.22
45			1.84
55			1.56
35		5	2.17
45			1.8
55			1.54
35	-50	2	2.2
45			1.82
55			1.56
35		3	2.16
45			1.79
55			1.53
35		4	2.11
45			1.76
55			1.51
35		5	2.06
45			1.73
55			1.48

APPENDIX I

CO_2/NH_3 cascade refrigeration system
Condition (T_{be}= -40^{0}C)

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	2.44
			5	2.40
			0	2.36
			-5	2.31
35	-40	2	-10	2.27
			-15	2.23
			-20	2.19
			-25	2.15
			-30	2.11
			10	2.39
			5	2.35
			0	2.31
			-5	2.27
35	-40	3	-10	2.23
			-15	2.19
			-20	2.15
			-25	2.12
			-30	2.08
			10	2.33
			5	2.30
			0	2.26
			-5	2.22
35	-40	4	-10	2.19
			-15	2.15
			-20	2.11
			-25	2.09
			-30	2.05
			10	2.27
			5	2.25
			0	2.22
			-5	2.19
35	-40	5	-10	2.15
			-15	2.12
			-20	2.08
			-25	2.06
			-30	2.03

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	1.99
			5	1.98
			0	1.96
			-5	1.95
45	-40	2	-10	1.93
			-15	1.91
			-20	1.89
			-25	1.87
			-30	1.85
			10	1.95
			5	1.94
			0	1.93
			-5	1.91
45	-40	3	-10	1.90
			-15	1.88
			-20	1.86
			-25	1.84
			-30	1.82
			10	1.91
			5	1.91
			0	1.90
			-5	1.88
45	-40	4	-10	1.87
			-15	1.85
			-20	1.83
			-25	1.82
			-30	1.80
			10	1.88
			5	1.87
			0	1.87
			-5	1.86
45	-40	5	-10	1.84
			-15	1.82
			-20	1.81
			-25	1.79
			-30	1.78

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	1.68
			5	1.68
			0	1.68
			-5	1.68
55	-40	2	-10	1.68
			-15	1.67
			-20	1.66
			-25	1.65
			-30	1.64
			10	1.65
			5	1.66
			0	1.66
			-5	1.66
55	-40	3	-10	1.65
			-15	1.65
			-20	1.64
			-25	1.63
			-30	1.62
			10	1.62
			5	1.63
			0	1.64
			-5	1.63
55	-40	4	-10	1.63
			-15	1.62
			-20	1.62
			-25	1.61
			-30	1.60
			10	1.60
			5	1.61
			0	1.61
			-5	1.61
55	-40	5	-10	1.61
			-15	1.60
			-20	1.60
			-25	1.59
			-30	1.58

APPENDIX J

CO_2/NH_3 cascade refrigeration system
Condition (T_{be}= -45^{0}C)

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	2.32
			5	2.29
			0	2.26
			-5	2.22
35	-45	2	-10	2.19
			-15	2.15
			-20	2.12
			-25	2.09
			-30	2.05
			10	2.27
			5	2.24
			0	2.21
			-5	2.18
35	-45	3	-10	2.15
			-15	2.12
			-20	2.08
			-25	2.06
			-30	2.03
			10	2.22
			5	2.20
			0	2.17
			-5	2.14
35	-45	4	-10	2.11
			-15	2.08
			-20	2.05
			-25	2.03
			-30	2.00
			10	2.17
			5	2.15
			0	2.13
			-5	2.10
35	-45	5	-10	2.08
			-15	2.05
			-20	2.02
			-25	2.00
			-30	1.97

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	1.90
			5	1.90
			0	1.89
			-5	1.88
45	-45	2	-10	1.87
			-15	1.85
			-20	1.84
			-25	1.82
			-30	1.80
			10	1.87
			5	1.87
			0	1.86
			-5	1.85
45	-45	3	-10	1.84
			-15	1.82
			-20	1.81
			-25	1.79
			-30	1.78
			10	1.84
			5	1.84
			0	1.83
			-5	1.82
45	-45	4	-10	1.81
			-15	1.80
			-20	1.79
			-25	1.77
			-30	1.76
			10	1.80
			5	1.80
			0	1.80
			-5	1.80
45	-45	5	-10	1.78
			-15	1.77
			-20	1.76
			-25	1.75
			-30	1.74

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	1.62
			5	1.63
			0	1.63
			-5	1.63
55	-45	2	-10	1.63
			-15	1.62
			-20	1.62
			-25	1.61
			-30	1.60
			10	1.59
			5	1.60
			0	1.61
			-5	1.61
55	-45	3	-10	1.61
			-15	1.60
			-20	1.60
			-25	1.59
			-30	1.58
			10	1.56
			5	1.58
			0	1.58
			-5	1.59
55	-45	4	-10	1.59
			-15	1.58
			-20	1.58
			-25	1.57
			-30	1.57
			10	1.54
			5	1.55
			0	1.56
			-5	1.57
55	-45	5	-10	1.57
			-15	1.56
			-20	1.56
			-25	1.56
			-30	1.55

APPENDIX K

CO_2/NH_3 cascade refrigeration system
Condition (T_{be}= -50^{0}C)

T_{tc}	T_{be}	ΔT	T_{mc}	COP
			10	2.20
			5	2.18
			0	2.16
			-5	2.12
35	-50	2	-10	2.11
			-15	2.08
			-20	2.05
			-25	2.02
			-30	2.00
			10	2.16
			5	2.14
			0	2.12
			-5	2.08
35	-50	3	-10	2.07
			-15	2.04
			-20	2.02
			-25	1.99
			-30	1.97
			10	2.11
			5	2.10
			0	2.08
			-5	2.04
35	-50	4	-10	2.04
			-15	2.01
			-20	1.99
			-25	1.97
			-30	1.94
			10	2.06
			5	2.06
			0	2.04
			-5	2.01
35	-50	5	-10	2.00
			-15	1.98
			-20	1.96
			-25	1.94
			-30	1.92

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	1.82
			5	1.83
			0	1.82
			-5	1.80
45	-50	2	-10	1.81
			-15	1.80
			-20	1.78
			-25	1.77
			-30	1.76
			10	1.79
			5	1.80
			0	1.79
			-5	1.77
45	-50	3	-10	1.78
			-15	1.77
			-20	1.76
			-25	1.75
			-30	1.74
			10	1.76
			5	1.77
			0	1.77
			-5	1.75
45	-50	4	-10	1.75
			-15	1.75
			-20	1.74
			-25	1.72
			-30	1.71
			10	1.73
			5	1.74
			0	1.74
			-5	1.72
45	-50	5	-10	1.73
			-15	1.72
			-20	1.71
			-25	1.70
			-30	1.69

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	1.56
			5	1.57
			0	1.58
			-5	1.57
55	-50	2	-10	1.58
			-15	1.58
			-20	1.58
			-25	1.57
			-30	1.57
			10	1.53
			5	1.55
			0	1.55
			-5	1.55
55	-50	3	-10	1.56
			-15	1.56
			-20	1.56
			-25	1.55
			-30	1.55
			10	1.51
			5	1.52
			0	1.53
			-5	1.53
55	-50	4	-10	1.54
			-15	1.54
			-20	1.54
			-25	1.54
			-30	1.53
			10	1.48
			5	1.50
			0	1.51
			-5	1.51
55	-50	5	-10	1.52
			-15	1.52
			-20	1.52
			-25	1.52
			-30	1.52

APPENDIX E

CO_2/R1234yf cascade refrigeration system
Condition (Tbe= -40^{0}C)

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	4.47
			5	4.83
			0	5.11
			-5	5.39
35	-40	2	-10	5.65
			-15	5.88
			-20	6.09
			-25	6.27
			-30	6.4
			10	4.43
			5	4.74
			0	5.04
			-5	5.32
35	-40	3	-10	5.57
			-15	5.79
			-20	6
			-25	6.17
			-30	6.32
			10	4.37
			5	4.69
			0	4.98
			-5	5.24
35	-40	4	-10	5.49
			-15	5.71
			-20	5.91
			-25	6.07
			-30	6.22
			10	4.32
			5	4.63
			0	4.91
			-5	5.17
35	-40	5	-10	5.41
			-15	5.63
			-20	5.82
			-25	5.98
			-30	6.12

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	4.1
			5	4.39
			0	4.66
			-5	4.92
45	-40	2	-10	5.16
			-15	5.37
			-20	5.56
			-25	5.73
			-30	5.88
			10	4.05
			5	4.34
			0	4.61
			-5	4.86
45	-40	3	-10	5.09
			-15	5.3
			-20	5.49
			-25	5.65
			-30	5.79
			10	4.01
			5	4.29
			0	4.55
			-5	4.8
45	-40	4	-10	5.02
			-15	5.23
			-20	5.41
			-25	5.57
			-30	5.7
			10	3.96
			5	4.24
			0	4.5
			-5	4.74
45	-40	5	-10	4.96
			-15	5.16
			-20	5.33
			-25	5.49
			-30	5.62

T_{tc}	T_{be}	Δ T	T_{mc}	COP
			10	3.8
			5	4.07
			0	4.32
			-5	4.56
55	-40	2	-10	4.78
			-15	4.98
			-20	5.16
			-25	5.32
			-30	5.45
			10	3.76
			5	4.03
			0	4.28
			-5	4.51
55	-40	3	-10	4.72
			-15	4.91
			-20	5.09
			-25	5.24
			-30	5.38
			10	3.72
			5	3.99
			0	4.23
			-5	4.46
55	-40	4	-10	4.66
			-15	4.85
			-20	5.02
			-25	5.17
			-30	5.3
			10	3.69
			5	3.94
			0	4.18
			-5	4.4
55	-40	5	-10	4.61
			-15	4.79
			-20	4.96
			-25	5.1
			-30	5.23

CO_2/R1234yf cascade refrigeration system
Condition (T_{be}= -45^{0}C)

T_{tc}	T_{be}	ΔT	T_{mc}	COP
			10	4.1
			5	4.42
			0	4.69
			-5	4.95
35	-45	2	-10	5.2
			-15	5.42
			-20	5.63
			-25	5.81
			-30	5.94
			10	4.06
			5	4.35
			0	4.63
			-5	4.89
35	-45	3	-10	5.13
			-15	5.35
			-20	5.55
			-25	5.72
			-30	5.87
			10	4.01
			5	4.3
			0	4.57
			-5	4.83
35	-45	4	-10	5.06
			-15	5.28
			-20	5.47
			-25	5.64
			-30	5.78
			10	3.97
			5	4.25
			0	4.52
			-5	4.77
35	-45	5	-10	5
			-15	5.21
			-20	5.39
			-25	5.56
			-30	5.70

T_{tc}	T_{be}	ΔT	T_{mc}	COP
			10	3.78
			5	4.05
			0	4.31
			-5	4.55
45	-45	2	-10	4.78
			-15	4.99
			-20	5.17
			-25	5.34
			-30	5.48
			10	3.74
			5	4.01
			0	4.26
			-5	4.5
45	-45	3	-10	4.72
			-15	4.92
			-20	5.11
			-25	5.27
			-30	5.41
			10	3.7
			5	3.97
			0	4.21
			-5	4.45
45	-45	4	-10	4.66
			-15	4.86
			-20	5.04
			-25	5.2
			-30	5.33
			10	3.66
			5	3.92
			0	4.17
			-5	4.4
45	-45	5	-10	4.61
			-15	4.8
			-20	4.97
			-25	5.13
			-30	5.26

T_{tc}	T_{be}	ΔT	T_{mc}	COP
			10	3.52
			5	3.78
			0	4.02
			-5	4.24
55	-45	2	-10	4.45
			-15	4.64
			-20	4.82
			-25	4.98
			-30	5.11
			10	3.49
			5	3.74
			0	3.97
			-5	4.2
55	-45	3	-10	4.4
			-15	4.59
			-20	4.76
			-25	4.91
			-30	5.05
			10	3.46
			5	3.7
			0	3.93
			-5	4.15
55	-45	4	-10	4.35
			-15	4.54
			-20	4.7
			-25	4.85
			-30	4.98
			10	3.42
			5	3.67
			0	3.89
			-5	4.1
55	-45	5	-10	4.3
			-15	4.48
			-20	4.65
			-25	4.79
			-30	4.91

CO_2/R1234yf cascade refrigeration system
Condition (T_{be}= -50°C)

T_{tc}	T_{be}	ΔT	T_{mc}	COP
35	-50	2	10	3.76
			5	4.07
			0	4.32
			-5	4.48
			-10	4.8
			-15	5.02
			-20	5.21
			-25	5.39
			-30	5.52
35	-50	3	10	3.73
			5	4.01
			0	4.27
			-5	4.43
			-10	4.74
			-15	4.95
			-20	5.14
			-25	5.32
			-30	5.47
35	-50	4	10	3.69
			5	3.97
			0	4.22
			-5	4.38
			-10	4.68
			-15	4.89
			-20	5.08
			-25	5.24
			-30	5.39
35	-50	5	10	3.66
			5	3.92
			0	4.17
			-5	4.33
			-10	4.63
			-15	4.83
			-20	5.01
			-25	5.17
			-30	5.31

T_{tc}	T_{be}	Δ T	T_{mc}	COP
45	-50	2	10	3.49
			5	3.75
			0	3.99
			-5	4.15
			-10	4.44
			-15	4.64
			-20	4.82
			-25	4.98
			-30	5.13
45	-50	3	10	3.46
			5	3.71
			0	3.95
			-5	4.11
			-10	4.39
			-15	4.58
			-20	4.76
			-25	4.92
			-30	5.06
45	-50	4	10	3.42
			5	3.68
			0	3.91
			-5	4.06
			-10	4.34
			-15	4.53
			-20	4.7
			-25	4.86
			-30	4.99
45	-50	5	10	3.39
			5	3.64
			0	3.87
			-5	4.02
			-10	4.29
			-15	4.47
			-20	4.64
			-25	4.79
			-30	4.93

T_{tc}	T_{be}	Δ T	T_{mc}	COP
55	-50	2	10	3.27
			5	3.51
			0	3.74
			-5	3.89
			-10	4.15
			-15	4.34
			-20	4.51
			-25	4.66
			-30	4.8
55	-50	3	10	3.24
			5	3.48
			0	3.7
			-5	3.85
			-10	4.11
			-15	4.29
			-20	4.46
			-25	4.61
			-30	4.74
55	-50	4	10	3.21
			5	3.45
			0	3.67
			-5	3.81
			-10	4.06
			-15	4.24
			-20	4.41
			-25	4.55
			-30	4.68
55	-50	5	10	3.18
			5	3.41
			0	3.63
			-5	3.77
			-10	4.02
			-15	4.2
			-20	4.35
			-25	4.5
			-30	4.62