PERFORMANCE IMPROVEMENT OF INTEGRATED VAPOR COMPRESSION REFRIGERATION SYSTEM THROUGH SUBCOOLING

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
(THERMAL ENGINEERING)

SUBMITTED BY

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I, Praveen Kumar, hereby certify that the work which is being presented in this thesis entitled "**Performance Improvement of Integrated Vapor Compression Refrigeration System through subcooling**" is submitted in the partial fulfilment of the requirement for degree of **Master of Technology (Thermal Engineering)** in Department of Mechanical Engineering at **Delhi Technological University** is an authentic record of my own work carried out under the supervision of Associate Prof. **Dr. Akhilesh Arora**. The matter presented in this thesis has not been submitted in any other University/Institute for the award of Master of Technology Degree. Also, it has not been directly copied from any source without giving its proper reference.

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This is to certify that this thesis report entitled, "**Performance Improvement of Integrated Vapor Compression Refrigeration System through subcooling**" being submitted by **Praveen Kumar (Roll No. 2K17/THE/501)** at Delhi Technological University, Delhi for the award of the Degree of Master of Technology as per academic curriculum. It is a record of bonafide research work carried out by the student under my supervision and guidance, towards partial fulfilment of the requirement for the award of Master of Technology degree in Thermal Engineering. The work is original as it has not been submitted earlier in part or full for any purpose before.

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ABSTRACT

The current work presents the comparative investigations of R134a and R152a for the performance improvement of simple vapor compression refrigeration system through subcooling using an integrated subcool vapor compression cycle. The analysis investigates the impact of operating parameter viz temperature of condenser, degree of subcooling and temperature of evaporator on perforamcne parament viz exergy efficiency and COP. An Engineeering Equation Solver (EES) program has been prepared to compute the results of analysis. The results predicts that the subcooling enhances the COP of the vapor compression refrigeration system and R152a can be considered as substitute of R134a.

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NOMENCLATURE

COP	Coefficient of performance
CFC	Chlorofluorocarbon
EES	Engineering equation solver
GWP	Global warming potential
h	Specific enthalpy (kJ/kg)
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
$\dot{m}_r$	Mass flow rate of refrigerant (kg/s)
ODP	Ozone depleting potential
P	Pressure (kPa)
$\dot{Q}$	Rate of net refrigerating effect (kW)
s	Specific entropy (kJ/kg°C)
T	Temperature (°C)
T_0	Dead state temperature (°C)
T_b	Boundary temperature (°C)
T_e	Evaporator temperature (°C)
VCR	Vapour compression refrigeration
$\dot{W}$	Work rate (kW)

Greek symbols

ε	Effectiveness
η	Efficiency

Subscripts

0	Dead state
SC	Subcooling

CHAPTER 1
INTRODUCTION

The energy requirements are increasing with the world-wide technological development. The prosperity of a country is evaluated by its energy production and development. India is a situated in tropical continent where the demand of energy increases in essentially in summer and Mansoon season due to increasing load of x air conditioning and refrigeration equipment. In order to accomplish increasing demand of electricity, improved air conditioning and refrigeration systems are required. In addition to energy efficient technologies of refrigeration and air conditioning systems, lower ozone depletion potential (ODP) and lower global warming potential (GWP) HFC refrigerants are required.

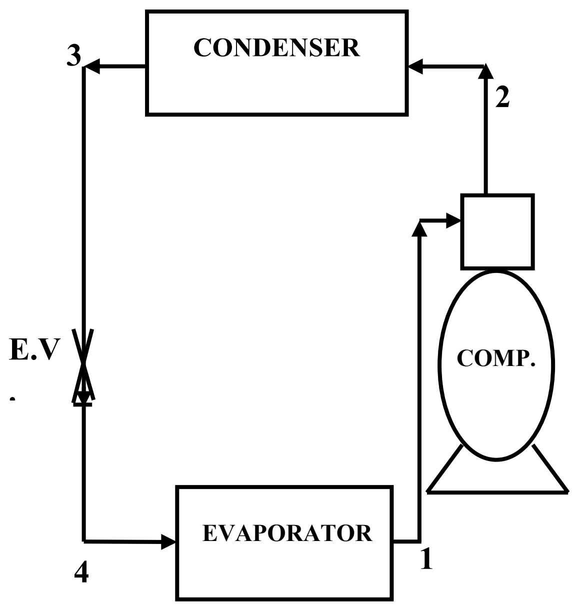

Figure 1.1: Block diagram of simple VCR system

Figure 1.1 & 1.2 show the simple vapor compression refrigeration system. The state points are shown at entry and exit of each system components. The system components are a compressor, a condenser, an expansion valve and an evaporator. The low temperature and low pressure vapor refrigerant at state point 1 which comes out from evaporator enters into the compressor and high pressure and high temperature vapor refrigerant enters into the condenser at state point 2. High pressure high temperature liquid refrigerant at state point 3 which comes out from the condenser and then enters into the expansion valve. After expansion the low temperature and pressure vapor refrigerant which comes out of the expansion valve at state point 4 enters into the evaporator and refrigeration effects produces in the evaporator.

The sub-cooling after the state point 3 increases the net refrigeration effect and hence increases the COP of the vapor compression system.

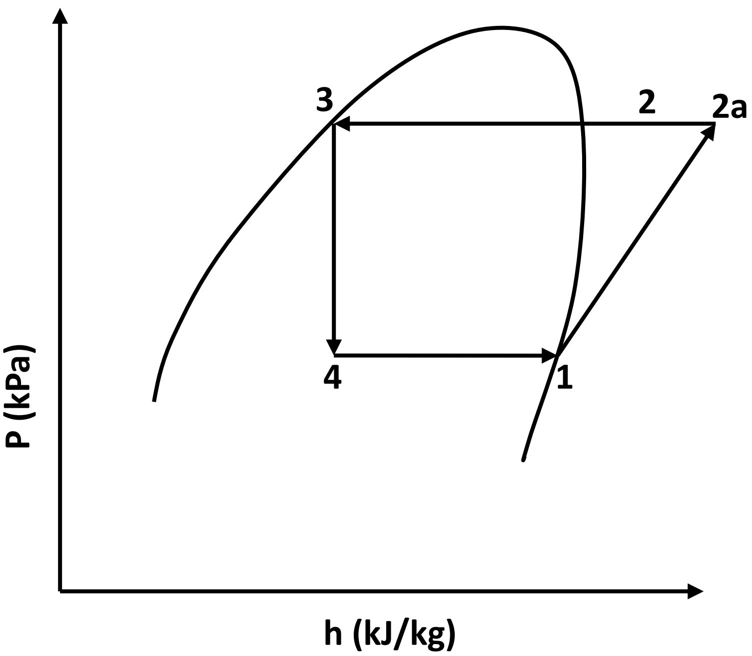

Figure 1.2: Pressure (P)-Enthalpy (h) chart of simple VCR cycle

The subcooling techniques includes liquid vapor heat exchange, dedicated meechanical subcooling, Integrated subcooling and ejector cooling etc. These technologies increases the net refrigeration effect of simple VCR cycle and hence COP of the simple VCR cycle increases.

The vast literature is available on the subcooling of simple VCR system using different technologies. Out of these, integrated subcooling is rarely used by researchers. Integrated subcooling to the simple VCR cycle increases the net refrigeration effect produced in the evaporator of the main VCR cycle consequently, the COP of the main VCR cycle enhances.

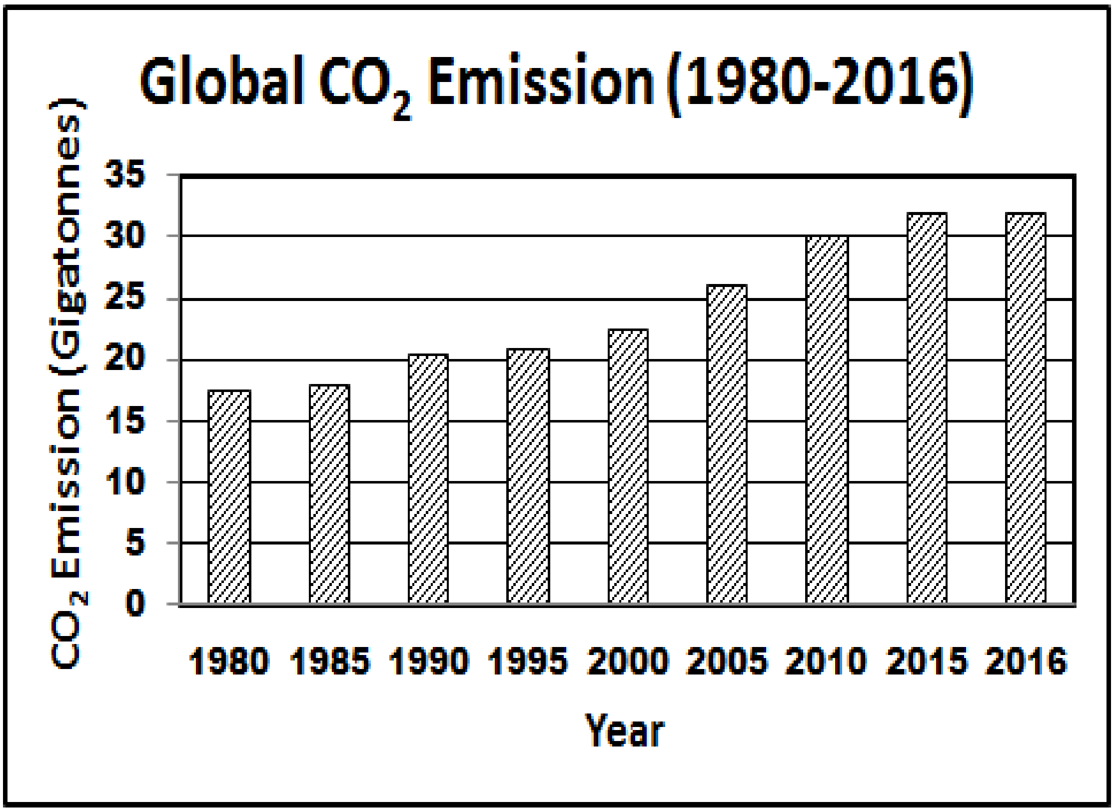

Figure 1.3 Carbon dioxide emission from fossil fuels world-wide (Source: www.earthpolicy.org)

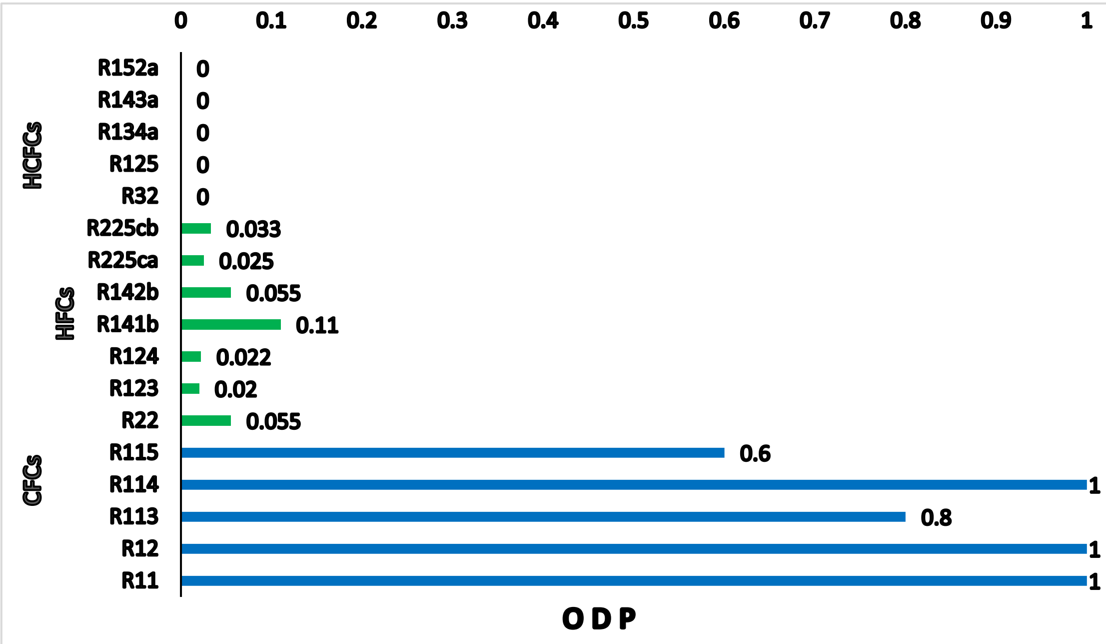

Figure 1.4 Comparison of Ozone Depletion Potential (ODP) of various refrigerants (Source: https://www.enggcyclopedia.com/2012/01/types-refrigerants/)

Table 1.1: Thermodynamic properties of R134a and R152a (Source: www.intarcon.com/fr/refrigerante-r152a/)

S. No.	**Thermodynamic Properties**	**R152a**	**R134a**
1.	ASHARE safety class	A2	A1
2.	Auto ignition temperature	454°C	----
3.	Molecular weight (g/mol)	66	102
4.	Combustion heat (kJ/mol)	1090	428
5.	Boiling Point at standard pressure	-24.0°C	-26.1°C
6.	Lower flammability limit (% Vol)	4%	---
7.	Latent heat of vaporization at -10°C, kJ/kg	307	199
8.	Volumetric cooling capacity, kJ/m^3	1283	1293
9.	GWP (IPCC AR4)	124	1430

Table 1.1 illustrates the different thermodynamic properties of R134a and R152a. The heat (latent) of vaporization of R152a is more than that of R134a and The GWP of R152a is much lesser than that of R134a. The B.P. of R152a is lower than R134a. These properties are considerable to use R152a in place of R134a.

CHAPTER 2

LITERATURE REVIEW AND RESEARCH GAP

The energy requirements are increasing with world-wide technological development. The prosperity of a country is evaluated by its energy production and development.

Arora and S. C. Kaushik [1] had presented a described exergy analysis of an actual vapor-compression refrigeration cycle. They compared the performance of refrigerants R502, 404A, and R507A. Observation had been made by them that the R507A perform better than R404A for the replacement of R502.

Hwang and Jeong [2] observed the effects of the parameters of a refrigeration system working with R600a on the non-equilibrium subcooled two-phase flow of the refrigerant. They experimented to investigate the effects of the operating conditions of the refrigeration system on the contents of the non-equilibrium vapor phase of R600a. They found that the void fraction was changed by the system parameters in addition to the pressure and temperature.

Bolaji [3] carried out an experimental study of R152a and R32 to replace R134a in a domestic refrigerator. He compared the performance of R152a and R32 with the R134a. He observed that for refrigerant R152a and R134a pull-down time and design temperature set by International Standard Organization (ISO) for a refrigerator (small) were achieved than using R32. The average coefficient of performance (COP) obtained for R134a was 4.7% lower than that of R152a while the average COP of R152a was 8.5% more than that of R32. For R152a, the energy consumed by the system is less. He added that for all operating conditions, the performance of R152a was better than those of R134a and R32in the domestic refrigerator. Hence, in a domestic refrigerator, R152a can be used as a replacement for R134a.

Sánchez et al. [4] conducted an energy assessment of an indirect refrigeration plant of R134a using R152a and R1234ze(E) as refrigerants. They used refrigerants R134a in direct and R152a and R1234ze(E) in the indirect system respectively. They concluded that the increase (average) was 18.7% for R152a, 27.2% for R1234ze(E) and 21.8% for R134a. They added that for the different refrigerants used, the refrigerant mass charge was reduced by the adoption of an indirect system up to 62%.

Brendel et al. [5] reviewed vapor compression refrigeration (VCR) in microgravity environments. They provided a revision of existing literature for vapor compression systems (VCS) operated in microgravity by outlining the history of vapor compression devices in space and presenting performance data. Moreover, gaps in the literature have been highlighted and open questions are posed based on the reviewed material. The next steps of research are suggested to support and ultimately achieve reliable vapor compression refrigeration (VCR) in space. Calculating equivalent masses for a fair comparison of various microgravity cooling technologies is suggested by capturing both energy consumption and used volume.

Alavi et al. [6] presented techniques of power regeneration in the VCR plant for upgrading already existing plants, main compressor, evaporator, condenser, and main expansion valve are assigned for the characterization of each plant. They observed that for a given main screw compressor the COP and cooling power improved up to 80% and 100% respectively. They added that for constant cooling power plants, main compressor delivery was reduced to 50%, and COP increasing up to 70%.

Humane et al. [7] carried out a comparison of the performance of low GWP refrigerants for a miniature vapor compression system (VCS) integrated with enhanced phase change material. They have compared the performance of R1234ze(E), R1234yf, and R32and R290. They concluded that compared to R134a, The reduction in system charge with R32, R1234ze (E), R290, and R1234yf was 1%, 30%, 52%, and 11% respectively. The change in COP was +8%, -3%, − 5% and − 12%, with R32,R290, R1234yf and R1234ze (E), respectively. The revolutions per minute (RPMs) of the compressor were 1700, 2900, 2400, 900, and 2100 were R90, R1234ze (E), R1234yf, R32, and R134arespectively.

Khan and Zubair [8] worked on the design and rating of an integrated mechanical-sub-cooling vapor-compression refrigeration system. They developed thermodynamic models of an integrated mechanical sub-cooling system to simulate the actual performance of the sub-cooling system. They predicted that the performance of the integrated vapor compression refrigeration cycle was better than that of the simple cycle using mechanical sub-cooling.

Zubair and Khan [9] carried out first and second-law-based thermodynamic analysis of two-stage and mechanical-sub-cooling refrigeration cycles. They analyzed each system component for their irreversibility losses. They compared theoretical results of a two-stage refrigeration system performance with experimental values for a CFC-22 system.

Jiang et al. [10] investigated a general model for two-stage vapor compression heat pump systems. They have also investigated eight different inter-stage configurations based on this model. They concluded that the general model was capable of performing performance analysis and comparison among different types of cycles, as well as the refrigerant selection and operational analysis.

Haitao Hu et al. [11] carried out research paper presentation of the cooling system through supplement integrated with VĆR cycles for commercial aircraft model has been proposed. Validated experiments with deviated cooling capacity had been also presented by them.

Binbin Yu et al. [12] provided the replacement of R410A for the reduction of low GWP in the environment. They had provided option many more for low flammable through various mixtures of coolants for the achievement of the same required vapor pressure. They had also investigated that the blends of refrigerants applied in both air-conditioning and heat-pump that could be equivalent to the properties of R410A. They found four mixtures as coolants R410A having the same properties as vapor pressure.

Qiangyu Wen et al. [13] carried out the theoretical method for enhancing the refrigerating capacity with the help of injection for the reduction of the energy stored in the exhaust temperature of SSRC. They provided an accurate method to calculate varied injection area. In addition to that, they also provide a mathematical model that described the internal working process in the single screw refrigeration compressor along with the effect of the liquid refrigerant injection.

B. Prasanna Nagasai et al. [14] they had presented an experimental investigation into the efficiency of an integrated sub-cooling VCR device by adding a counter-flow tube between compressor and condenser in a tube heat exchanger. The COP (performance coefficient increased with condenser subcooling due to the tradeoff between reducing compressor function and increasing cooling effect. To find the superlative increase in COP with condenser sub cooling, thermodynamic properties related to refrigerant effects such as latent vaporization heat and liquid specific heat were used to detect the superlative increase in COP with condenser subcooling.

Justin P. Koeln and Andrew G. Alleyne [15] showed that substantial efforts have been made to establish control strategies aimed at optimizing system performance while providing the desired cooling, with vapor compression systems consuming a large portion of the total U.S. energy consumption per year. Previous control methods, however, underutilize a degree of freedom relating to the amount of refrigerant in the device that is correlated with subcooling the condenser which can have a major effect on system performance. An alternative system architecture that uses a receiver and an external electronic expansion valve is used in this paper to provide independent control of the subcooling of condensers. Simulation and experimental findings indicate that there is an optimal subcooling that maximizes the performance of the system; but with operating conditions, this optimal subcooling shifts.

The literature was collected from various sources i.e. Science Direct, Google School and SCI Hub, etc., there is a large number of research papers available on vapor compression refrigeration systems. Some research papers are on sub-cooling are also found. However, very little research work has been carried out on integrated vapor compression refrigeration systems having R134a and R152a.

CHAPTER 3

DESCRIPTION AND MODELLING OF SYSTEM

A simple vapor compression refrigeration system is widely used for the air-conditioning and refrigeration purpose world-wide. The sub-cooling of refrigerant increases the efficiency of the system [1]. The research studies reported various sub-cooling techniques of vapor compression system in which integrated vapor compression refrigeration technique is used by very few researchers as far as literature concerned. The present work presents performance improvement analysis of an integrated vapor compression refrigeration system through sub-cooling. The present system consists two vapor compression cycles. One is the main VCR cycle and other is a simple VCR cycle whose evaporator acts as sub-cooler. The evaporator of other cycle provides sub-cooling to the main VCR cycle to enhance the performance of the main VCR cycle. R152a and R134a are the refrigerants considered.

3.1 Description of System

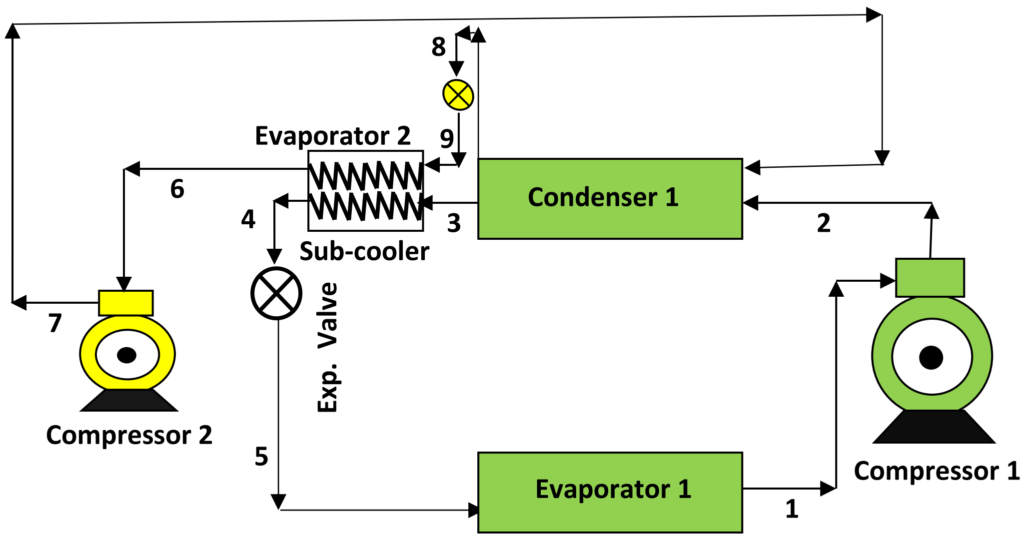

Figure 1 Block diagram of integrated vapor compression refrigeration (VCR) system

Figure 1 shows the block diagram of integrated VCR system, It consists of two VCR cycles. The main VCR cycle is in lower evaporator temperature circuit and the other vapor compression refrigeration cycle is designated as cycle for subcooling is in higher evaporator temperature circuit. The two refrigeration cycles are integrated to each other by a subcooler. The subcooler is the evaporator of the other cycle for subcooling. The refrigerants considered in the cycles are R134a and R152a. The main VCR cycle and the other cycle with subcooler are having same refrigerant at a time during the operation.

The main VCR cycle comprises of, a compressor, a condenser, an evaporator and an expansion valve and the sub-cooler cycle consists of an expansion valve, a compressor and an evaporator designated as sub-cooler. The condenser of both the cycles is common.

The sub-cooler sub-cools the liquid refrigerant which comes out the condenser of the main VCR system. The sub-cooler couples the two cycles such that the heat removed by the liquid refrigerant condensate of the main VCR system is absorbed by the vapor refrigerant of the sub-cooler VCR cycle. No external heat rejection is considered in the sub-cooler.

The refrigerant vapor which comes out from the evaporator 1 of the main VCR system goes into the compressor 1 at point of state 1. The high temperature and high pressure refrigerant vapor goes into the condenser 1 at point of state 2 after compression. The vapor refrigerant changes into the liquid refrigerant in the condenser 1. The condensate vapor of the main cycle leaving the condenser 1 and enters into the sub-cooler at point of state 3. The condensate vapor of the main VCR cycle is subcooled by the sub-cooler which increase the net refrigeration effect of the main VCR cycle.

The evaporator 2 of the sub-cooler cycle is also a sub-cooler. The liquid-vapor refrigerant receives heat from the liquid condensate of the main VCR cycle in the sub-cooler from point of state 9 to 6. The compressor 2 compresses the refrigerant vapor from point of state 6 to 7. The high temperature and high pressure refrigerant vapor is condensed by the condenser of the main cycle from point of state 2 to 3.

The liquid refrigerant leaving the condenser is expanded from point of state 4 to 5 & 8 to 9 by expansion valves of the main and sub-cooler cycle respectively. Finally, the refrigerant vapor after expansion enters into the sub-cooler. In this way, the use of a sub-cooler enhances the COP of the main VCR cycle.

3.2 Modelling of System

Thermodynamic analysis of expander incorporated vapor compression refrigeration cycle has been carried out in the current presentation. Steady state governing equations have been formed using the laws of thermodynamics i.e. first and second laws. Energy, work and mass balances have been carried out for each component of the system. An EES (Energy Equation Solver) software bases program has been developed to solve the governing equation used in the analysis.

The COP of the integrated VCR system is given by the equation (1):

$$COP_{overall} = \frac{\dot{Q}_e}{\dot{W}_{comp1}+\dot{W}_{comp2}} \quad (1)$$

Where $\dot{Q}_e$ is the net refrigeration load of the evaporator 1 in kJ/s and $\dot{W}_{comp1}$and $\dot{W}_{comp2}$ are the net compressor work of compressor 1 and 2 in kJ/s.

The The COP of the main VCR system is given by equation (2):

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp1}} \quad (2)$$

The exergetic efficiency of the integrated VCR system is given by the equation (3):

$$\eta_{ex} = COP * \left|\left(1 - \frac{T_0}{T_e}\right)\right| \quad (3)$$

Where T_o is the temperature (ambient) and T_e is the evaporator 1 temperature in K.

The energy balance in the sub-cooler (evaporator 2) is given by equation (4).

$$\dot{m}_{r,m}\,(h_3 - h_4) = \dot{m}_{r,sc}\,(h_6 - h_9) \quad (4)$$

Where $\dot{m}_{r,m}$ and $\dot{m}_{r,sc}$ are the flow rate of mass of refrigerant flowing in main and sub-cooler vapor refrigeration cycle in kg/s.

3.3 Assumptions

The following assumptions have been assumed for the thermodynamic analysis and performance improvement of an integrated VCR system through sub-cooling [1].

- The evaportor temperature of main vapor compression refrigeration system has range of variation -25ºC to 0ºC.
- Dry and saturated refrigerant vapor has been assumed at the entry of compressor at point of state 1 and 6.
- The condenser temperature has range of variation 30ºC to 50ºC.
- It is assumed that each component of the integrated VCR system has achieved steady state.
- The degree of subcooling (DOS) has the range 1 to 19ºC.

CHAPTER 4
RESULTS AND DISCUSSION

A simple vapor compression refrigeration system is widely used for the refrigeration purpose world-wide. The sub-cooling of refrigerant increases the efficiency of the system [1]. The research studies reported various sub-cooling techniques of vapor compression system in which integrated vapor compression refrigeration technique is used by very few researchers as far as literature concerned. The present work presents performance improvement of an integrated vapor compression refrigeration system through sub-cooling. The present system consists two vapor compression cycles. One is the main and other is a VCR cycle for subcooling. The evaporator of cycle for subcooling provides sub-cooling to the main VCR cycle to enhance the performance of the VCR cycle. Refrigerants R152a and R134a have been considered.

4.1 Methodology

The present work represents performance improvement of an integrated VCR system through sub-cooling. It comprises a VCR system which has been integrated to a sub-cooler of another VCR cycle. The evaporator of sub-cooler cycle has been used as a sub-cooler of main VCR system. However, both the cycles have common condenser. R134a and R152a are refrigerant considered. An Engineering Equation Solver program has been developed to compute the various performance parameters i.e. COP and exergetic efficiency. The analysis of performance parameters have also been carried out varying the input parameters i.e. condenser temperature, evaporator temperature and degree of sub-cooling (DOS).

4.2 Model Validation

The current work investigates performance improvement of an integrated VCR system through sub-cooling and the comparison of performance of R134a and R152a. Model validation has been done with [1].

Table 4: Input data for the analysis of integrated VCR system **[1]**

S.No.	Input variables	Values
1.	Temperature of evaporator 1 (T_e)	-25^{0}C

2.	Net refrigerating effect ($\dot{Q}_e$)	3.5167 kW
3.	DOS (3-4)	5^0C
4.	Condenser temperature(T_c)	45^0C
5.	Isentropic efficiency of compressor ($\eta_{comp1}, \eta_{comp2}$)	80%
6.	Subcooler effectiveness (ε_{SC})	0.8
7.	Dead state or Ambient pressure (P_0) and temperature (T_0)	101.325 kPa & 25^0C

4.3 Impact of Degree of Sub-cooling

The effect of DOS on the performance parameters COP, % increase in COP and exergetic efficiency has been shown in Table 4.1 to 4.4 and Fig. 4.1 to 4.3.

Table 4.1: Variation in COP of the main cycle vs DOS for R134a and R152a

Sl. No.	**Degree of Sub-cooling (DOS) (ºC)**	**COP**	
		R134a	**R152a**
1	1^0C	1.193	2.07
2	3^0C	1.193	2.07
3	5^0C	1.193	2.07
4	7^0C	1.193	2.07
5	9^0C	1.193	2.07
6	11^0C	1.193	2.07
7	13^0C	1.193	2.07
8	15^0C	1.193	2.07
9	17^0C	1.193	2.07
10	19^0C	1.193	2.07

Table 4.2: Variation in overall COP of integrated VCRS vs DOS for R134a and R152a

Sl. No.	Degree of Sub-cooling (DOS) (^oC)	Overall COP	
		R134a	R152a
1	1	**2.094**	**2.213**
2	3	**2.134**	**2.244**
3	5	**2.174**	**2.276**
4	7	**2.214**	**2.307**
5	9	**2.253**	**2.338**
6	11	**2.293**	**2.37**
7	13	**2.333**	**2.401**
8	15	**2.372**	**2.432**
9	17	**2.411**	**2.464**
10	19	**2.451**	**2.495**

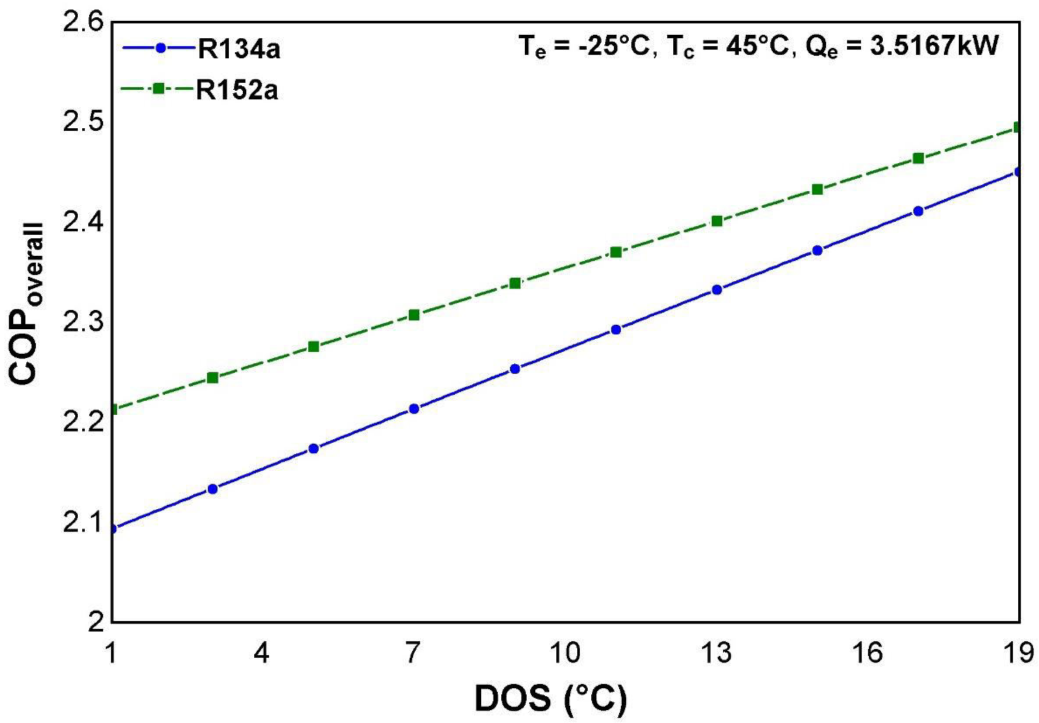

Figure 4.1 Effect of DOS on overall COP of the main VCR system

Table 4.2 and Figure 4.1 show the effect of DOS on overall COP of the main VCR cycle. The magnitude of overall COP increments with the increase in DOS. It is also noted that the magnitude of overall COP for R152a is more than that of R134a.

Table 4.3 Variation in % increase in COP of main VCR cycle vs DOS for R134a and R152a

Sl. No.	**Degree of Sub-cooling (DOS) (^oC)**	**% increment in COP**	
		R134a	**R152a**
1	1	**9.438**	**6.894**
2	3	**11.42**	**8.334**
3	5	**13.27**	**9.677**
4	7	**14.98**	**10.92**
5	9	**16.53**	**12.04**
6	11	**17.92**	**13.06**
7	13	**19.14**	**13.95**
8	15	**20.19**	**14.72**
9	17	**21.05**	**15.36**
10	19	**21.72**	**15.87**

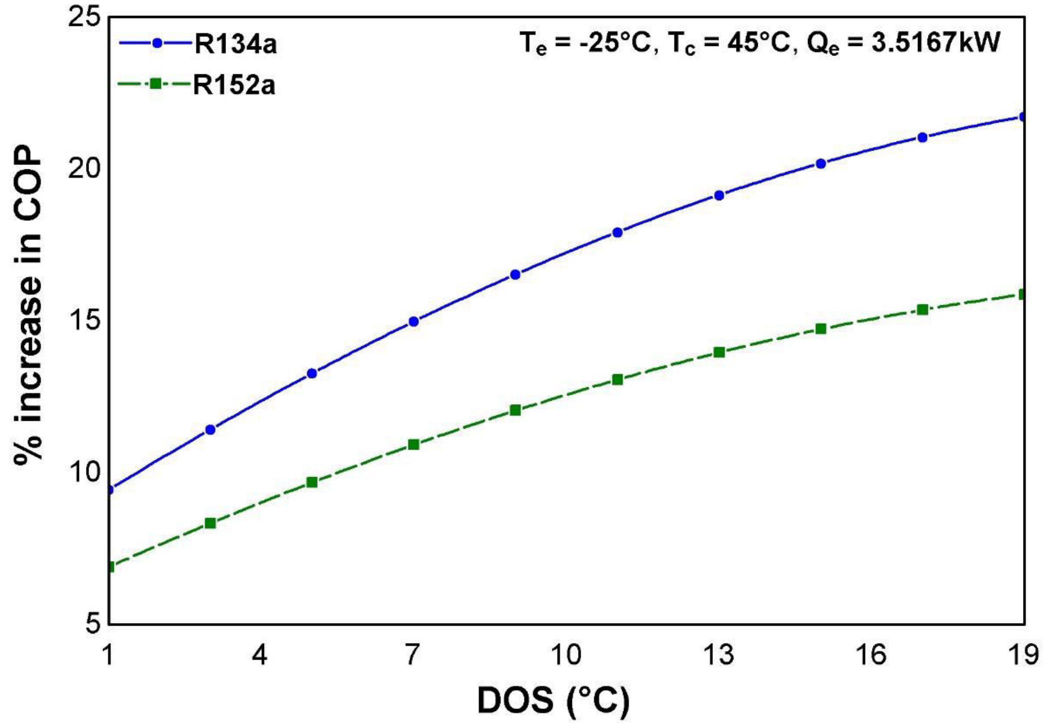

Figure 4.2 Effect of DOS on % increase in COP of the main VCR system

Table 4.3 and Figure 4.2 depict the effect of DOS on percentage increase in COP. The magnitude of % increase in COP increments with the increase in DOS. It has been noted that the magnitude of % increase in COP is more for R134a than that of R152a.

Table 4.4: Variation in exergetic efficiency of main VCR cycle vs DOS for R134a and R152a

Sl. No.	Degree of Sub-cooling (DOS) (^{o}C)	Exergetic efficiency ($\eta_{exergetic}$)	
		R134a	R152a
1	1	0.5284	0.5166
2	3	0.5267	0.5152
3	5	0.5246	0.5136
4	7	0.5222	0.5117
5	9	0.5194	0.5096
6	11	0.5163	0.5072

7	13	**0.5127**	**0.5046**
8	15	**0.5088**	**0.5016**
9	17	**0.5045**	**0.4983**
10	19	**0.4998**	**0.4947**

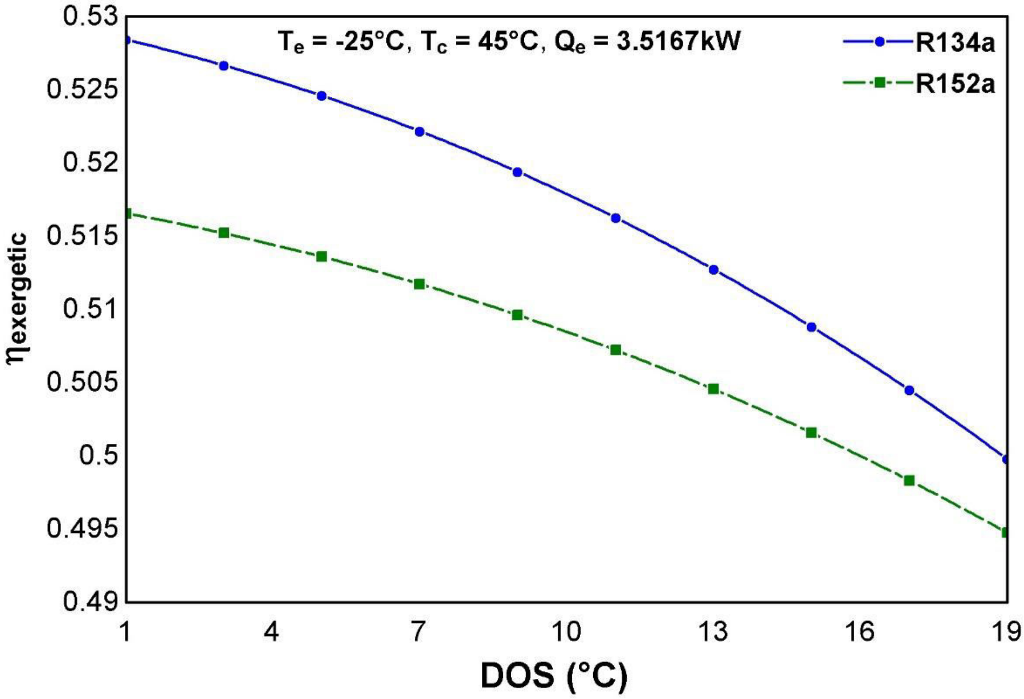

Figure 4.3 Exergetic efficiency ($\eta_{exergetic}$) vs Degree of sub-cooling (DOS)

Table 4.4 and Figure 4.3 predict the variation in exergetic efficiency of main system with DOS. The magnitude of exergetic efficiency decreases with increment in degree of sub-cooling. It has also been noted that the magnitude of exergetic efficiency is more for R134a than that of R152a.

4.4 Impact of temperature of Evaporator

The impact of temperature of evaporator on the performance parameters COP, % increase in COP and exergetic efficiency has been shown in Table 4.5 to 4.8 and Fig. 4.4 to 4.6.

Table 4.5: COP of the main system vs temperature of evaporator (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (^oC)	COP	
		R134a	R152a
1	-25	1.913	2.07
2	-20	2.165	2.327
3	-15	2.461	2.63
4	-10	2.814	2.989
5	-5	3.239	3.423
6	0	3.762	3.955

Table 4.6: Overall COP of the main system vs temperature of evaporator (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (^oC)	Overall COP	
		R134a	R152a
1	-25	2.174	2.276
2	-20	2.431	2.538
3	-15	2.734	2.846
4	-10	3.096	3.213
5	-5	3.534	3.657
6	0	4.074	4.203

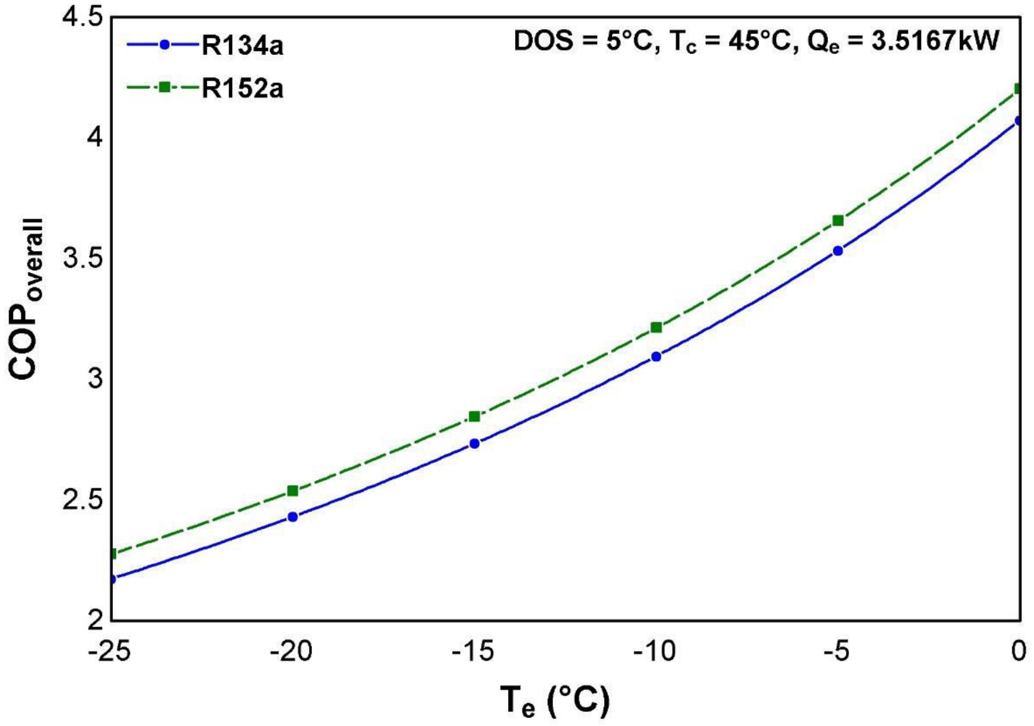

Figure 4.4 Impact of temperature of evaporator (T_e) on overall COP of main VCR system

Table 4.6 and Figure 4.4 represent variation in overall COP vs temperature of evaporator. The value of overall COP of main VCR cycle increments with increment in evaporator temperature. It has been noted that the magnitude of overall COP is more for R152a than that of R134a.

Table 4.7: Variation in percentage increase in COP of the main cycle vs evaporator temperature (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (^oC)	% increase in COP	
		R134a	R152a
1	-25	13.27	9.677
2	-20	11.89	8.742
3	-15	10.66	7.893

4	-10	9.547	7.124
5	-5	8.554	6.426
6	0	7.662	5.793

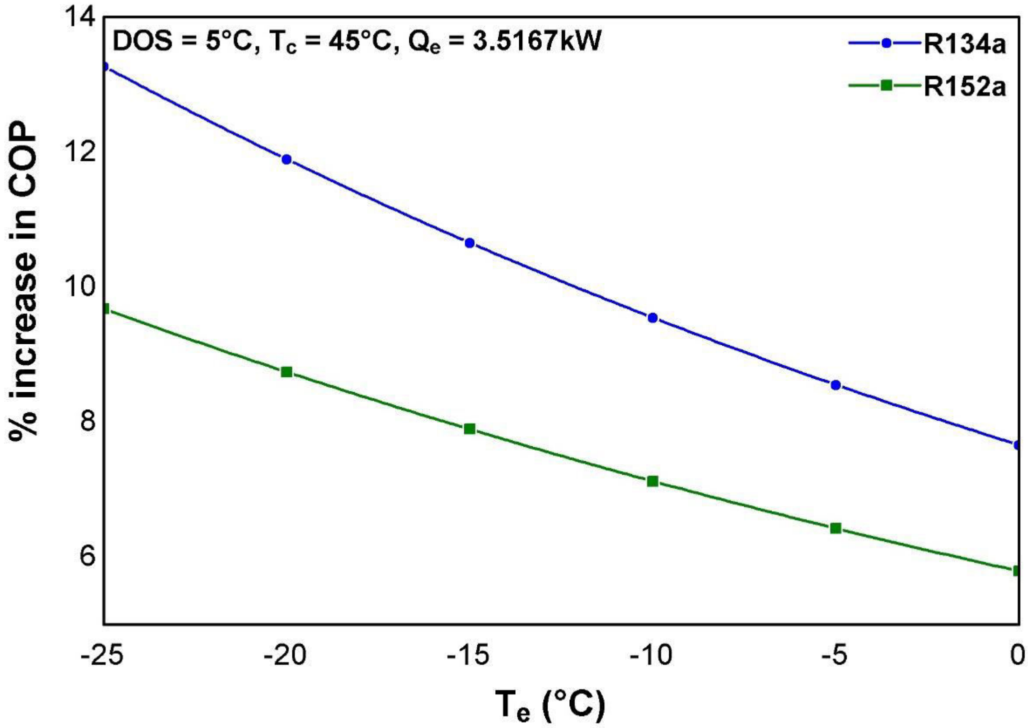

Figure 4.5 %increase in COP of the main VCR system vs temperature of evaporator (T_e)

Table 4.7 and Figure 4.5 predict the impact of temperature of evaporator (T_e) with increase in % increase in COP of the main VCR system. The magnitude of % increase in COP increments with increment in temperature of evaporator. It has also been noted that the magnitude of % increase in COP is more for R134a than that of R152a.

Table 4.8: Exergetic efficiency ($\eta_{exergetic}$) of the main VCR system vs temperature of evaporator (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (^oC)	Exergetic efficiency ($\eta_{exergetic}$)	
		R134a	R152a

1	-25	0.5246	0.5136
2	-20	0.5075	0.4967
3	-15	0.4868	0.476
4	-10	0.4614	0.4507
5	-5	0.4301	0.4193
6	0	0.3909	0.3799

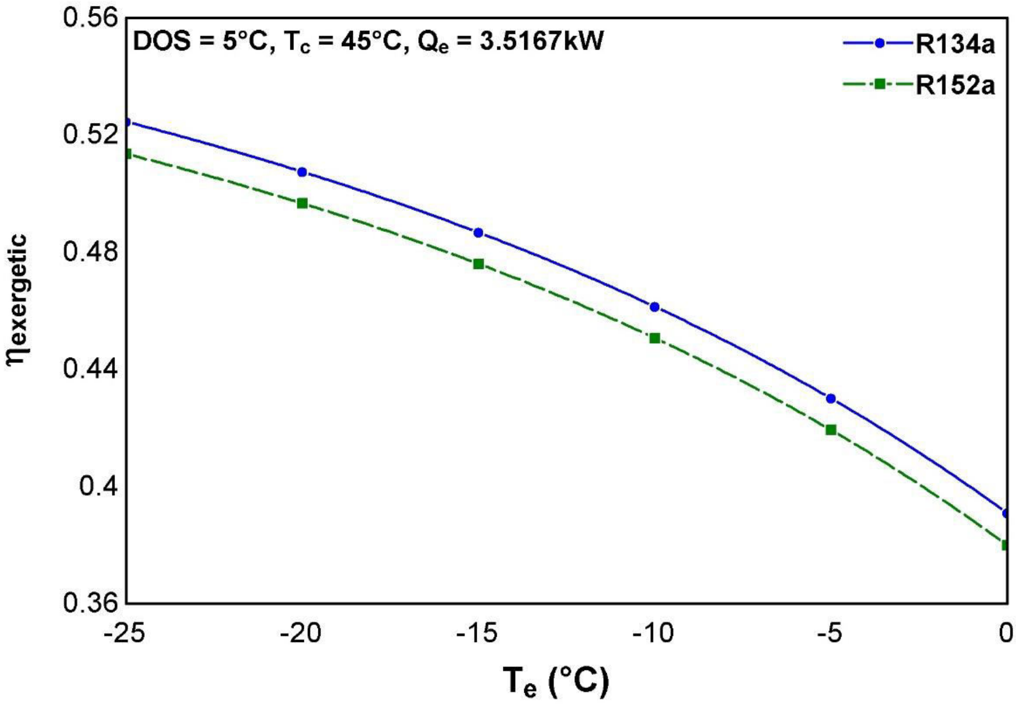

Figure 4.6 Temperature of evaporator (T_e) vs exergetic efficiency ($\eta_{exergetic}$) of main VCR system

Table 4.8 and Figure 4.6 show the impact of temperature of evaporator (T_e) on exergetic efficiency ($\eta_{exergetic}$). The magnitude of exergetic efficiency decreases with increment in temperature of evaporator (T_e). It has perceived that the magnitude of exergetic efficiency is more for R134a than that of R152a.

4.5 Impact of temperature of condenser

The impact of temperature of condenser on the performance parameters COP, % increase in COP and exergetic efficiency has been shown in Table 4.9 to 4.12 and Fig. 4.7 to 4.9.

Table 4.9: COP of the main system vs temperature of condenser (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (^oC)	COP	
		R134a	R152a
1	30	2.759	2.888
2	35	2.436	2.573
3	40	2.157	2.304
4	45	1.913	2.07
5	50	1.696	1.864

Table 4.10: Overall COP of the main system vs temperature of condenser (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (^oC)	Overall COP	
		R134a	R152a
1	30	3.001	3.081
2	35	2.682	2.769
3	40	2.41	2.504
4	45	2.174	2.276
5	50	1.967	2.076

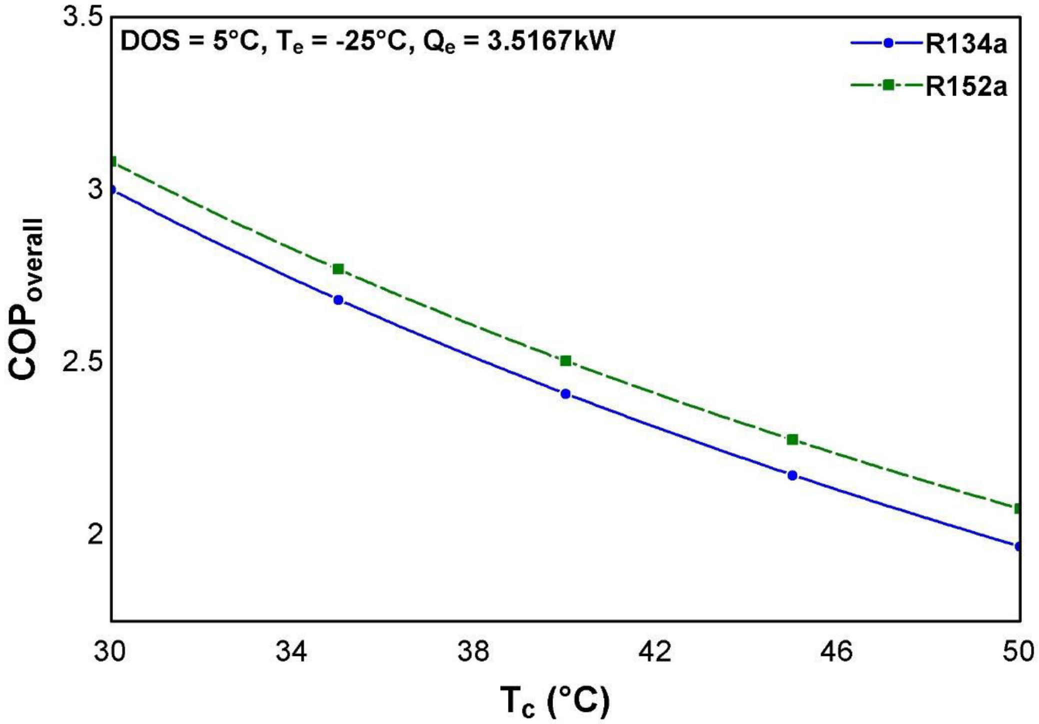

Figure 4.7 Overall COP of the main system vs temperature of condenser (T_c) for R134a and R152a

Table 4.10 and Figure 4.7 depict variation in overall COP with condenser temperature. The value of overall COP of main VCR cycle decreases with increment in temperature of condenser. It is perceived that the magnitude of overall COP is more for R152a than that of R134a.

Table 4.11: Variation in percentage increase in COP of the main cycle with condenser temperature (T_c) for R134a and R152a

Sl. No.	**Condenser Temperature (T_c) (°C)**	**% increase in COP**	
		R134a	**R152a**
1	30	8.33	6.364
2	35	9.708	7.317
3	40	11.34	8.394

4	45	13.27	9.677
5	50	15.59	11.12

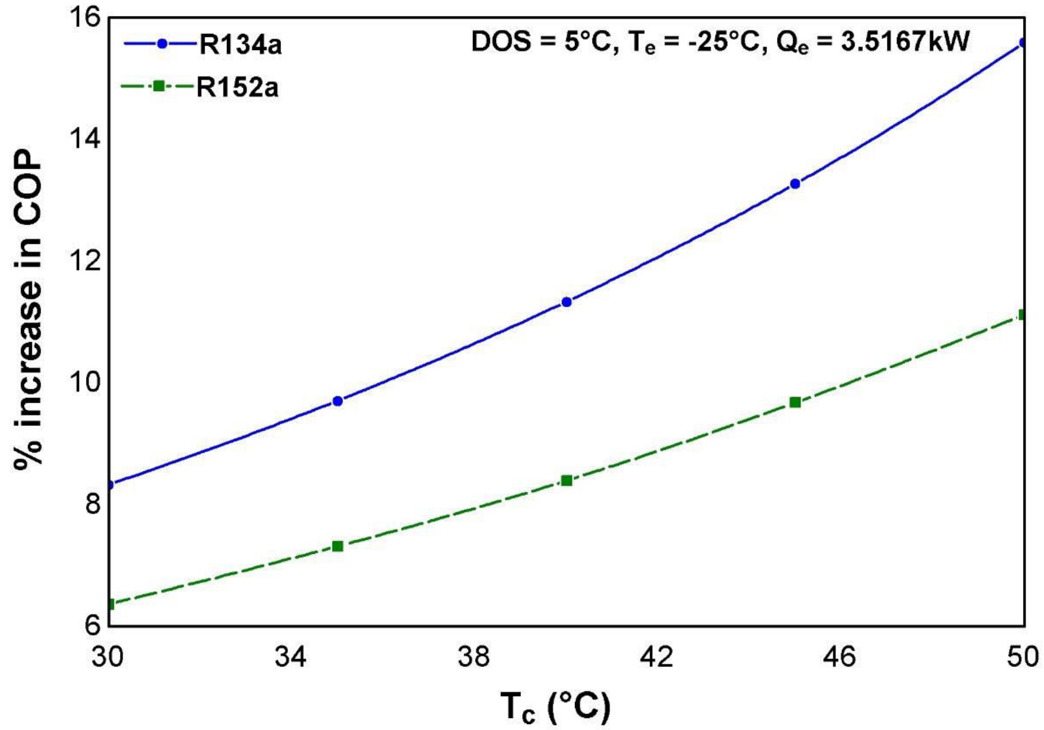

Figure 4.8 Temperature of evaporator vs % increase in COP of the main VCR system

Table 4.11 and Figure 4.8 illustrate the impact of temperature of condensser on % increase in COP of main VCR circuit. The magnitude of % increase in COP increases with increment in temperature of condenser. It has also been perceived that the magnitude of % increase in COP is more for R134a than that of R152a.

Table 4.12: Exergetic efficiency ($\eta_{exergetic}$) of the main VCR system vs temperature of condenser (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (^oC)	Exergetic efficiency ($\eta_{exergetic}$)	
		R134a	R152a

1	30	0.633	0.6271
2	35	0.5888	0.5814
3	40	0.5533	0.5442
4	45	0.5246	0.5136
5	50	0.5015	0.4884

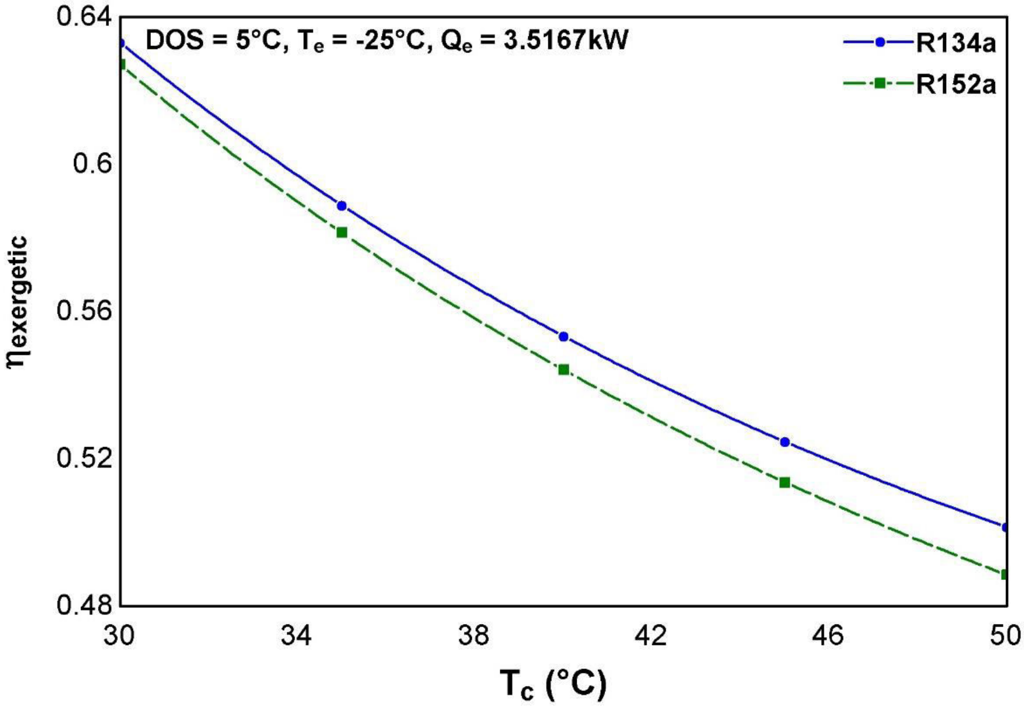

Figure 4.9 Exergetic efficiency ($\eta_{exergetic}$) of the main VCR system vs temperature of condenser (T_c) for R134a and R152a

Table 4.12 and Figure 4.9 show the impact of temperature of condenser (T_c) on exergetic efficiency ($\eta_{exergetic}$)**.** The magnitude of exergetic efficiency decreases with increase in condenser temperature. It has perceived that the value of exergetic efficiency ($\eta_{exergetic}$) is more for R134a than that of R152a.

CONCLUSIONS AND FUTURE SCOPE

In this work, the present work illustrate performance improvement of an integrated vapor compression refrigeration system through sub-cooling. The performance analysis of integrated VCR system has been carried out. An Engineering Equation Solver (EES) program has been prepared and used to compute the results of the analysis. The effect of input parameters i.e. subcooling degree (DOS), temperature of evaporator and temperature of condenser has been investigated on the performance parameters i.e. overall COP, percentage increase in COP and exergy efficiency. Following are the concluding remarks of the present analysis.

- The magnitude of overall COP of the integrated VCR system enhances with sub-cooling.
- The overall COP of the integrated VCR system is more than that of main VCR system.
- The percentage increase in COP is 9.438 to 21.7 for R134a and 6.894 to 15.87 for R152a.
- R152a performs better than that of R134a regarding COP of the system.
- R152a may be a substitute of R134a.

Future Scope:

- The exergy investigations of the integrated VCR system may be carried out.
- Cost investigations of integrated VCR system may be carried out.
- Exergy-economic investigations of integrated VCR system may be carried out.

REFERNCES

[1] Arora, A. and Kaushik, S.C., 2008. Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A. *International journal of refrigeration*, *31*(6), pp.998-1005.

[2] Hwang, S. and Jeong, J.H., 2020. The effects of the parameters of a refrigeration system working with R600a on the non-equilibrium subcooled two-phase flow of the refrigerant. *International Journal of Refrigeration*, *118*, pp.462-469.

[3] Bolaji, B.O., 2010. Experimental study of R152a and R32 to replace R134a in a domestic refrigerator. *Energy*, *35*(9), pp.3793-3798.

[4] Sánchez, D., Cabello, R., Llopis, R., Catalán-Gil, J. and Nebot-Andrés, L., 2018. Energy assessment of an R134a refrigeration plant upgraded to an indirect system using R152a and R1234ze (E) as refrigerants. *Applied Thermal Engineering*, *139*, pp.121-134.

[5] Brendel, L.P., Caskey, S.L., Ewert, M.K., Hengeveld, D., Braun, J.E. and Groll, E.A., 2020. Review of Vapor Compression Refrigeration in Microgravity Environments. *International Journal of Refrigeration*.

[6] Alavi, S., Cerri, G. and Chennaoui, L., 2019. Power regeneration upgrading of vapour compression refrigeration plants. *International Journal of Refrigeration*, *103*, pp.9-15.

[7] Dhumane, R., Ling, J., Aute, V. and Radermacher, R., Performance comparison of low GWP refrigerants for a miniature vapor compression system integrated with enhanced phase change material. *Applied Thermal Engineering*, *182*, p.116160.

[8] Zubair, S.M., 2000. Design and rating of an integrated mechanical-subcooling vapor-compression refrigeration system. *Energy Conversion and Management*, *41*(11), pp.1201-1222.

[9] Zubair, S.M., Yaqub, M. and Khan, S.H., 1996. Second-law-based thermodynamic analysis of two-stage and mechanical-subcooling refrigeration cycles. *International Journal of Refrigeration*, *19*(8), pp.506-516.

[10] Jiang, S., Wang, S., Jin, X. and Zhang, T., 2015. A general model for two-stage vapor compression heat pump systems. *International Journal of Refrigeration*, *51*, pp.88-102.

[11] Hu, H., Sun, H., Wu, C., Wang, X. and Lv, Z., 2020. A steady-state simulation model of supplemental cooling system integrated with vapor compression refrigeration cycles for commercial airplane. *Applied Thermal Engineering*, *166*, p.114692.

[12] Yu, B., Ouyang, H., Junye, S.H.I., Wuchan, L.I.U. and Jiangping, C.H.E.N., Evaluation of low-GWP and mildly flammable mixtures as new alternatives for R410A in air-conditioning and heat pump system. *International Journal of Refrigeration*, *121*, pp.95-104.

[13] Wen, Q., Zhi, R., Wu, Y., Lei, B., Liu, S. and Shen, L., 2020. Performance optimization of a heat pump integrated with a single-screw refrigeration compressor with liquid refrigerant injection. *Energy*, *207*, p.118197.

[14] Qureshi, B.A., Inam, M., Antar, M.A. and Zubair, S.M., 2013. Experimental energetic analysis of a vapor compression refrigeration system with dedicated mechanical sub-cooling. *Applied Energy*, *102*, pp.1035-1041.

[15] Koeln, J.P. and Alleyne, A.G., 2014. Optimal subcooling in vapor compression systems via extremum seeking control: Theory and experiments. *International journal of refrigeration*, *43*, pp.14-25.

[16] Ma, Z., Liu, F., Tian, C., Jia, L. and Wu, W., 2020. Experimental comparisons on a gas engine heat pump using R134a and low-GWP refrigerant R152a. *International Journal of Refrigeration*.

[17] Sánchez, D., Cabello, R., Llopis, R., Catalán-Gil, J. and Nebot-Andrés, L., 2019. Energy assessment and environmental impact analysis of an R134a/R744 cascade refrigeration plant upgraded with the low-GWP refrigerants R152a, R1234ze (E), propane (R290) and propylene (R1270). *International Journal of Refrigeration*, *104*, pp.321-334.

[18] Longo, G.A., Mancin, S., Righetti, G. and Zilio, C., 2019. Saturated vapour condensation of R134a inside a 4 mm ID horizontal smooth tube: Comparison with the low GWP substitutes R152a, R1234yf and R1234ze (E). *International Journal of Heat and Mass Transfer*, *133*, pp.461-473.

[19] Cabello, R., Sánchez, D., Llopis, R., Arauzo, I. and Torrella, E., 2015. Experimental comparison between R152a and R134a working in a refrigeration facility equipped with a hermetic compressor. *International Journal of Refrigeration*, *60*, pp.92-105.

[20] Klein, S. A., Alvarado, F., 2012. Engineering Equation Solver, *F Chart Software*, Middleton, WI. Version 9, 22.

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ABSTRACT

The current work presents the comparative investigations of R134a and R152a for the performance improvement of simple vapor compression refrigeration system through subcooling using an integrated subcool vapor compression cycle. The analysis investigates the impact of operating parameter viz temperature of condenser, degree of subcooling and temperature of evaporator on perforamcne parament viz exergy efficiency and COP. An Engineeering Equation Solver (EES) program has been prepared to compute the results of analysis. The results predicts that the subcooling enhances the COP of the vapor compression refrigeration system and R152a can be considered as substitute of R134a.

CHAPTER 1

INTRODUCTION

The energy requirements are increasing with the world-wide technological development. The prosperity of a country is evaluated by its energy production and development. India is a situated in tropical continent where the demand of energy increases in essentially in summer and Mansoon season due to increasing load of x air conditioning and refrigeration equipment. In order to accomplish increasing demand of electricity, improved air conditioning and refrigeration systems are required. In addition to energy efficient technologies of refrigeration and air conditioning systems, lower ozone depletion potential (ODP) and lower global warming potential (GWP) HFC refrigerants are required.

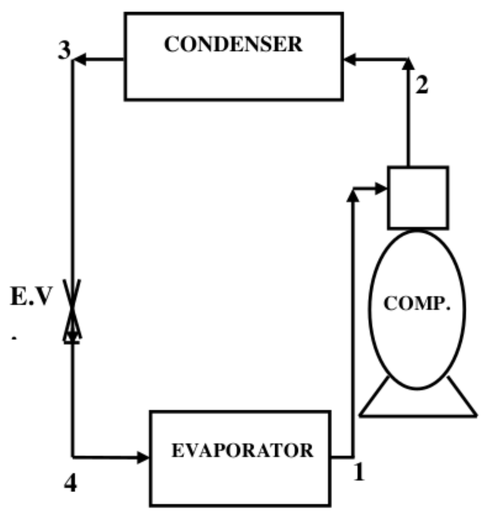

Figure 1.1: Block diagram of simple VCR system

Figure 1.1 & 1.2 show the simple vapor compression refrigeration system. The state points are shown at entry and exit of each system components. The system components are a compressor, a condenser, an expansion valve and an evaporator. The low temperature and low pressure vapor refrigerant at state point 1 which comes out from evaporator enters into the compressor and high pressure and high temperature vapor refrigerant enters into the condenser at state point 2. High pressure high temperature liquid refrigerant at state point 3 which comes out from the condenser and then enters into the expansion valve. After expansion the low temperature and pressure vapor refrigerant which comes out of the expansion valve at state point 4 enters into the evaporator and refrigeration effects produces in the evaporator.

The sub-cooling after the state point 3 increases the net refrigeration effect and hence increases the COP of the vapor compression system.

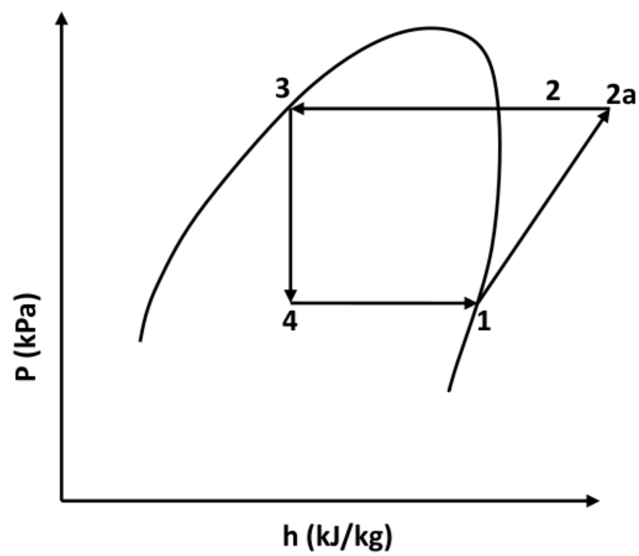

Figure 1.2: Pressure (P)-Enthalpy (h) chart of simple VCR cycle

The subcooling techniques includes liquid vapor heat exchange, dedicated meechanical subcooling, Integrated subcooling and ejector cooling etc. These technologies increases the net refrigeration effect of simple VCR cycle and hence COP of the simple VCR cycle increases.

The vast literature is available on the subcooling of simple VCR system using different technologies. Out of these, integrated subcooling is rarely used by researchers. Integrated subcooling to the simple VCR cycle increases the net refrigeration effect produced in the evaporator of the main VCR cycle consequently, the COP of the main VCR cycle enhances.

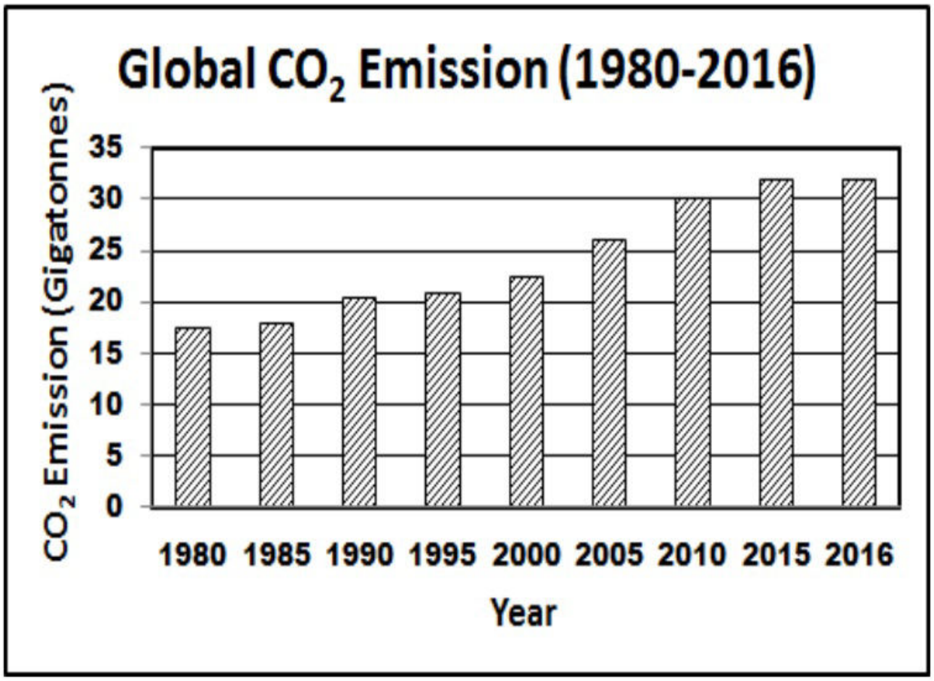

Figure 1.3 Carbon dioxide emission from fossil fuels world-wide (Source: www.earthpolicy.org)

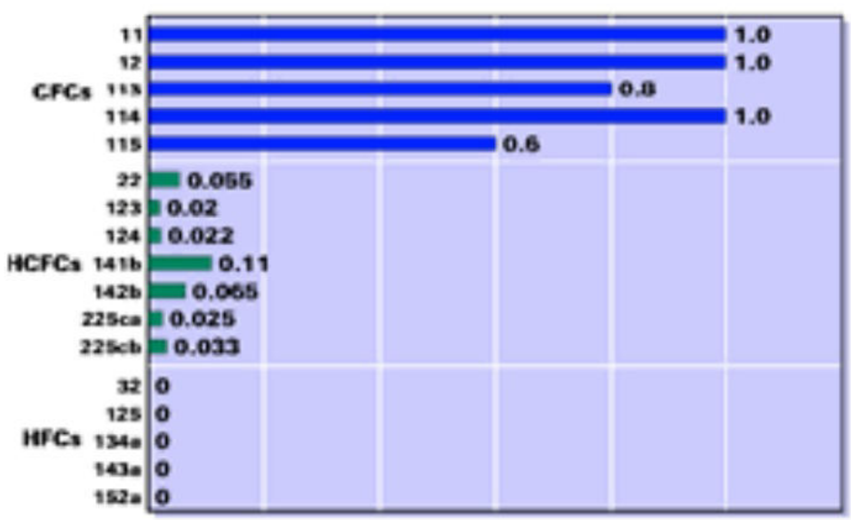

Figure 1.4 Comparison of Ozone Depletion Potential (ODP) of various refrigerants (Source: https://www.enggcyclopedia.com/2012/01/types-refrigerants/)

Table 1.1: Thermodynamic properties of R134a and R152a (Source: www.intarcon.com/fr/refrigerante-r152a/)

S. No.	Thermodynamic Properties	R152a	R134a
1.	ASHARE safety class	A2	A1
2.	Auto ignition temperature	454°C	----
3.	Molecular weight (g/mol)	66	102
4.	Combustion heat (kJ/mol)	1090	428
5.	Boiling Point at standard pressure	-24.0°C	-26.1°C
6.	Lower flammability limit (% Vol)	4%	---
7.	Latent heat of vaporization at -10°C, kJ/kg	307	199
8.	Volumetric cooling capacity, kJ/m^3	1283	1293
9.	GWP (IPCC AR4)	124	1430

Table 1.1 illustrates the different thermodynamic properties of R134a and R152a. The heat (latent) of vaporization of R152a is more than that of R134a and The GWP of R152a is much lesser than that of R134a. The B.P. of R152a is lower than R134a. These properties are considerable to use R152a in place of R134a.

CHAPTER 2

LITERATURE REVIEW AND RESEARCH GAP

The energy requirements are increasing with world-wide technological development. The prosperity of a country is evaluated by its energy production and development.

Arora and S. C. Kaushik [1] had presented a described exergy analysis of an actual vapor-compression refrigeration cycle. They compared the performance of refrigerants R502, 404A, and R507A. Observation had been made by them that the R507A perform better than R404A for the replacement of R502.

Hwang and Jeong [2] observed the effects of the parameters of a refrigeration system working with R600a on the non-equilibrium subcooled two-phase flow of the refrigerant. They experimented to investigate the effects of the operating conditions of the refrigeration system on the contents of the non-equilibrium vapor phase of R600a. They found that the void fraction was changed by the system parameters in addition to the pressure and temperature.

Bolaji [3] carried out an experimental study of R152a and R32 to replace R134a in a domestic refrigerator. He compared the performance of R152a and R32 with the R134a. He observed that for refrigerant R152a and R134a pull-down time and design temperature set by International Standard Organization (ISO) for a refrigerator (small) were achieved than using R32. The average coefficient of performance (COP) obtained for R134a was 4.7% lower than that of R152a while the average COP of R152a was 8.5% more than that of R32. For R152a, the energy consumed by the system is less. He added that for all operating conditions, the performance of R152a was better than those of R134a and R32in the domestic refrigerator. Hence, in a domestic refrigerator, R152a can be used as a replacement for R134a.

Sánchez et al. [4] conducted an energy assessment of an indirect refrigeration plant of R134a using R152a and R1234ze(E) as refrigerants. They used refrigerants R134a in direct and R152a and R1234ze(E) in the indirect system respectively. They concluded that the increase (average) was 18.7% for R152a, 27.2% for R1234ze(E) and 21.8% for R134a. They added that for the different refrigerants used, the refrigerant mass charge was reduced by the adoption of an indirect system up to 62%.

Brendel et al. [5] reviewed vapor compression refrigeration (VCR) in microgravity environments. They provided a revision of existing literature for vapor compression systems (VCS) operated in microgravity by outlining the history of vapor compression devices in space and presenting performance data. Moreover, gaps in the literature have been highlighted and open questions are posed based on the reviewed material. The next steps of research are suggested to support and ultimately achieve reliable vapor compression refrigeration (VCR) in space. Calculating equivalent masses for a fair comparison of various microgravity cooling technologies is suggested by capturing both energy consumption and used volume.

Alavi et al. [6] presented techniques of power regeneration in the VCR plant for upgrading already existing plants, main compressor, evaporator, condenser, and main expansion valve are assigned for the characterization of each plant. They observed that for a given main screw compressor the COP and cooling power improved up to 80% and 100% respectively. They added that for constant cooling power plants, main compressor delivery was reduced to 50%, and COP increasing up to 70%.

Humane et al. [7] carried out a comparison of the performance of low GWP refrigerants for a miniature vapor compression system (VCS) integrated with enhanced phase change material. They have compared the performance of R1234ze(E), R1234yf, and R32and R290. They concluded that compared to R134a, The reduction in system charge with R32, R1234ze (E), R290, and R1234yf was 1%, 30%, 52%, and 11% respectively. The change in COP was +8%, -3%, − 5% and − 12%, with R32,R290, R1234yf and R1234ze (E), respectively. The revolutions per minute (RPMs) of the compressor were 1700, 2900, 2400, 900, and 2100 were R90, R1234ze (E), R1234yf, R32, and R134arespectively.

Khan and Zubair [8] worked on the design and rating of an integrated mechanical-sub-cooling vapor-compression refrigeration system. They developed thermodynamic models of an integrated mechanical sub-cooling system to simulate the actual performance of the sub-cooling system. They predicted that the performance of the integrated vapor compression refrigeration cycle was better than that of the simple cycle using mechanical sub-cooling.

Zubair and Khan [9] carried out first and second-law-based thermodynamic analysis of two-stage and mechanical-sub-cooling refrigeration cycles. They analyzed each system component for their irreversibility losses. They compared theoretical results of a two-stage refrigeration system performance with experimental values for a CFC-22 system.

Jiang et al. [10] investigated a general model for two-stage vapor compression heat pump systems. They have also investigated eight different inter-stage configurations based on this model. They concluded that the general model was capable of performing performance analysis and comparison among different types of cycles, as well as the refrigerant selection and operational analysis.

Haitao Hu et al. [11] carried out research paper presentation of the cooling system through supplement integrated with VĆR cycles for commercial aircraft model has been proposed. Validated experiments with deviated cooling capacity had been also presented by them.

Binbin Yu et al. [12] provided the replacement of R410A for the reduction of low GWP in the environment. They had provided option many more for low flammable through various mixtures of coolants for the achievement of the same required vapor pressure. They had also investigated that the blends of refrigerants applied in both air-conditioning and heat-pump that could be equivalent to the properties of R410A. They found four mixtures as coolants R410A having the same properties as vapor pressure.

Qiangyu Wen et al. [13] carried out the theoretical method for enhancing the refrigerating capacity with the help of injection for the reduction of the energy stored in the exhaust temperature of SSRC. They provided an accurate method to calculate varied injection area. In addition to that, they also provide a mathematical model that described the internal working process in the single screw refrigeration compressor along with the effect of the liquid refrigerant injection.

B. Prasanna Nagasai et al. [14] they had presented an experimental investigation into the efficiency of an integrated sub-cooling VCR device by adding a counter-flow tube between compressor and condenser in a tube heat exchanger. The COP (performance coefficient increased with condenser subcooling due to the tradeoff between reducing compressor function and increasing cooling effect. To find the superlative increase in COP with condenser sub cooling, thermodynamic properties related to refrigerant effects such as latent vaporization heat and liquid specific heat were used to detect the superlative increase in COP with condenser subcooling.

Justin P. Koeln and Andrew G. Alleyne [15] showed that substantial efforts have been made to establish control strategies aimed at optimizing system performance while providing the desired cooling, with vapor compression systems consuming a large portion of the total U.S. energy consumption per year. Previous control methods, however, underutilize a degree of freedom relating to the amount of refrigerant in the device that is correlated with subcooling the condenser which can have a major effect on system performance. An alternative system architecture that uses a receiver and an external electronic expansion valve is used in this paper to provide independent control of the subcooling of condensers. Simulation and experimental findings indicate that there is an optimal subcooling that maximizes the performance of the system; but with operating conditions, this optimal subcooling shifts.

The literature was collected from various sources i.e. Science Direct, Google School and SCI Hub, etc., there is a large number of research papers available on vapor compression refrigeration systems. Some research papers are on sub-cooling are also found. However, very little research work has been carried out on integrated vapor compression refrigeration systems having R134a and R152a.

CHAPTER 3

DESCRIPTION AND MODELLING OF SYSTEM

A simple vapor compression refrigeration system is widely used for the air-conditioning and refrigeration purpose world-wide. The sub-cooling of refrigerant increases the efficiency of the system [1]. The research studies reported various sub-cooling techniques of vapor compression system in which integrated vapor compression refrigeration technique is used by very few researchers as far as literature concerned. The present work presents performance improvement analysis of an integrated vapor compression refrigeration system through sub-cooling. The present system consists two vapor compression cycles. One is the main VCR cycle and other is a simple VCR cycle whose evaporator acts as sub-cooler. The evaporator of other cycle provides sub-cooling to the main VCR cycle to enhance the performance of the main VCR cycle. R152a and R134a are the refrigerants considered.

3.1 Description of System

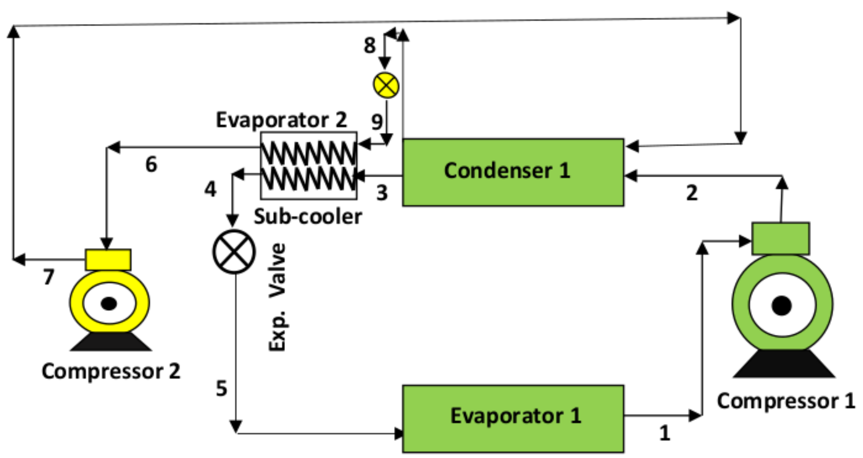

Figure 1 Block diagram of integrated vapor compression refrigeration (VCR) system

Figure 1 shows the block diagram of integrated VCR system, It consists of two VCR cycles. The main VCR cycle is in lower evaporator temperature circuit and the other vapor compression refrigeration cycle is designated as cycle for subcooling is in higher evaporator temperature circuit. The two refrigeration cycles are integrated to each other by a subcooler. The subcooler is the evaporator of the other cycle for subcooling. The refrigerants considered in the cycles are R134a and R152a. The main VCR cycle and the other cycle with subcooler are having same refrigerant at a time during the operation.

The main VCR cycle comprises of, a compressor, a condenser, an evaporator and an expansion valve and the sub-cooler cycle consists of an expansion valve, a compressor and an evaporator designated as sub-cooler. The condenser of both the cycles is common.

The sub-cooler sub-cools the liquid refrigerant which comes out the condenser of the main VCR system. The sub-cooler couples the two cycles such that the heat removed by the liquid refrigerant condensate of the main VCR system is absorbed by the vapor refrigerant of the sub-cooler VCR cycle. No external heat rejection is considered in the sub-cooler.

The refrigerant vapor which comes out from the evaporator 1 of the main VCR system goes into the compressor 1 at point of state 1. The high temperature and high pressure refrigerant vapor goes into the condenser 1 at point of state 2 after compression. The vapor refrigerant changes into the liquid refrigerant in the condenser 1. The condensate vapor of the main cycle leaving the condenser 1 and enters into the sub-cooler at point of state 3. The condensate vapor of the main VCR cycle is subcooled by the sub-cooler which increase the net refrigeration effect of the main VCR cycle.

The evaporator 2 of the sub-cooler cycle is also a sub-cooler. The liquid-vapor refrigerant receives heat from the liquid condensate of the main VCR cycle in the sub-cooler from point of state 9 to 6. The compressor 2 compresses the refrigerant vapor from point of state 6 to 7. The high temperature and high pressure refrigerant vapor is condensed by the condenser of the main cycle from point of state 2 to 3.

The liquid refrigerant leaving the condenser is expanded from point of state 4 to 5 & 8 to 9 by expansion valves of the main and sub-cooler cycle respectively. Finally, the refrigerant vapor after expansion enters into the sub-cooler. In this way, the use of a sub-cooler enhances the COP of the main VCR cycle.

3.2 Modelling of System

Thermodynamic analysis of expander incorporated vapor compression refrigeration cycle has been carried out in the current presentation. Steady state governing equations have been formed using the laws of thermodynamics i.e. first and second laws. Energy, work and mass balances have been carried out for each component of the system. An EES (Energy Equation Solver) software bases program has been developed to solve the governing equation used in the analysis.

The COP of the integrated VCR system is given by the equation (1):

$$COP_{overall} = \frac{\dot{Q}_e}{\dot{W}_{comp1}+\dot{W}_{comp2}} \quad (1)$$

Where $\dot{Q}_e$ is the net refrigeration load of the evaporator 1 in kJ/s and $\dot{W}_{comp1}$and $\dot{W}_{comp2}$ are the net compressor work of compressor 1 and 2 in kJ/s.

The The COP of the main VCR system is given by equation (2):

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp1}} \quad (2)$$

The exergetic efficiency of the integrated VCR system is given by the equation (3):

$$\eta_{ex} = COP * \left|\left(1 - \frac{T_0}{T_e}\right)\right| \quad (3)$$

Where T_o is the temperature (ambient) and T_e is the evaporator 1 temperature in K.

The energy balance in the sub-cooler (evaporator 2) is given by equation (4).

$$\dot{m}_{r,m}\ (h_3 - h_4) = \dot{m}_{r,sc}\ (h_6 - h_9) \quad (4)$$

Where $\dot{m}_{r,m}$ and $\dot{m}_{r,sc}$ are the flow rate of mass of refrigerant flowing in main and sub-cooler vapor refrigeration cycle in kg/s.

3.3 Assumptions

The following assumptions have been assumed for the thermodynamic analysis and performance improvement of an integrated VCR system through sub-cooling [1].

- The evaportor temperature of main vapor compression refrigeration system has range of variation -25°C to 0°C.
- Dry and saturated refrigerant vapor has been assumed at the entry of compressor at point of state 1 and 6.
- The condenser temperature has range of variation 30°C to 50°C.
- It is assumed that each component of the integrated VCR system has achieved steady state.
- The degree of subcooling (DOS) has the range 1 to 19°C.

CHAPTER 4

RESULTS AND DISCUSSION

A simple vapor compression refrigeration system is widely used for the refrigeration purpose world-wide. The sub-cooling of refrigerant increases the efficiency of the system [1]. The research studies reported various sub-cooling techniques of vapor compression system in which integrated vapor compression refrigeration technique is used by very few researchers as far as literature concerned. The present work presents performance improvement of an integrated vapor compression refrigeration system through sub-cooling. The present system consists two vapor compression cycles. One is the main and other is a VCR cycle for subcooling. The evaporator of cycle for subcooling provides sub-cooling to the main VCR cycle to enhance the performance of the VCR cycle. Refrigerants R152a and R134a have been considered.

4.1 Methodology

The present work represents performance improvement of an integrated VCR system through sub-cooling. It comprises a VCR system which has been integrated to a sub-cooler of another VCR cycle. The evaporator of sub-cooler cycle has been used as a sub-cooler of main VCR system. However, both the cycles have common condenser. R134a and R152a are refrigerant considered. An Engineering Equation Solver program has been developed to compute the various performance parameters i.e. COP and exergetic efficiency. The analysis of performance parameters have also been carried out varying the input parameters i.e. condenser temperature, evaporator temperature and degree of sub-cooling (DOS).

4.2 Model Validation

The current work investigates performance improvement of an integrated VCR system through sub-cooling and the comparison of performance of R134a and R152a. Model validation has been done with [1].

Table 4 Input data for the analysis of integrated VCR system **[1]**

S.No.	Input variables	Values
1.	Temperature of evaporator 1 (T_e)	-25^0C

2.	Net refrigerating effect ($\dot{Q}_e$)	3.5167 kW
3.	DOS (3-4)	5^0C
4.	Condenser temperature(T_c)	45^0C
5.	Isentropic efficiency of compressor ($\eta_{comp1}, \eta_{comp2}$)	80%
6.	Subcooler effectiveness (ε_{SC})	0.8
7.	Dead state or Ambient pressure (P_0) and temperature (T_0)	101.325 kPa & 25^0C

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4.3 Impact of Degree of Sub-cooling

The effect of DOS on the performance parameters COP, % increase in COP and exergetic efficiency has been shown in Table 4.1 to 4.4 and Fig. 4.1 to 4.3.

Table 4.1: Variation in COP of the main cycle vs DOS for R134a and R152a

Sl. No.	Degree of Sub-cooling (DOS) (^{o}C)	COP	
		R134a	**R152a**
1	1^0C	1.193	2.07
2	3^0C	1.193	2.07
3	5^0C	1.193	2.07
4	7^0C	1.193	2.07
5	9^0C	1.193	2.07
6	11^0C	1.193	2.07
7	13^0C	1.193	2.07
8	15^0C	1.193	2.07
9	17^0C	1.193	2.07
10	19^0C	1.193	2.07

Table 4.2 Variation in overall COP of integrated VCRS vs DOS for R134a and R152a

Sl. No.	Degree of Sub-cooling (DOS) (°C)	Overall COP	
		R134a	R152a
1	1	**2.094**	**2.213**
2	3	**2.134**	**2.244**
3	5	**2.174**	**2.276**
4	7	**2.214**	**2.307**
5	9	**2.253**	**2.338**
6	11	**2.293**	**2.37**
7	13	**2.333**	**2.401**
8	15	**2.372**	**2.432**
9	17	**2.411**	**2.464**
10	19	**2.451**	**2.495**

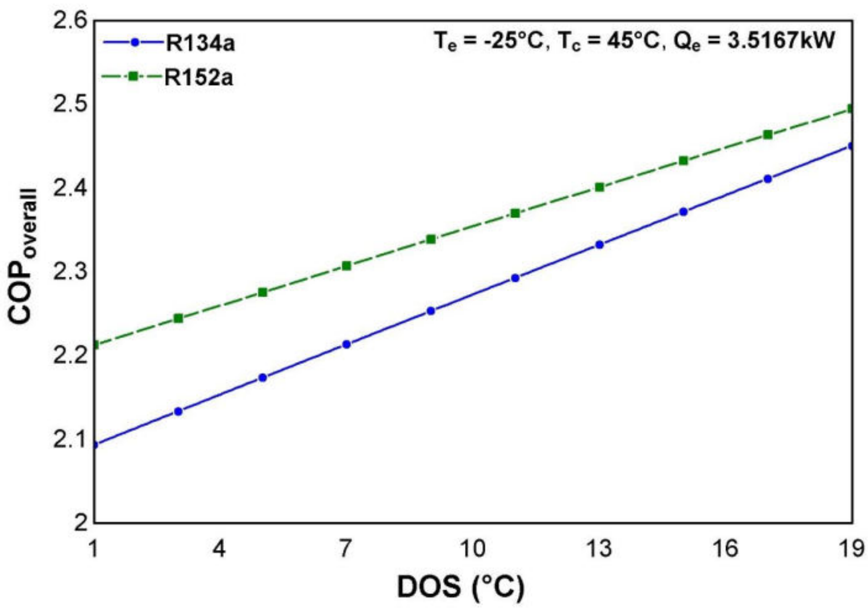

Figure 4.1 Effect of DOS on overall COP of the main VCR system

Table 4.2 and Figure 4.1 show the effect of DOS on overall COP of the main VCR cycle. The magnitude of overall COP increments with the increase in DOS. It is also noted that the magnitude of overall COP for R152a is more than that of R134a.

Table 4.3 Variation in % increase in COP of main VCR cycle vs DOS for R134a and R152a

Sl. No.	Degree of Sub-cooling (DOS) (°C)	% increment in COP	
		R134a	R152a
1	1	9.438	6.894
2	3	11.42	8.334
3	5	13.27	9.677
4	7	14.98	10.92
5	9	16.53	12.04
6	11	17.92	13.06
7	13	19.14	13.95
8	15	20.19	14.72
9	17	21.05	15.36
10	19	21.72	15.87

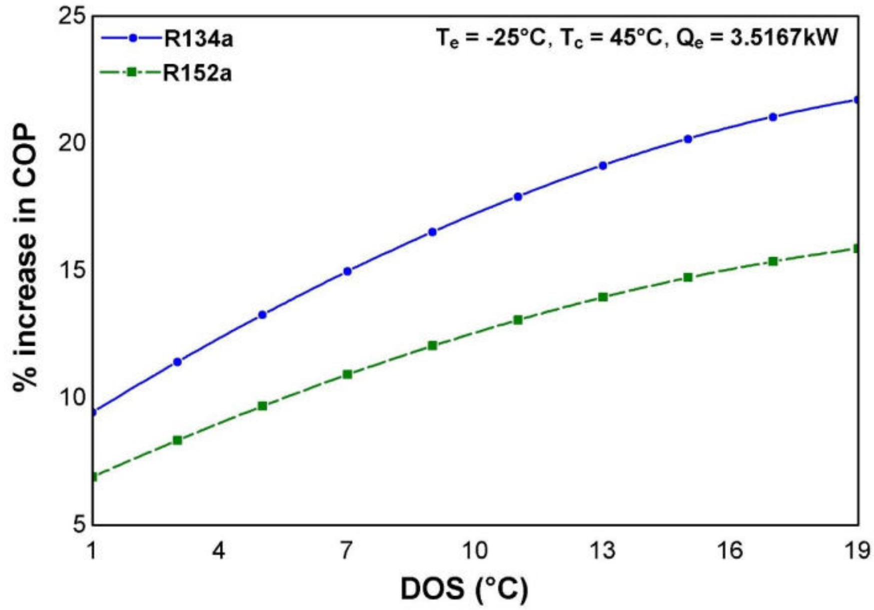

Figure 4.2 Effect of DOS on % increase in COP of the main VCR system

Table 4.3 and Figure 4.2 depict the effect of DOS on percentage increase in COP. The magnitude of % increase in COP increments with the increase in DOS. It has been noted that the magnitude of % increase in COP is more for R134a than that of R152a.

Table 4.4 Variation in exergetic efficiency of main VCR cycle vs DOS for R134a and R152a

Sl. No.	**Degree of Sub-cooling (DOS) (°C)**	**Exergetic efficiency ($\eta_{exergetic}$)**	
		R134a	**R152a**
1	1	**0.5284**	**0.5166**
2	3	**0.5267**	**0.5152**
3	5	**0.5246**	**0.5136**
4	7	**0.5222**	**0.5117**
5	9	**0.5194**	**0.5096**
6	11	**0.5163**	**0.5072**

7	13	**0.5127**	**0.5046**
8	15	**0.5088**	**0.5016**
9	17	**0.5045**	**0.4983**
10	19	**0.4998**	**0.4947**

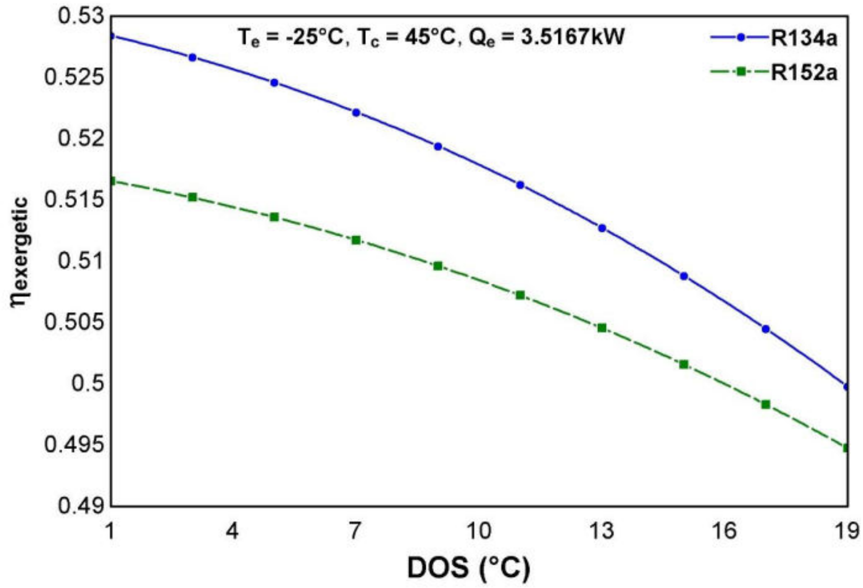

Figure 4.3 Exergetic efficiency ($\eta_{exergetic}$) vs Degree of sub-cooling (DOS)

Table 4.4 and Figure 4.3 predict the variation in exergetic efficiency of main system with DOS. The magnitude of exergetic efficiency decreases with increment in degree of sub-cooling. It has also been noted that the magnitude of exergetic efficiency is more for R134a than that of R152a.

4.4 Impact of temperature of Evaporator

The impact of temperature of evaporator on the performance parameters COP, % increase in COP and exergetic efficiency has been shown in Table 4.5 to 4.8 and Fig. 4.4 to 4.6.

Table 4.5: COP of the main system vs temperature of evaporator (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (°C)	COP	
		R134a	R152a
1	-25	1.913	2.07
2	-20	2.165	2.327
3	-15	2.461	2.63
4	-10	2.814	2.989
5	-5	3.239	3.423
6	0	3.762	3.955

Table 4.6: Overall COP of the main system vs temperature of evaporator (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (°C)	Overall COP	
		R134a	R152a
1	-25	2.174	2.276
2	-20	2.431	2.538
3	-15	2.734	2.846
4	-10	3.096	3.213
5	-5	3.534	3.657
6	0	4.074	4.203

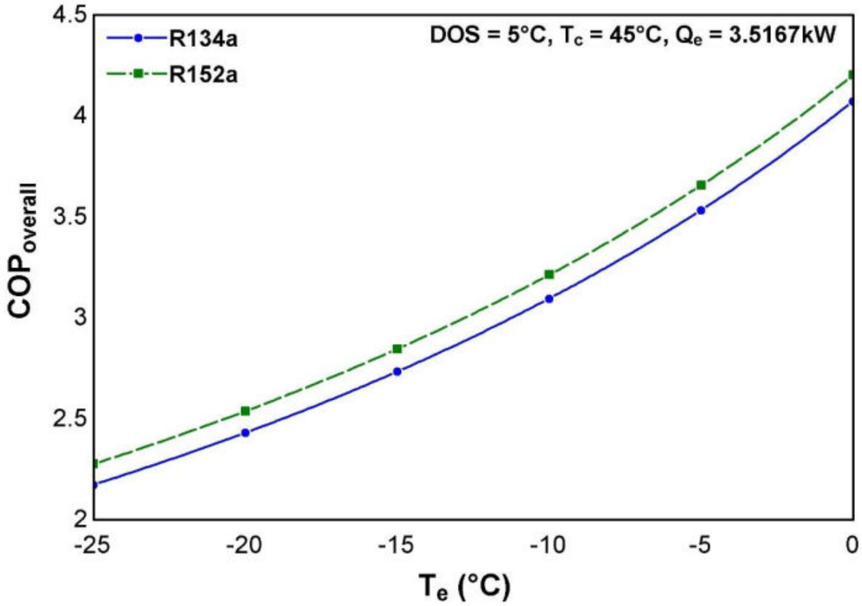

Figure 4.4 Impact of temperature of evaporator (T_e) on overall COP of main VCR system

Table 4.6 and Figure 4.4 represent variation in overall COP vs temperature of evaporator. The value of overall COP of main VCR cycle increments with increment in evaporator temperature. It has been noted that the magnitude of overall COP is more for R152a than that of R134a.

Table 4.7: Variation in percentage increase in COP of the main cycle vs evaporator temperature (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (°C)	% increase in COP	
		R134a	R152a
1	-25	13.27	9.677
2	-20	11.89	8.742
3	-15	10.66	7.893

4	-10	9.547	7.124
5	-5	8.554	6.426
6	0	7.662	5.793

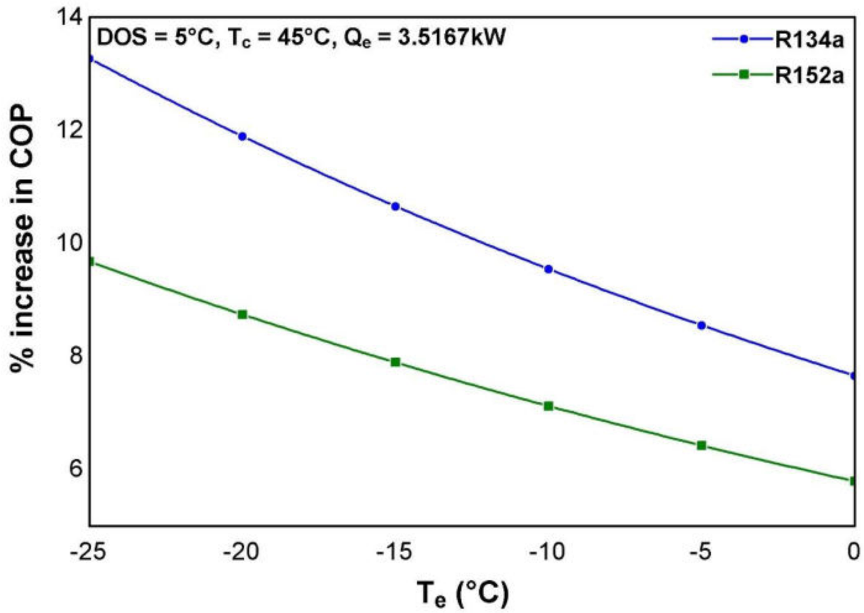

Figure 4.5 %increase in COP of the main VCR system vs temperature of evaporator (T_e)

Table 4.7 and Figure 4.5 predict the impact of temperature of evaporator (T_e) with increase in % increase in COP of the main VCR system. The magnitude of % increase in COP increments with increment in temperature of evaporator. It has also been noted that the magnitude of % increase in COP is more for R134a than that of R152a.

Table 4.8: Exergetic efficiency ($\eta_{exergetic}$) of the main VCR system vs temperature of evaporator (T_e) for R134a and R152a

Sl. No.	Evaporator Temperature (T_e) (°C)	Exergetic efficiency ($\eta_{exergetic}$)	
		R134a	R152a
1	-25	0.5246	0.5136

2	-20	0.5075	0.4967
3	-15	0.4868	0.476
4	-10	0.4614	0.4507
5	-5	0.4301	0.4193
6	0	0.3909	0.3799

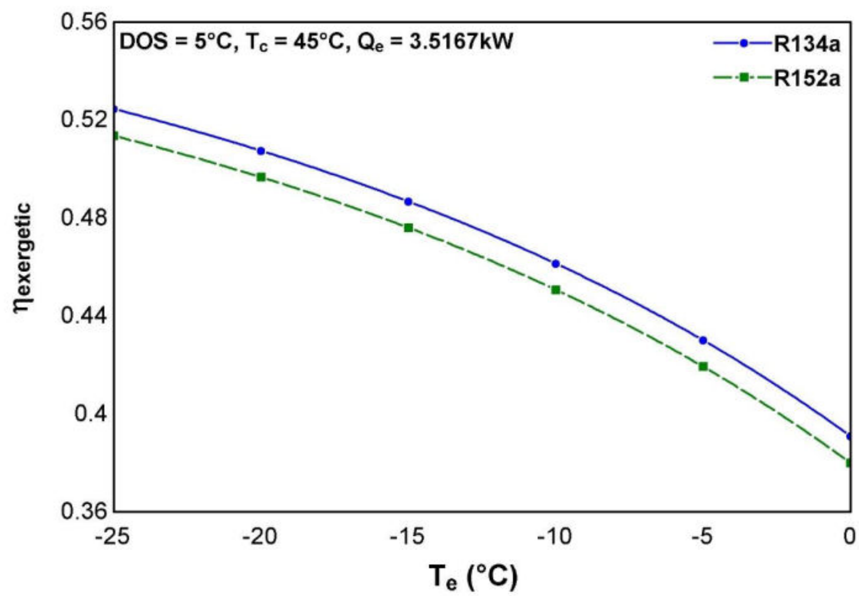

Figure 4.6 Temperature of evaporator (T_e) vs exergetic efficiency ($\eta_{exergetic}$) of main VCR system

Table 4.8 and Figure 4.6 show the impact of temperature of evaporator (T_e) on exergetic efficiency ($\eta_{exergetic}$). The magnitude of exergetic efficiency decreases with increment in temperature of evaporator (T_e). It has perceived that the magnitude of exergetic efficiency is more for R134a than that of R152a.

4.5 Impact of temperature of condenser

The impact of temperature of condenser on the performance parameters COP, % increase in COP and exergetic efficiency has been shown in Table 4.9 to 4.12 and Fig. 4.7 to 4.9.

Table 4.9: COP of the main system vs temperature of condenser (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (^oC)	COP	
		R134a	**R152a**
1	30	2.759	2.888
2	35	2.436	2.573
3	40	2.157	2.304
4	45	1.913	2.07
5	50	1.696	1.864

Table 4.10: Overall COP of the main system vs temperature of condenser (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (^oC)	Overall COP	
		R134a	**R152a**
1	30	3.001	3.081
2	35	2.682	2.769
3	40	2.41	2.504
4	45	2.174	2.276
5	50	1.967	2.076

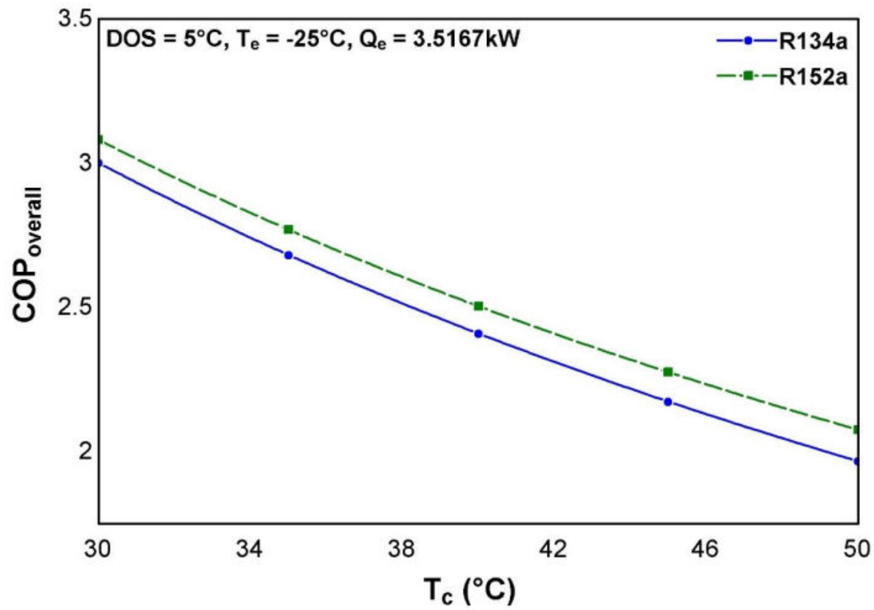

Figure 4.7 Overall COP of the main system vs temperature of condenser (T_c) for R134a and R152a

Table 4.10 and Figure 4.7 depict variation in overall COP with condenser temperature. The value of overall COP of main VCR cycle decreases with increment in temperature of condenser. It is perceived that the magnitude of overall COP is more for R152a than that of R134a.

Table 4.11: Variation in percentage increase in COP of the main cycle with condenser temperature (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (ºC)	% increase in COP	
		R134a	R152a
1	30	8.33	6.364
2	35	9.708	7.317
3	40	11.34	8.394

4	45	13.27	9.677
5	50	15.59	11.12

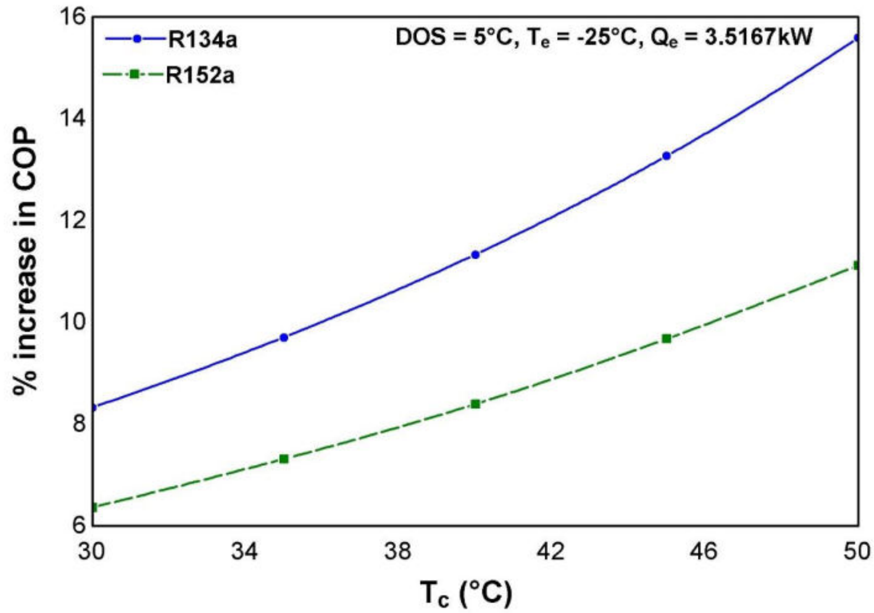

Figure 4.8 Temperature of evaporator vs % increase in COP of the main VCR system

Table 4.11 and Figure 4.8 illustrate the impact of temperature of condensser on % increase in COP of main VCR circuit. The magnitude of % increase in COP increases with increment in temperature of condenser. It has also been perceived that the magnitude of % increase in COP is more for R134a than that of R152a.

Table 4.12: Exergetic efficiency ($\eta_{exergetic}$) of the main VCR system vs temperature of condenser (T_c) for R134a and R152a

Sl. No.	Condenser Temperature (T_c) (°C)	Exergetic efficiency ($\eta_{exergetic}$)	
		R134a	R152a

1	30	0.633	0.6271
2	35	0.5888	0.5814
3	40	0.5533	0.5442
4	45	0.5246	0.5136
5	50	0.5015	0.4884

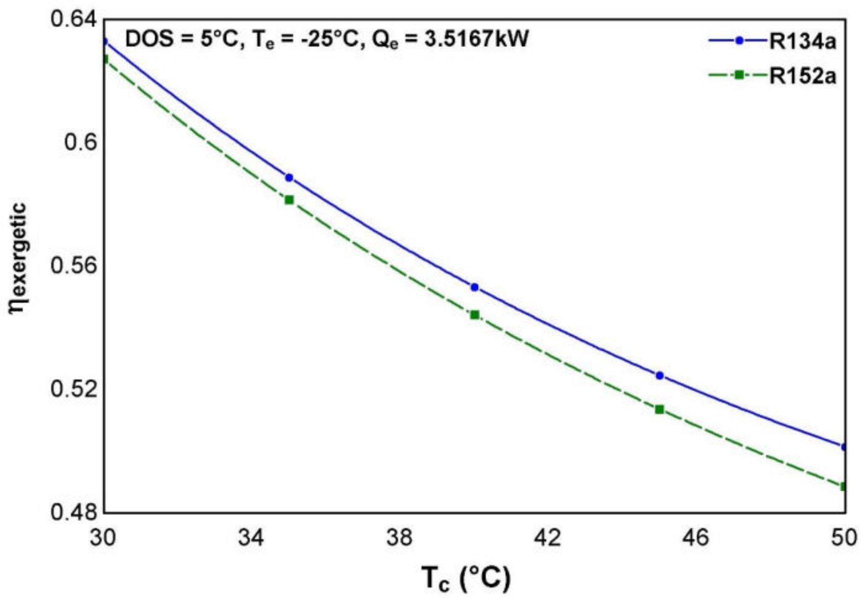

Figure 4.9 Exergetic efficiency ($\eta_{exergetic}$) of the main VCR system vs temperature of condenser (T_c) for R134a and R152a

Table 4.12 and Figure 4.9 show the impact of temperature of condenser (T_c) on exergetic efficiency ($\eta_{exergetic}$). The magnitude of exergetic efficiency decreases with increase in condenser temperature. It has perceived that the value of exergetic efficiency ($\eta_{exergetic}$) is more for R134a than that of R152a.

CONCLUSIONS AND FUTURE SCOPE

In this work, the present work illustrate performance improvement of an integrated vapor compression refrigeration system through sub-cooling. The performance analysis of integrated VCR system has been carried out. An Engineering Equation Solver (EES) program has been prepared and used to compute the results of the analysis. The effect of input parameters i.e. subcooling degree (DOS), temperature of evaporator and temperature of condenser has been investigated on the performance parameters i.e. overall COP, percentage increase in COP and exergy efficiency. Following are the concluding remarks of the present analysis.

- The magnitude of overall COP of the integrated VCR system enhances with sub-cooling.
- The overall COP of the integrated VCR system is more than that of main VCR system.
- The percentage increase in COP is 9.438 to 21.7 for R134a and 6.894 to 15.87 for R152a.
- R152a performs better than that of R134a regarding COP of the system.
- R152a may be a substitute of R134a.

Future Scope:

- The exergy investigations of the integrated VCR system may be carried out.
- Cost investigations of integrated VCR system may be carried out.
- Exergy-economic investigations of integrated VCR system may be carried out.

REFERNCES

[1] Arora, A. and Kaushik, S.C., 2008. Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A. *International journal of refrigeration*, *31*(6), pp.998-1005.

[2] Hwang, S. and Jeong, J.H., 2020. The effects of the parameters of a refrigeration system working with R600a on the non-equilibrium subcooled two-phase flow of the refrigerant. *International Journal of Refrigeration*, *118*, pp.462-469.

[3] Bolaji, B.O., 2010. Experimental study of R152a and R32 to replace R134a in a domestic refrigerator. *Energy*, *35*(9), pp.3793-3798.

[4] Sánchez, D., Cabello, R., Llopis, R., Catalán-Gil, J. and Nebot-Andrés, L., 2018. Energy assessment of an R134a refrigeration plant upgraded to an indirect system using R152a and R1234ze (E) as refrigerants. *Applied Thermal Engineering*, *139*, pp.121-134.

[5] Brendel, L.P., Caskey, S.L., Ewert, M.K., Hengeveld, D., Braun, J.E. and Groll, E.A., 2020. Review of Vapor Compression Refrigeration in Microgravity Environments. *International Journal of Refrigeration*.

[6] Alavi, S., Cerri, G. and Chennaoui, L., 2019. Power regeneration upgrading of vapour compression refrigeration plants. *International Journal of Refrigeration*, *103*, pp.9-15.

[7] Dhumane, R., Ling, J., Aute, V. and Radermacher, R., Performance comparison of low GWP refrigerants for a miniature vapor compression system integrated with enhanced phase change material. *Applied Thermal Engineering*, *182*, p.116160.

[8] Zubair, S.M., 2000. Design and rating of an integrated mechanical-subcooling vapor-compression refrigeration system. *Energy Conversion and Management*, *41*(11), pp.1201-1222.

[9] Zubair, S.M., Yaqub, M. and Khan, S.H., 1996. Second-law-based thermodynamic analysis of two-stage and mechanical-subcooling refrigeration cycles. *International Journal of Refrigeration*, *19*(8), pp.506-516.

[10] Jiang, S., Wang, S., Jin, X. and Zhang, T., 2015. A general model for two-stage vapor compression heat pump systems. *International Journal of Refrigeration*, *51*, pp.88-102.

[11] Ma, Z., Liu, F., Tian, C., Jia, L. and Wu, W., 2020. Experimental comparisons on a gas engine heat pump using R134a and low-GWP refrigerant R152a. *International Journal of Refrigeration*.

[12] Sánchez, D., Cabello, R., Llopis, R., Catalán-Gil, J. and Nebot-Andrés, L., 2019. Energy assessment and environmental impact analysis of an R134a/R744 cascade refrigeration plant upgraded with the low-GWP refrigerants R152a, R1234ze (E), propane (R290) and propylene (R1270). *International Journal of Refrigeration*, *104*, pp.321-334.

[13] Longo, G.A., Mancin, S., Righetti, G. and Zilio, C., 2019. Saturated vapour condensation of R134a inside a 4 mm ID horizontal smooth tube: Comparison with the low GWP substitutes R152a, R1234yf and R1234ze (E). *International Journal of Heat and Mass Transfer*, *133*, pp.461-473.

[14] Cabello, R., Sánchez, D., Llopis, R., Arauzo, I. and Torrella, E., 2015. Experimental comparison between R152a and R134a working in a refrigeration facility equipped with a hermetic compressor. *International Journal of Refrigeration*, *60*, pp.92-105.

[15] Klein, S. A., Alvarado, F., 2012. Engineering Equation Solver, *F Chart Software*, Middleton, WI. Version 9, 224-3D.