PERFORMANCE ANALYSIS OF MODIFIED VAPOR COMPRESSION REFRIGERATION SYSTEM USING ECOFRIENDLY REFRIGERANTS

A THESIS SUBMITTED IN FULFILMENT OF
THE REQUIREMENT FOR THE AWARD OF THE DEGREE

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IN

THERMAL ENGINEERING

SUBMITTED BY:

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CANDIDATE'S DECLERATION

I VISHAL TOMER, Roll No 2K17/THE/20 student of M. Tech (Thermal Engineering), hereby declare that the project dissertation titled, "Performance Analysis of modified Vapor Compression Refrigeration System using ecofriendly refrigerants" which is submitted by me to the department of Mechanical Engineering ,Delhi Technological University ,Delhi in partial fulfillment of the requirements for the award of degree of **Master of Technology ,** is original and not copied from any source without proper citation . The work has not previously formed the basis for the award of Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the project Dissertation titled “Performance Analysis of modified Vapor Compression Refrigeration System using ecofriendly refrigerants” which is submitted by Vishal Tomer, Roll no 2K17/THE/20, Mechanical Engineering Department, Delhi Technological university. Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this university or elsewhere.

Place: Delhi
Dr. NAUSHAD A. ANSARI

Date:
(SUPERVISOR)

ACKNOWLEDGEMENT

Generally, individuals set aims, but more often than not, their conquest are by the efforts of not just one but many determined people. This complete project could be accomplished because of contribution of a number of people. I take it as a privilege to appreciate and acknowledge the efforts of all those who have directly or indirectly, helped me achieving my aim.

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VISHAL TOMER

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LIST OF SYMBOLS

GWP	Global Warming Potential
ODP	Ozone Depletion Potential
COP	Coefficient of Performance
EDR	Exergy destruction ratio
$\dot{Q}$	Rate of heat transfer (kW)
$\dot{W}$	Work rate (kW)
$\dot{ED}$	Exergy destruction rate (kW)
$\dot{X}$	Exergy rate (kW)
$\dot{X}^{Q}$	Rate of thermal exergy flow rate (kW)
$\dot{m}_r$	Mass flow rate of refrigerant (kg/s)
T	Temperature (K)
s	Specific entropy (kJ/kg-K)
h	Specific enthalpy (kJ/kg)
V	Velocity of fluid (m/s)

Greek symbols

η	Efficiency
ε	Effectiveness
x	Specific exergy
δ	Efficiency defect

Subscripts

E	Evaporator
comp	Compressor
c	Condenser
lvhe	Liquid vapour heat exchanger
t	Throttle valve
j	jth component of the system
r	Region to be cooled or refrigerant
i	Inlet to the control region
e	Outlet to the control region
R	refrigerator
O	Ambient state

rev	Reversible
sub	Sub-cooling
su	Superheat
vcr	Vapour compression refrigeration system

ABSTRACT

An Exergy method for theoretical analysis of a traditional vapor-compression refrigeration system equipped with liquid vapour heat exchanger (lvhe) for refrigerants like R134a, R423A, R507A, R1233zd(E), R1234ze(Z), R1234ze(E) and R1243zf were carried out. All are ultra-low GWP and zero ODP refrigerants and comparison of the results with HFC-134a refrigerant as possible alternative replacements in Automotive air-conditioning and stationary refrigeration is presented. A mathematical computational model has been developed for calculating Coefficient of performance (COP), exergetic efficiency, exergy destruction and efficiency defects for the above mention refrigerants. During the investigation, condenser temperature is kept at 313K and 323K, evaporator temperature is kept in the range from 223K to 273K. Results obtained for selected condenser temperature are compared and discussed elaborately. It indicates that R1234ze(Z) can be a good drop-in replacement of HFC-134a and R1234ze(Z) can replace the HFC-134a after some modifications as the results are almost similar. Among the system components, evaporator shows highest efficiency defect value and liquid vapor heat exchanger shows the lowest.

Chapter 1

INTRODUCTION

The initiatory artificial refrigeration began when Scottish professor William Cullen invented a small refrigerating machine in 1755. Following that, in 1820 the English scientist Michael Faraday liquified ammonia vapor and different gases and then the first refrigerator was invented. During the early years of 1900's chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) were largely used in the refrigeration systems [1].These refrigeration systems were depleting the ozone layer when this problem became recognized, a general accord was formed which stated that the next generation of refrigerants should have zero ozone depleting potential and low global warming potential. This accord was supported was also supported by prospective legislation in different countries all around the world to implement a shift to refrigerants which have less environmental impact and are more energy efficient [2].The initial step toward this situation came in form of Montreal Protocol which was agreed on 26 August 1987 , and entered into force on 16 September 1989.The Montreal protocol is an international treaty designed to protect the ozone layer by phasing out the production of numerous substances that are responsible for ozone depletion.

Nonetheless, next severe global environmental problem is regarding this refrigerant. It was the global warming situation. The Kyoto Protocol is an international agreement which extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that perpetrate its state parties to diminish emission of greenhouse gases (GHGs). It was approved in Kyoto, Japan, in December 1997 and enforced in February 2005 [3]. Emissions from the refrigeration systems comprising HFC-134a has a global warming potential (GWP) of 1300 and developing interest because the damage it can do on the climate. Thus, it needs to be reinstated by more eco-friendly refrigerants in the vapor compression systems. This has motivated to research and study low GWP refrigerants. Survey done by IPCC indicates that HFC's atmospheric concentrations elevated at rate of 12% - 16% per year amid 2001 and 2003. So, to assure the restriction of some fluorinated greenhouse gases is effective, it is required to lessen the probability of retrofitting air conditioning system in the motor vehicles, these systems are designed to accommodate fluorinated greenhouse gases with a global warming potential greater than 150 and to forbid stuffing refrigeration systems with such gas. HFC-134a will be phased out from all the new models in the of year 2011[4].

In order to develop new refrigerant with less global warming potential fluids for refrigeration industry, comprehensive research is carried out. The leading candidate to take over HFC-134a in the refrigeration system are some natural refrigerants like ammonia, hydrocarbon (HC) mixtures or carbon dioxide; HFCs with less global warming potential such as HFC-32 and HFC-152a; and hydrofluoroolefin (HFO) such as HFO-1234yf and HFO-1234ze, invented by Honeywell and DuPont [5] [6]. HF0-1234yf can be used as alternative replacement of HFC-134a as it has low GWP as compared to HFC-134a and vehicle manufacturers need not to make an significant changes in the assembly lines of vehicles [7].

In the near future we might see the refrigerants containing chlorine again. A few of new olefin based consists of chlorine but still manage to have relatively no ODP. These chemicals are hydrochlorofluoro-olefins (HCFOs). In order to develop chemicals with low GWP manufacturers are taking new look at chemicals containing chlorine. Then there comes the question of how about ODP? As it turns out removing chlorine is not the only way to make refrigerant that will not deplete the ozone layer.

1.1 OVERVIEW OF REFIGERANTS

“Refrigeration is the process of maintaining space at a lower temperature compared to the surroundings. The working fluid which circulates through the refrigeration equipment to provide refrigeration is called refrigerant.”

The advancement of refrigerants all through the history occurred due to various logic such as security, endurance and environment concern. The figure given below epitomize the four distinct generation of refrigerants. [24]

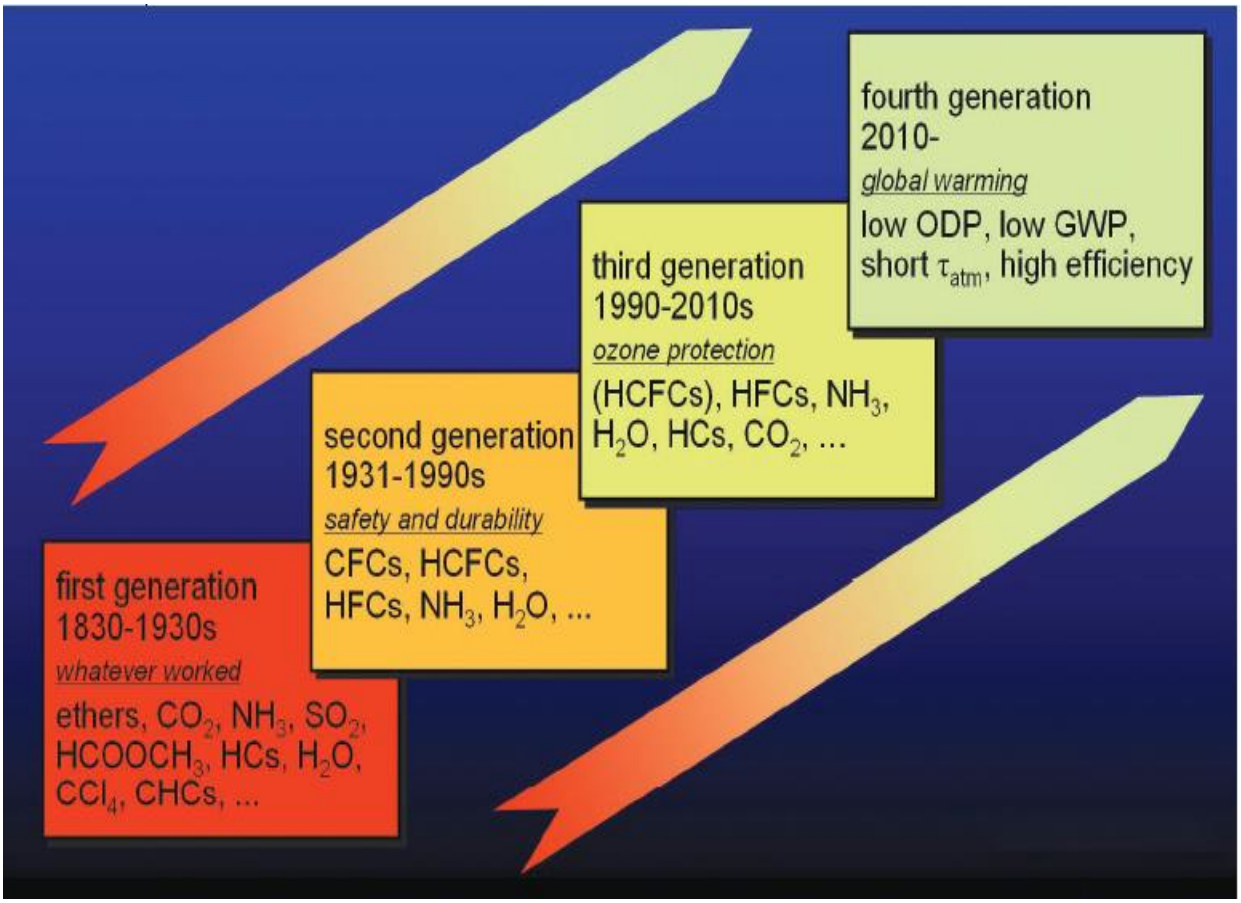


Figure 1.1: The progression of refrigerants [24]

1.1.1 FIRST GENERATION OF REFRIGERANTS

Most of the refrigerants used in the early refrigeration systems were natural and the refrigeration systems works on refrigerants like water, ethers, halogenated hydrocarbons, methyl chloride, ammonia and sulfur dioxide, etc. Generally, all of the refrigerants of the first generation were toxic, flammable and highly reactive. These refrigerants were the heart of refrigeration industry back in the day. As these refrigerants were highly dangerous to work with therefore the manufacturers researched and studied the refrigerants that were safer and durable and that lead to the second generation of refrigerants.

1.1.2 SECOND GENERATION OF REFRIGERANTS

These refrigerants shift their interest towards the goal of safe and durability. The focus of refrigerants of this generation was to reduce the toxicity and flammability. The discovery of these refrigerants flourished the refrigeration and air conditioning industry and increased their growth at the cost of ozone layer destruction. These refrigerants like carbon tetrafluoride, ammonia, water, hydrocarbons, etc. leaked in the air and destroy the ozone layer which is protecting the earth from the dangerous UV rays. In regard to this serious situation countries all over the world formed treaty in the Montreal protocol to look forward for the new generation of refrigerants which have low ozone depleting potential.

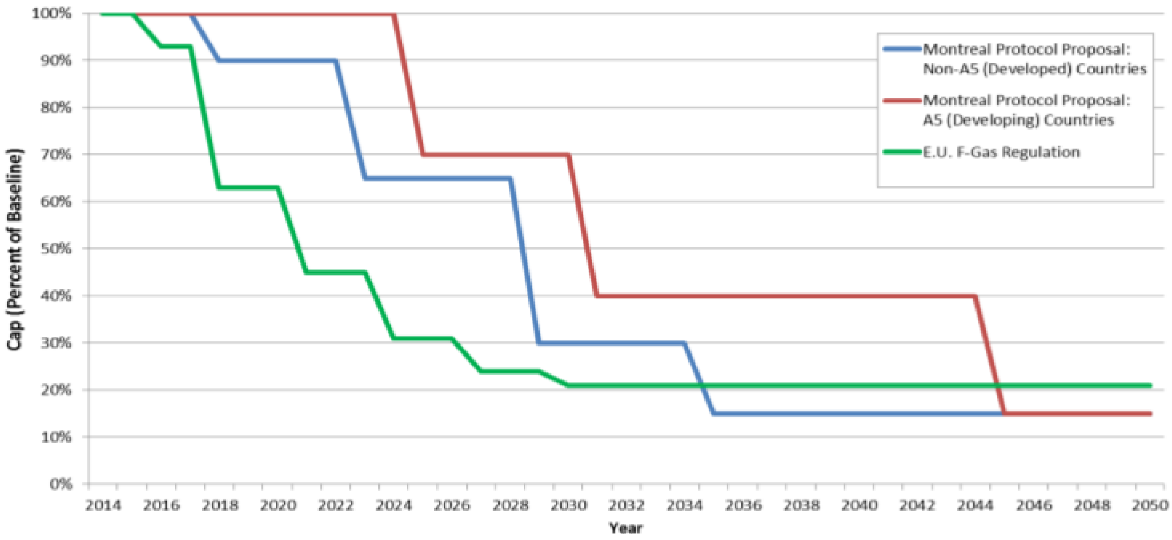


Figure 1.2: HFC phasedown agenda for North American Montreal Protocol proposition and European F-gas regulation [25]

1.1.3 THIRD GENERATION OF REFRIGERANTS

To overcome the challenge of ozone depletion caused by CFCs and HCFCs the focus shift to the natural refrigerants such as ammonia, water, carbon dioxide, etc. Later a wide range of blends and derivates of HFCs were made to meet the needs of the refrigeration industry and these refrigerants were called hydrofluorocarbon (HFCs). The refrigerants of these generation have very low ozone depletion potential but these refrigerants had high global warming potential. Due to high global warming the sea level rose and there was land loss in the coastal areas and it impacted all aspects of life. To counter this global warming problem the United Nations used Kyoto protocol as the implementing tool for managing greenhouse gases emissions. They are expected to phased out HFCs by 2030.

1.1.4 FOURTH GENERATION OF REFRIGERANTS

The new challenge for the manufacturers was to develop a new refrigerant with low global warming potential. The manufacturers came up with hydrofluoroolefins (HFOs) which is an unsaturated organic compound of hydrogen, fluorine, and carbon. These refrigerants are said to have zero ozone depletion potential and very less global warming potential but they tend to have mild flammability. In these HFOs there is a double bond between carbon to carbon and it is less stable in the atmosphere but it is very stable in the refrigeration system. Some examples of these type of refrigerants are HFO-1234yf, HFO-1234ze, etc. These refrigerants are the future of the refrigeration industry

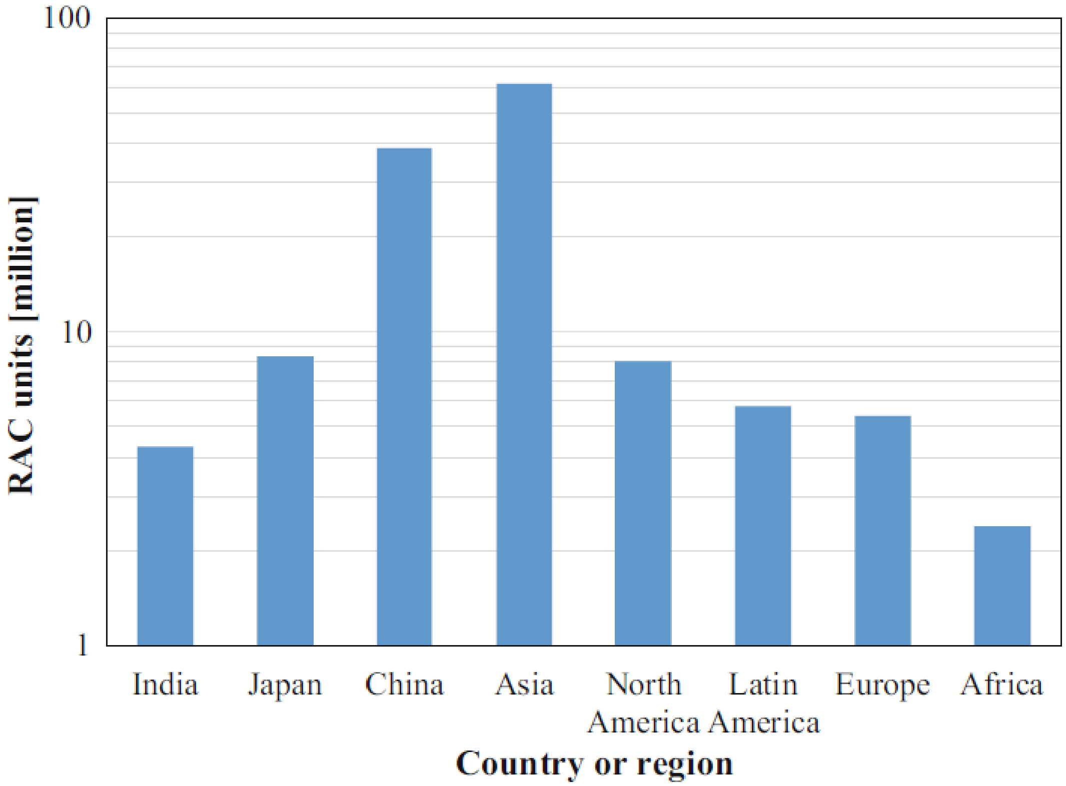


Figure 1.3 World room air-conditioning demand (RAC) in 2016. [25]

Table 1.1: Classification of 100 years GWP levels [26]

100 Year GWP	Classification
<30	Ultra-Low or Negligible
<100	Very Low
<300	Low
300-1000	Medium
>1000	High

1.2 PRIMARY AND SECONDARY REFRIGERANT

The fluids suited for refrigerating function are classified into primary and secondary refrigerants.

1.2.1 PRIMARY REFRIGERANT: Primary refrigerant is the refrigerant which circulates through the refrigeration equipment. When there is no harm to human life from the refrigerant then the refrigerant is allowed to flow freely in the space which is to be cooled.

1.2.2 SECONDARY REFRIGERANT: The refrigerant which absorbs heat from the refrigerated space and in turn discard heat to the primary refrigerant is called secondary refrigerant. Secondary refrigerant used in milk chilling plant is brine solution. Glycol can also be used but brine solution is preferred. The secondary refrigerant used in air conditioning applications is air. The secondary refrigerant helps in:

1. Saving the cost associated with the amount of primary refrigerant.
2. It helps us in using a refrigerant with good thermodynamic properties irrespective of its toxic nature for example ammonia.
3. It helps in saving the cost associated with operation of refrigeration machine.

1.3 REFRIGERANT BLEND

Refrigerant blends are a combination of different refrigerants that have been developed to provide a test for some of the properties of the previous refrigerants used. These blends are being investigated and matured by different chemical manufacturers since the rule is issued for the discontinuation of the ozone depleting chemicals. The blend can consist of either 2-3 components or more than that, and can have considerable amount of HCFCs, HFCs, or HCs. Generally, blends are the combinations of the given chemicals. [27]

These blends have their own business names. The acknowledged ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) refrigerant number also exerts to blends.

The refrigerant mixture can be classified into:

1. Azeotropic refrigerant mixture
2. Near-azeotropic refrigerant mixture
3. Non-azeotropic refrigerant mixtures

Azeotropic mixtures sometimes are known as constant boiling point mixtures. The proportions of the refrigerants cannot be altered via distillation. This is because these mixtures behave like pure refrigerants. Some examples of these mixtures are R-500 and R-502. R-500 constitutes of 73.7% of CFC-12 and 26.3% of HFC-152a by weight. R-502 constitutes of 48.7% of HCFC-22 and 51.3% of CFC-115.

Near azeotropic mixture are the ones which have little temperature variation during phase change and minor change in composition in the liquid vapor phases at equilibrium. Example can be mixing little amount of propane in R-502 to increase its solubility in the lubricating oil.

Non azeotropic mixtures sometimes also called as zeotropic mixture are the ones that have different boiling points. In this the constitutes of the mixture do not evaporate or condense at the same temperature as one substance. Some of the examples are R407c, a blend of R32, R125, and R134a. [28]

1.3.1 SCIENTIFIC DETAILS OF REFRIGERANT BLEND

The HCFC blends such as R-401A, R-401B, R-401C, R-406A, R-409A, R409B, R415B, R416A and zero ODP HFC/HC based R407A, R-413A, R-600a/R-290 are accustomed to take over R-12. Above mentioned blends are suitable with almost all of the material used in R-12 established refrigeration system, also perform well alongside the regular used mineral oil in the refrigerant system. These blends were manufactured as a drop-in replacement of the R-12 based systems with a decent performance but a small amount of energy comes as a penalty. Yet, there comes some cases in which there is need to make the change in the system. These blends however are not used in the R-134a as retrofit as the R-134a system was designed for the HFCs, and there will be problems regarding the lubrication, also in these types of cases there is serious loss of energy in the system. As these blends are non-azeotropic in nature, these causes problems for multiple components like liquid removal from the from containers and refrigerant dispatched to miniature containers by trader. The examination organized by ARI implies “refrigerant mixtures can have composition changes during the handling procedures that lead to out-of-specification composition”. [27]

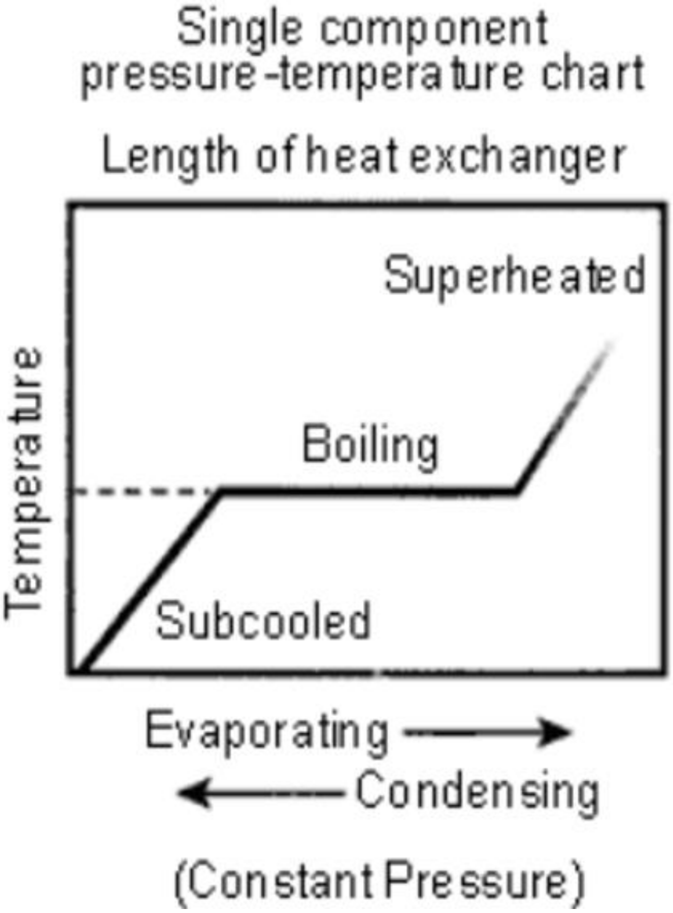


Figure 1.4: A near azeotropic refrigerant blend indicating single temperature for a given pressure as it boils [28]

Figure 1.4 emphasize a pressure/temperature graph of a near-azeotropic refrigerant blend indicating the refrigerants boiling at numerous temperatures for a given pressure throughout the dimension of the heat exchanger. The pressure/temperature chart is a helpful tool that is used by technicians. It most commonly serves these three aims, it is used for setting desired coil pressure so that the refrigeration system produces desired temperature, to confirm the amount of saturated vapor at the departure of evaporator, also to confirm the amount of sub cooling at the bottom of the saturated liquid at the exit of condenser. [28]

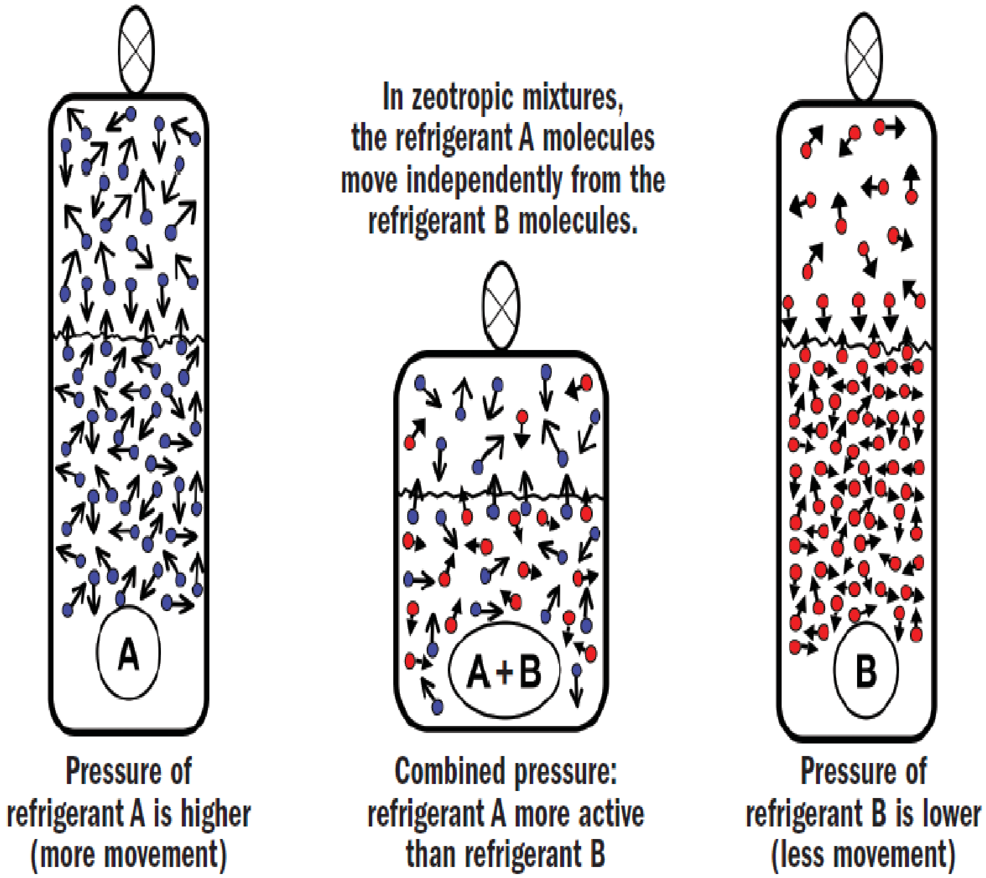


Figure 1.5: Behavior of individual refrigerant molecules [29]

Near azeotropic blends sometimes experience fractionation. Fractionation is basically a separation process, in this a configuration of a mixture is alternated because one or more than one of the constituents is vanished or detached quickly than the others. This difference in rate is due to varying vapour pressure of every chemical present in the blend. Figure 1.5 emphasizes the key nature of the molecules of the constituent of the blend. In the figure pure refrigerant A and B exert pressure on the walls of cylinder. As we know that speed of the molecules increases as the temperature increases, and molecules move at lower rate at low temperature. These refrigerant molecules exert different energies at same temperature, this is the reason they generate high or low pressure at same temperature. The refrigerant is continuously changing its phase in the equipment. When refrigerants mix, they don’t form azeotropic mixture, the refrigerant molecules B bounces harder than the molecule A thus forming more pressure to the blend. When liquid and vapor are together at equilibrium, then it is always the vapor that goes to the wrong composition. [29]

1.3.2 MERITS AND DEMERITS OF REFROGERANT BLEND

1.3.2.1 MERITS:

It is step forward to fulfil the interest of the humans while phasing out the global warming generating refrigerants in compliance with the Montreal protocol. They are cheaper than R-134a and other refrigerants, carrying these refrigerants are also easier. They work well with the lubrication oil, and provide acceptable performance in the modified refrigeration system.

1.3.2.2 DEMERITS:

These blends are temporary solution for CFC replacement. As they are zeotropic in nature they are flammable and need skilled technicians and follow proper handling procedures. With new refrigerants in the market can confuse the technician in which they can cause problems like cross-contamination, which in turns lower the performance of the system.

1.4 OZONE LAYER DEPLETION (ODP) AND GLOBAL WARMING POTENTIAL (GWP)

1.4.1 OZONE LAYER DEPLETION

Ozone layer depletion of a alchemical substance is the dependent measure of degeneration which it can do to ozone layer surrounding earth, compared to R-11 (ODP = 1). Ozone depletion potential is used as an indicator for smooth manner to correlate the relative ability of the other ozone depleting substances which are damaging the ozone [30]. It is defined as the amount of fatal outcomes of a compound correlation allusion to compound. The ODP of different substances is measured with respect to a reference substance, the reference substance in this is CFC-11 which has an ODP of 1. Absolutely, the ODP of the compound is defined as the ratio of the ozone lost the given compound of same mass to the ozone loss due the same mass of CFC-11[31].

$$\text{ODP} = \frac{\Delta global\ ozone\ due\ X}{\Delta global\ ozone\ due\ to\ emissions\ of\ CFC{-}11}$$

The ODP of the substance is affected by the following:

1. Halogens have more ODP than the chlorocarbons because halogen contains bromine which is far more deteriorating catalyst than the chlorine.
2. It also depends on the number of bromine or chlorine in a compound.
3. Since ODP is dependent on the molecular mass of the substances in equal, it depends on molecular mass.
4. Atmospheric lifetime.

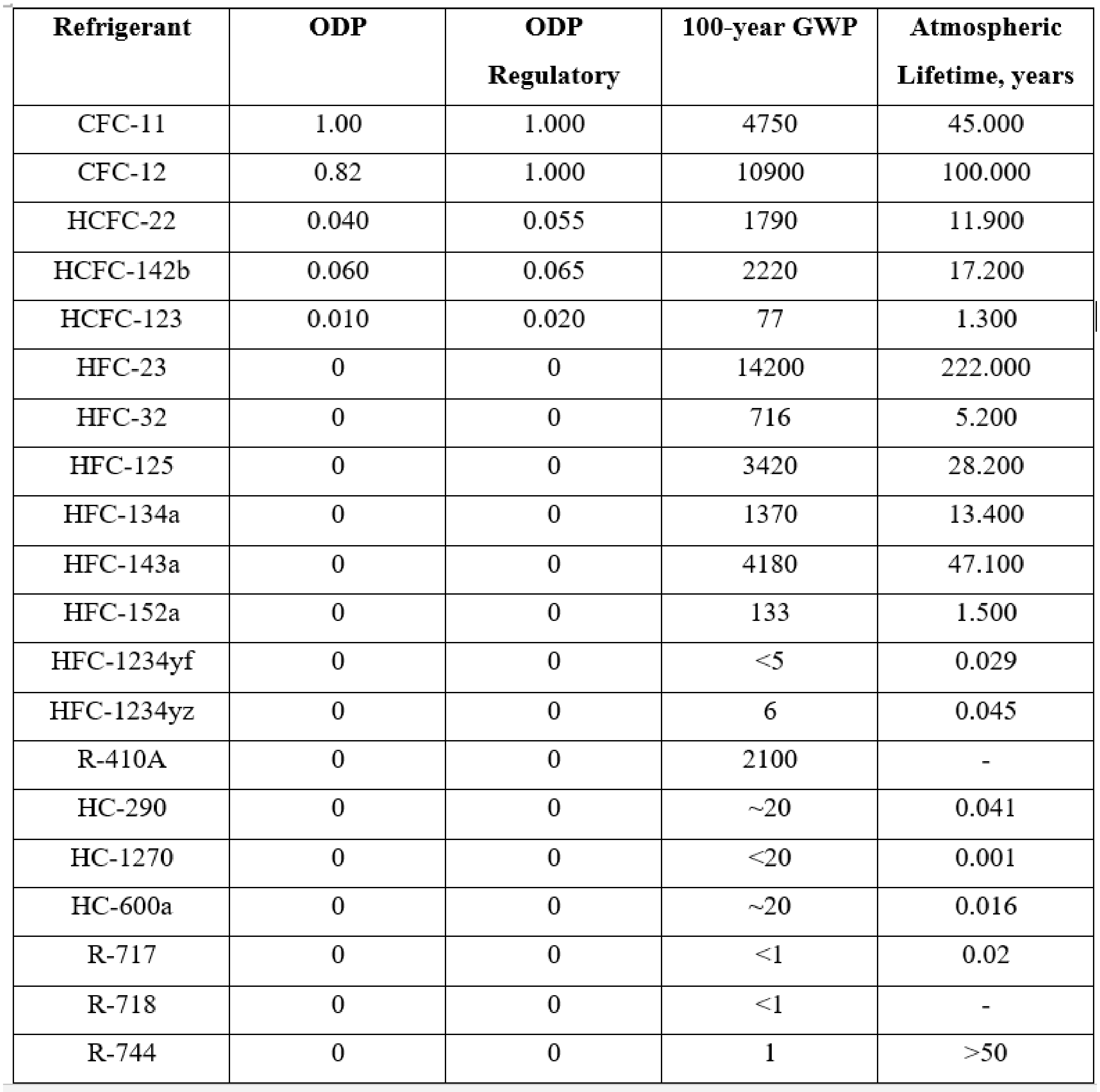
1.4.2 GLOBAL WARMING POTENTIAL

Global warming potential is relative capacity of the amount of heat a greenhouse gas confines in the aerosphere. Solar radiations are the ultimate source that powers the earth. More than 29% of the solar radiations are reflected back, however the rest of the radiations have to pierce the earth's aerosphere to enter the ground of the earth. The earth's surface absorbs so much radiation and it acts as a black body emitting infrared rays back to the aerosphere. Because of this greenhouse gases like carbon dioxide, methane, halogenated refrigerants, etc. are trapped inside the earth's atmosphere thus increasing the temperature of the earth. It is defined as the heat confined by mass of the gas to the heat confined by same amount of mass by carbon dioxide. Carbon dioxide is taken as reference it has GWP of 1 [32].

The GWP is determined by the given aspects:

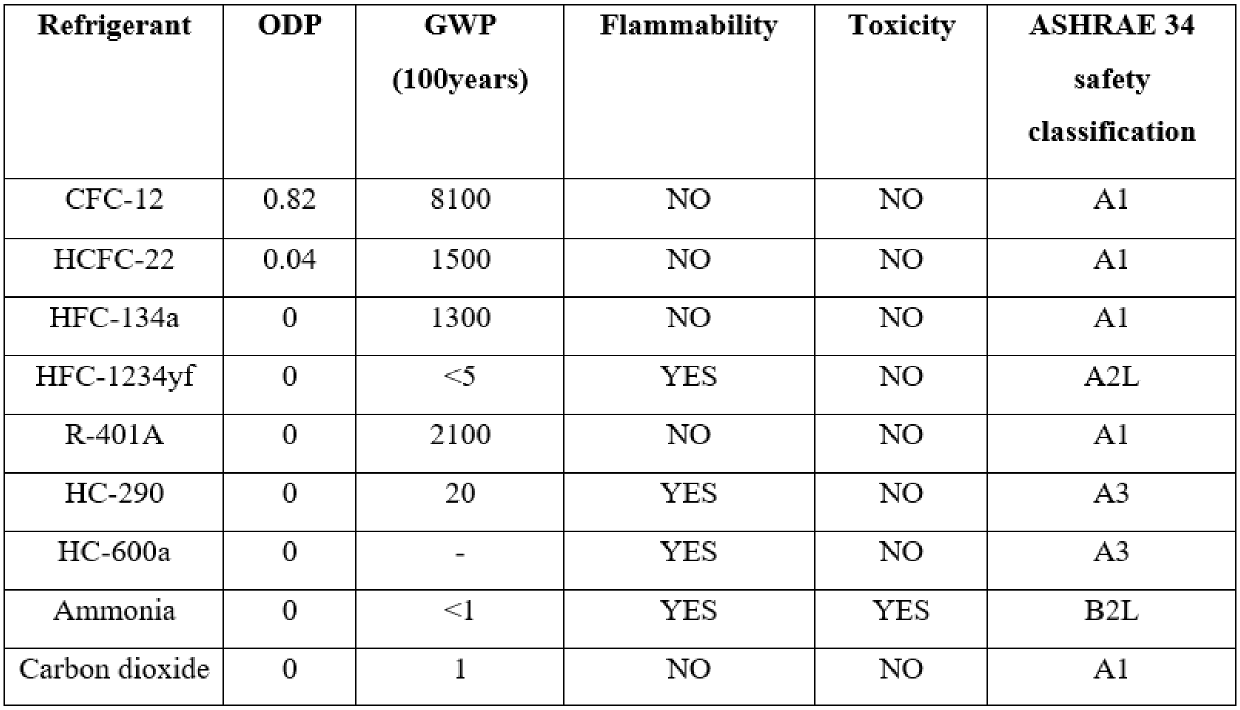
1. The rate of absorption by the given species.
2. The spectral location of the absorbing wavelengths.
3. The atmospheric life of the given species

Table 1.2: Environmental data of some refrigerants [33]



Refrigerant	ODP	ODP Regulatory	100-year GWP	Atmospheric Lifetime, years
CFC-11	1.00	1.000	4750	45.000
CFC-12	0.82	1.000	10900	100.000
HCFC-22	0.040	0.055	1790	11.900
HCFC-142b	0.060	0.065	2220	17.200
HCFC-123	0.010	0.020	77	1.300
HFC-23	0	0	14200	222.000
HFC-32	0	0	716	5.200
HFC-125	0	0	3420	28.200
HFC-134a	0	0	1370	13.400
HFC-143a	0	0	4180	47.100
HFC-152a	0	0	133	1.500
HFC-1234yf	0	0	<5	0.029
HFC-1234yz	0	0	6	0.045
R-410A	0	0	2100	-
HC-290	0	0	~20	0.041
HC-1270	0	0	<20	0.001
HC-600a	0	0	~20	0.016
R-717	0	0	<1	0.02
R-718	0	0	<1	-
R-744	0	0	1	>50

Table 1.3: Thermo-physical characteristics of some refrigerants [33]

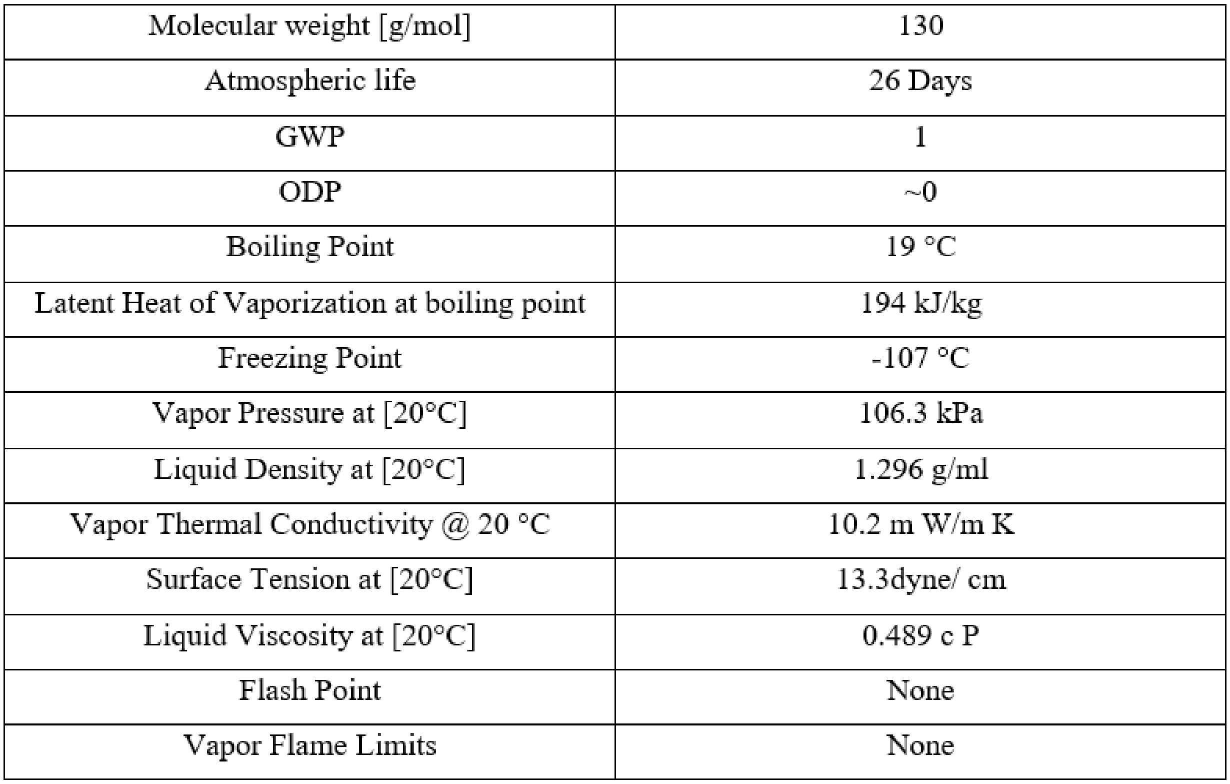


Refrigerant	**ODP**	**GWP (100years)**	**Flammability**	**Toxicity**	**ASHRAE 34 safety classification**
CFC-12	0.82	8100	NO	NO	A1
HCFC-22	0.04	1500	NO	NO	A1
HFC-134a	0	1300	NO	NO	A1
HFC-1234yf	0	<5	YES	NO	A2L
R-401A	0	2100	NO	NO	A1
HC-290	0	20	YES	NO	A3
HC-600a	0	-	YES	NO	A3
Ammonia	0	<1	YES	YES	B2L
Carbon dioxide	0	1	NO	NO	A1

1.5 REFRIGERANT ‘HCFO-1233zd (E)’

It is the latest low GWP chemical. Trans-isomer of 1-chloro-3,3,3-trifluoropropene (HCFO-1233zd(E)) is a liquid halogenated olefin. It is developed and marketed by Honeywell. The environmental and thermo-physical properties of the refrigerant is given in the table 2.4.

Table 1.4: Physical and Environmental Properties of HCFO-1233zd (E). [34]



Molecular weight [g/mol]	130
Atmospheric life	26 Days
GWP	1
ODP	~0
Boiling Point	19 °C
Latent Heat of Vaporization at boiling point	194 kJ/kg
Freezing Point	-107 °C
Vapor Pressure at [20°C]	106.3 kPa
Liquid Density at [20°C]	1.296 g/ml
Vapor Thermal Conductivity @ 20 °C	10.2 m W/m K
Surface Tension at [20°C]	13.3dyne/ cm
Liquid Viscosity at [20°C]	0.489 c P
Flash Point	None
Vapor Flame Limits	None

1.5.1 TOXICITY

The results from the studies carried out for this refrigerant imply that it is a non-mutagenic and non-teratogenic. Honeywell carries out extensive toxic testing and fixed preliminary Occupational

Exposure Limit (OEL) of 800 ppm. Material Safety Data Sheets are provided by Honeywell and it should be carefully reviewed by the consumer before the installation. [35]

1.5.2 ENVIRONMENTAL EFFECTS

It has a GWP of 1. However, treatment and dumping of the refrigerant should be taken care of reckon on the nature of waste and medium of discharge, treatment or dumping. Storage and handling of the refrigerant is to be taken care of [35].

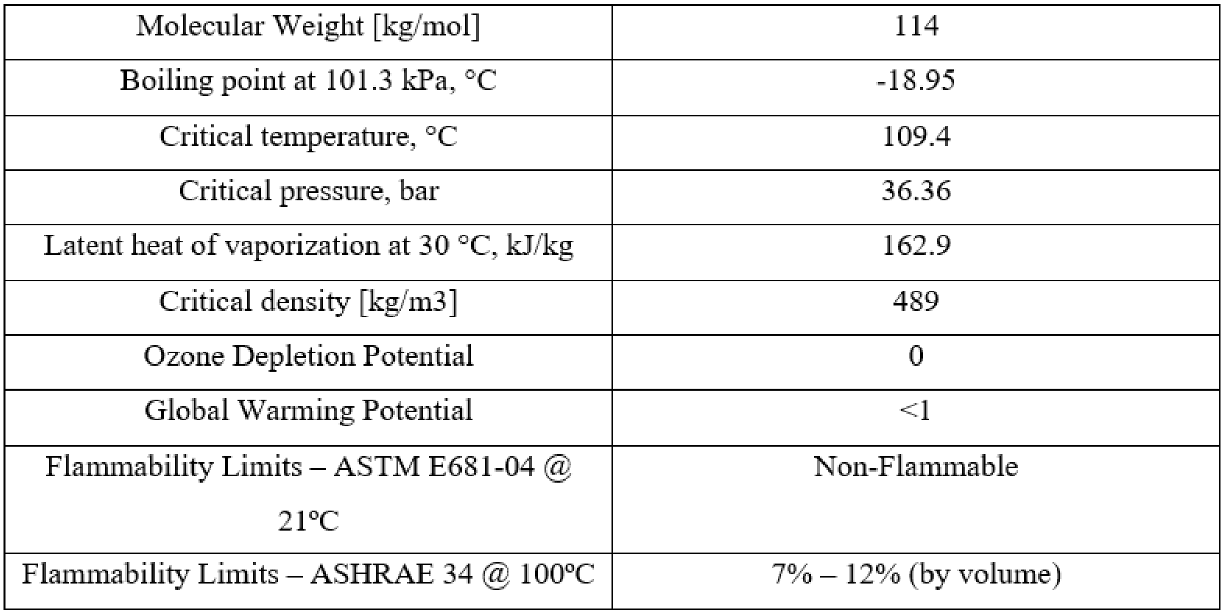
1.5.3 MISCIBILITY

It exhibits acceptable miscibility in a wide range of polyols and in polymeric Methylene diphenyl diisocyanate (MDI). [34]

1.6 REFRIGERANT ‘R1234ze(E)’

Refrigerant R1234ze(E) exists in the family of halogenated olefins. Its chemical formula is trans-1,3,3,3-Tetrafluoroprop-1-ene, CF3CH=CHF. It has very low GWP. Some of the thermo-physical properties of the refrigerant is given in the table 2.5.

Table 1.5: Thermo-physical properties of R1234ze(E) [35]



Molecular Weight [kg/mol]	114
Boiling point at 101.3 kPa, °C	-18.95
Critical temperature, °C	109.4
Critical pressure, bar	36.36
Latent heat of vaporization at 30 °C, kJ/kg	162.9
Critical density [kg/m3]	489
Ozone Depletion Potential	0
Global Warming Potential	<1
Flammability Limits – ASTM E681-04 @ 21ºC	Non-Flammable
Flammability Limits – ASHRAE 34 @ 100ºC	7% – 12% (by volume)

1.6.1 TOXICITY

It has gone under heavy research, and it is safe to say that it meets the accord with the safety guidelines and is in favorable condition. It is mildly flammable. No such reports of the illness are caused due to this refrigerant.

1.6.2 ENVIRONMENTAL IMPACT

Is has a GWP of less than 1, it surpasses the climate protection guidelines. It reduces the carbon dioxide emissions by 99.5%. Atmospheric life about 18 days as compared to other refrigerants like R-134a.

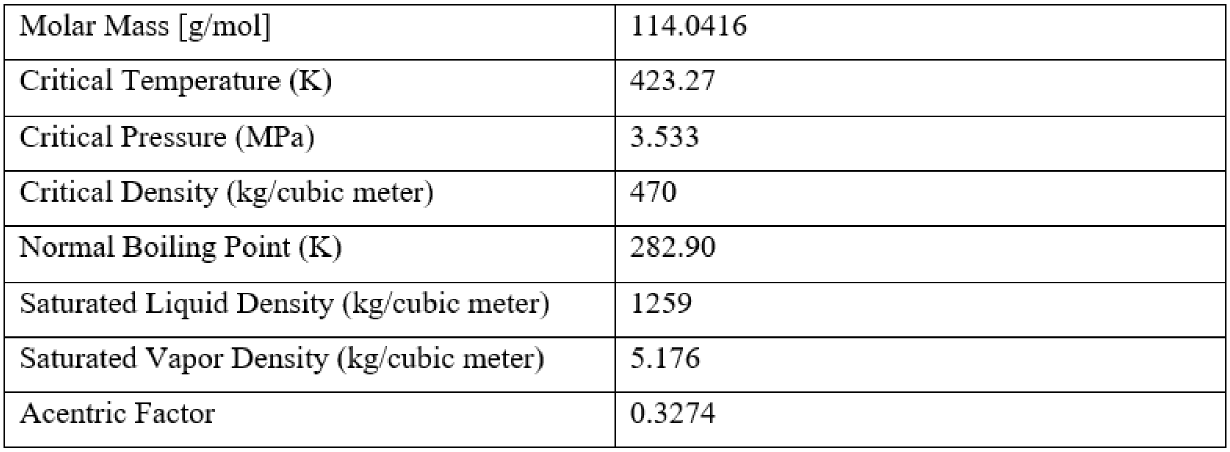
1.6.3 STORAGE AND HANDLING

As it is mildly combustible and contact with the heat is avoided, and must be stored in chilled, dehydrated and well open space. Precaution must be taken for filling empty cylinder with refrigerant.

1.7 REFRIGERANT ‘R1234ze(Z)’

Cis 1,3,3,3-tetrafluoropropene was one of the refrigerants which is a member of liquid halogenated olefins which was developed after heavy research was carried out. It has zero ODP and very less GWP. It can be a future refrigerant for the heat pumps working at medium and high temperatures. Some of the fundamental constants and characteristic and characteristics properties of the refrigerant is given below in the table 2.6.[36]

Table 1.6: Fundamental Thermo-physical properties of R-1234ze(Z).[36]



Molar Mass [g/mol]	114.0416
Critical Temperature (K)	423.27
Critical Pressure (MPa)	3.533
Critical Density (kg/cubic meter)	470
Normal Boiling Point (K)	282.90
Saturated Liquid Density (kg/cubic meter)	1259
Saturated Vapor Density (kg/cubic meter)	5.176
Acentric Factor	0.3274

1.7.1 TOXICITY

It has gone under heavy research, and it is safe to say that it meets the accord with the safety guidelines and is in favorable condition. It is mildly flammable. No such reports of the illness are caused due to this refrigerant.

1.7.2 ENVIRONMENTAL IMPACT

Is has a GWP of less than 1, it surpasses the climate protection guidelines. It reduces the carbon dioxide emissions by 99.5%. Atmospheric life about 18 days as compared to other refrigerants like R-134a.

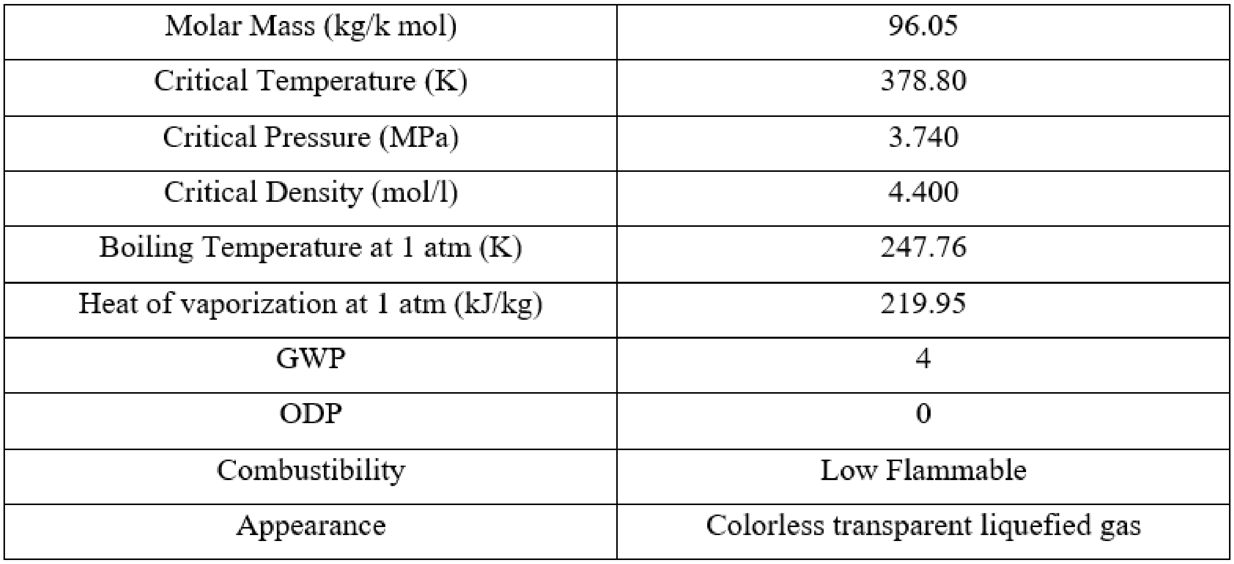
1.7.3 STORAGE AND HANDLING

As it is mildly combustible and contact with the heat is avoided, and must be stored in chilled, dehydrated and well open space. Precaution must be taken for filling empty cylinder with refrigerant.

1.8 REFRIGERANT ‘R1243zf’

Hydrofluoroolefin named 3,3,3- trifluoropropene also named as R1243zf. It is manufactured to replace R134a due to high global warming, it has similar thermodynamic properties as of R134a. Some of the thermodynamic properties of R1243zf are given in table 2.7. [37]

Table 1.7: Typical thermodynamic properties of HFO-1243zf. [37]



Molar Mass (kg/k mol)	96.05
Critical Temperature (K)	378.80
Critical Pressure (MPa)	3.740
Critical Density (mol/l)	4.400
Boiling Temperature at 1 atm (K)	247.76
Heat of vaporization at 1 atm (kJ/kg)	219.95
GWP	4
ODP	0
Combustibility	Low Flammable
Appearance	Colorless transparent liquefied gas

1.8.1 ENVIRONMENTAL FATE

R1243zf can have subtle effects on the human health as it is used in the manufacturing of fluorine-containing silicones used in hydraulic fluids, it might get release in the environment through various waste flow.

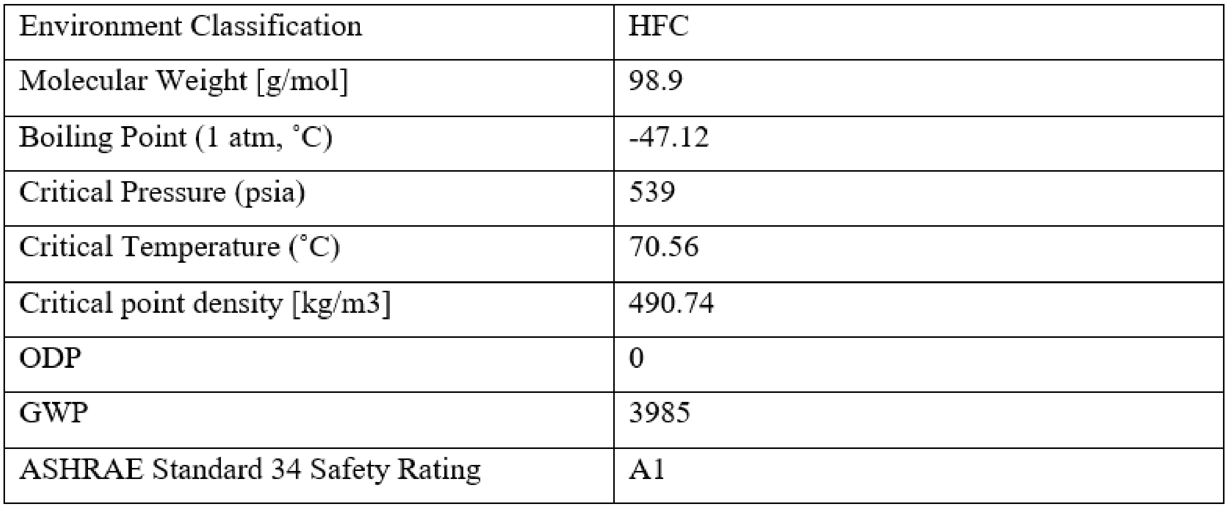
1.8.2 SAFETY AND HAZARD

R1243zf is mildly flammable as should be handled with precaution. It should be stores in dry and cool place. Exposure to this refrigerant can cause severe respiratory problems, dizziness, drowsiness.

1.9 REFRIGERANT ‘R507A’

R507A is an azeotropic refrigerant blend which was manufactured to replace R502 in the refrigeration system working in the less or medium temperature range. This refrigerant does not easily get fractionated and also does not glide and hence exceeds its applications to compressor such as centrifugal types. Some of the thermo-physical properties of refrigerant is given below in table 2.8. [38]

Table 1.8: Thermo-Physical Properties of Refrigerant R507A [38]



Environment Classification	HFC
Molecular Weight [g/mol]	98.9
Boiling Point (1 atm, ˚C)	-47.12
Critical Pressure (psia)	539
Critical Temperature (˚C)	70.56
Critical point density [kg/m3]	490.74
ODP	0
GWP	3985
ASHRAE Standard 34 Safety Rating	A1

Chapter 2

LITERATURE REVIEW AND PROBLEM IDENTIFICATION

Mota-Babiloni et al. [8] studied the R1234ze refrigerant and commented on the Environmental effect of the refrigerants. This refrigerant presents good environmental properties and can be used in most of HVACR applications, pure or mixed with HFC or natural refrigerants (mainly CO2).they studied the various properties of the refrigerant mainly thermophysical and compatibility properties, heat transfer and pressure drop characteristics, and vapor compression system performance; separating those works that consider R1234ze(E) pure or blended and commented on its replaceability as the refrigerants. Arora and Kaushik [9] experimented the exergy analysis of an actual vapor compression refrigeration (VCR) cycle. The Researcher studied exergy destruction, exegetic efficiency and efficiency defects for R502, R404A and R507A with the help of the computational model for computing coefficient of performance. The temperature range was taken about -50 C to 0C and 40 C to 55 C. After going through the detailed experiment, they concluded that the R507A is a better substitute to R502 than R404A. Liu et al. [10] studied the vapor condensation processes of 3,3,3-trifluoroprop-1-ene (R1243zf), trans-1,3,3,3-tetrafluoropropene (R1234ze(E)) and 2,3,3,3-tetrafluoropropene (R1234yf) from (343.15 K, 385 kPa) to eight condensation states (283.15 K, 1 MPa; 283.15 K, 1.5 MPa; 283.15 K, 2 MPa; 283.15K, 2.5 MPa; 283.15K, 3 MPa; 268.15K, 1MPa; 273.15K, 1MPa; 278.15K, 1MPa) after the study the researcher successfully commented on the various physical properties of the refrigerant which were listed on the paper. The researcher also made a simulated model of the concept to verify the results. Llopis et al. [11] used refrigerants R404A and R507A in the double-stage vapor compression plant driven by a compound compressor which was initially working on the CFC-502. The researchers carried out performance correlation based on the investigation. The evaporation temperature was ranged between 237 K to 253 K. with a constant condensation temperature of 313 K at constant compressor speed of 1450 rpm. The findings are R404A performs significantly better at high evaporation temperature with original system, while R507A performs better at low evaporation temperature when a subcooler is attached to it in the modification. R404A gives more efficiency of the system when system works at high evaporation temperatures and does not work inter stage. Nawaz et al. [12] made a model to evaluate about HFOs as a replacement of HPWH. the researchers also evaluated the UEF, FHR and heat pump COP for R-1234yf, R-1234ze(E) and R-134a. The researcher went through various designed parameters to optimize the impact on performance. Critical performance parameters for the heat pump and water tank have been evaluated and compared to the baseline system. E. Mancuhan [13] investigated and correlated different refrigerants in EES, and carried out theoretical analysis for the refrigeration system with flash intercooling. The fluids used are R717, R134a, R152a and R290, R404A, R507. The analysis of every fluid is carried out in various operating conditions distinct to their physical properties. The objective was to find optimized intermediate pressure with respect to evaporator and condensation temperature for every refrigerant and also find maximum COP. The author came to conclusion that intermediate pressure increases with the increase in evaporator and condenser temperature and R507A has best intermediate pressure and R290 has least intermediate pressure in low temperature applications. In terms of COP the best performance corresponding to R134a was given by R717.

Antonio Giuffrida [14] examined the performance of a scroll expander in an organic Rankine cycle with the help of empirical model. The scroll was of hermetic type of 2 kW. In this study the initial working fluid R245fa was substituted with seven different refrigerants and a relation between efficiency of the cycle and the maximum temperature is carried out. The researcher found out that refrigerants like R1234yf, R1243zf and R1234ze(E) need a less refrigerant temperature at the inlet compared to R245fa and the efficiency of the cycle also decreases. R1234ze(E) gives better performance result as compared to the original working refrigerant. Sergio Bobbo et al. [15] reviewed the thermophysical properties of low GWP refrigerants with aim to replace them in the current HVAC systems and organic Rankine cycle applications. Due to different properties these fluids have limited application in devices not all the fluids can be used in each and every component of the system. The researcher concluded that fluids such as R1234yf and R1234ze(E), have been thoroughly studied and broad chunk of thermodynamic properties data is known for R1234ze(Z) and the author urges to carry out more investigations on HFOs and their blends for the more property data knowledge. The long research on low GWP fluids has been going on for a long time, and these new fluids are the expected substitute to R134a for vehicle refrigeration systems, although the fluids like R1234ze(Z) and R1233zd(E) are the expected substitute to R245fa in applications of heat pump and organic Rankine cycle. Nagata et al. [16] investigated the free convective condensation and pool boiling heat transfer coefficients (HTCs) of the given fluids on a horizontal smooth tube made of copper with an outer diameter of 19.12 mm. The researchers concluded that HTC of R1234ze(E) is marginally less than R134a. The HTC of R1234ze(Z) is fairly larger than R245fa, while for R1233zd(E) is the HTC is similar with R245fa. The pool boiling HTC of R1234ze(E) follows the previous pattern that is less than R134a. While the pool boiling HTC of R1234ze(Z) is larger than R245fa and R1233zd(E) is less than R245fa. Zhang et al. [17] carried out an experimental research to review the condensation and pressure drop characteristics of original fluids as R134a, R245fa and their expected substitutes like R1234ze(E) and R1233zd(E) in a plate heat exchanger within the temperature range of 30ºC to 70ºC. The researchers found out that HTC and pressure drop rise with the rising liquid Reynolds number and reducing saturation temperature. The fluids R1233zd(E) and R1234ze(E) have greater HTC and pressure drop their fellow fluids R134a and R245fa. In most of the countries in Europe R134a is being replaced by liquid halogenated olefins and it is a work undergoing continuously but as replacement is important the cooling capacity performance with the new fluid is important. Mota-Babiloni et al. [18] carried out an experimental correlation between the the R134a and R1234ze(E) under several conditions. The researchers concluded that to achieve same cooling capacity that of the original fluid there should be made a modification in the design of the system and a compressor greater of 43% and an internal heat exchanger. In the search of new refrigerant with very less ODP and GWP, many manufacturers are making blends of the different fluids. Here the Kou et al. [19] studied the phase behavior of R1234ze(E) blended with two of the HFCs which are R32 and R134a and correlation of isothermal vapor-liquid equilibria (VLE) for the two cases which is combination of R1234ze(E) with both of the other fluids and VLE was executed in the temperature of range (283.15-323.14) K. The researchers concluded that the maximum absolute deviations and relative deviations comes out to be 0.14 % and 0.0096 for the R-32 and R-1234ze(E) combination, and 0.09 % and 0.0072 for the combination of R-134a and R-1234ze(E). In order to improve the energy parameters of low performing refrigerating system with the working fluid as R134a Oruç et al. [20] carried out an experimental study and adding an liquid to suction heat exchanger and using other refrigerant like R1234yf and R1234ze(E) and comparing it with the original set up. The evaporation temperature was set to -9, -4.5 and 0°C and the condenser temperature was set to 40, 45, and 50°C. The cooing capacity and power consumption of the system with working fluid R1234ze(E) was less, while its COP was greater correlated to R1234yf. Also the performance of the system with heat exchanger using R1234ze(E) was superior by 3% than that without the heat exchanger with working fluid as R134a. Fukuda et al. [21] carried out thermodynamic, experimental, and numerical evaluation for the new generation fluids that is R1234ze(E) and R1234ze(Z). The researchers concluded in the thermodynamic evaluation shows that the theoretical COP escalated when the condensation temperature of each of the fluids was nearly 20 K below the critical temperature. From the experimental findings the researchers concluded that pressure drop was the one loss that contributed the most to the irreversible losses. The numerical evaluation proposed that R1234ze(Z) acquires the larger COP at temperature of 105 and 125 ºC as the losses due to pressure are reduced extremely. Mikielewicz and Wajs [22] studied high temperature vapour-compressor based single stage and cascade heat pumps with a number of working fluids by assuming the temperature of heat source to be 50 degree and the temperature of the condensate to be 130 degree. Finally, the researchers computed the value of COP (coefficient of performance) and the heat rates of the working fluid so obtained. Wu et al. [23] focused their study on R1234Ze refrigerants for its low global warming potential and proposed a hybrid heat pump system consisting of carbon di oxide gas trans critical system of heat pump with this refringent. Several test like exergy analysis and economic analysis were done and also comparison of performance of hybrid system and single source of heat pump system was done by comparing the thermal characteristic. After the study the researcher claimed that the capacity of proposed system is proportional to discharge of CO_2. Best COP of the hybrid system is achieved at the optimum level of CO_2 discharge. as the CO2 discharge level goes high, its exergy also goes high. The Cop and exergy efficiency of the are improved by 24.8 and 27.2 percent for 100 condensing temperature.

2.1 Gaps Identified

Out of all the refrigerants used in this study only refrigerant R134a has been previously used in the simple vapor compression refrigeration system which is modified with a liquid vapor heat exchanger. Rest of the refrigerants in this study such as R507A, R423A, R1233zd(E), R1234ze(Z), R1234ze(E) and R1243zf have not been used in this type of system.

So, a detailed performance analysis of these eco-friendly refrigerants on the given system will be carried out in this study.

Chapter 3

THERMODYNAMICS

Thermodynamics is the part of science which concerns with the conversion of disorganized form of energy into organized form, or sometimes it is also called the study of the equilibrium, energy and entropy. [39]

3.1 FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is known by other names such as Law of conservation of energy, Joule's Law and Quantitative Law. It states that for a closed system undergoing a cyclic process the net heat rejection is equal to the net work interaction when they are expressed in their own units.

$$\begin{pmatrix} \text{Total energy} \\ \text{entering the system} \end{pmatrix} - \begin{pmatrix} \text{Total energy} \\ \text{leaving the system} \end{pmatrix} = \begin{pmatrix} \text{Change in the total} \\ \text{energy of the system} \end{pmatrix}$$

Or

$$E_{in} - E_{out} = \Delta E_{system}$$

This is also called **energy balance,** and it can be applied to any system undergoing energy interaction.

$$\Delta E = \Delta\ (U + KE + PE)$$

Here

U = Internal Energy

KE = Kinetic Energy

PE = Potential Energy

3.1.1 ENERGY BALANCED FOR A CLOSED SYSTEM

If a closed system is having an energy interaction with its surrounding, generally the energy interactions are in the form of heat and work.

$$\Delta Q = \Delta E + \Delta W$$

Where

ΔQ = Net Heat Input

ΔW= Net Work Output

3.1.2 ENERGY BALANCED IN A STEADY FLOW PROCESS

Steady flow means when the properties does not vary with respect to time therefore, mass flow rate at the entry and departure of the control volume are same. The two main aspects of the steady flow process are the mass balance and energy balance.

Mass balance: $\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}}$

Mass balance means rate of mass arriving in the system is equal to the rate of mass of exiting the system.

Energy balance: $\dot{E}_{in} = \dot{E}_{out}$

Energy balance means the rate of energy arriving in the system is equal to the rate of energy exiting the system.

General equation of steady flow is given below:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

APPLICATION

A broad list of equipment concerns to engineers such as heat exchanger, turbine, nozzle, diffuser, compressor, pump, boiler, evaporator, condenser, throttling, etc. work under long term steady state conditions.

3.2 SECOND LAW OF THERMODYNAMICS

It is known by many names such as law of degradation of energy, directional law, qualitative law. First law of thermodynamics simply says that total energy is preserved but it doesn't provide knowledge regarding the direction of possible energy conversion

It is this law which provides the feasibility or the direction of possible energy conversion through the concept of entropy. It is this law which is applied first in the numerical to find out direction of the possible conversion and then apply the first law.

Second law of thermodynamics consist to two classical statements:

3.2.1 KELVIN-PLANCK STATEMENT

This is linked with the heat engines. It states that it is impossible to construct a device which operate in a cycle produces work constantly while interacting with single thermal reservoir.

This statement provides the concept of work producing device such as heat engine.

$$W_{net,out} = Q_{in} - Q_{out}$$

$$\eta_{thermal} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

3.2.2 CLAUSIUS STATEMENT

Clausius statement is linked with the refrigerator or heat pump. It states that it is impossible to construct a device which operates in a cycle transfer heat from low temperature reservoir to high temperature reservoir without consuming any other form of energy.

This statement provides the concept of work absorbing device such as heat pump and refrigerator. Both heat pump and refrigerator are known as reversed heat engine.

The measure of performance of work absorbing devices is indicated in terms of coefficient of performance (COP). Coefficient of performance is defined as the ratio of desired effect to the work input.

For refrigerator the COP is calculated as:

$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{Q_L}{W_{net,in}}$$

$$W_{net,in} = Q_H - Q_L$$

Where $Q_L = heat\ to\ be\ removed\ from\ the\ refrigerated\ space.$

$Q_H = heat\ rejected\ at\ higher\ temperature$

For heat pump the COP is calculated as:

$$COP_{HP} = \frac{Desired\ output}{Required\ input} = \frac{Q_H}{W_{net,in}}$$

3.2.3 ENTROPY

It is the measurement of degree of disorderness or randomness associated with the molecules.

The entropy principle states that entropy change of the universe can never have negative value.

$$\Delta S_{universe} >= 0$$

Where;

ΔS = Change in entropy of the universe

The conditions for different processes are shown below:

1. If the $\Delta S_{universe} > 0$, then the device is irreversible.
2. If the $\Delta S_{universe} = 0$, then the device is reversible.
3. If the $\Delta S_{universe} < 0$, then the device is impossible.

The variation in entropy of system is summation of entropy variation due to internal irreversibility and entropy change due to external interaction. The value of entropy generation is always positive.

Chapter 4

THEORETICAL ANALYSIS

4.1 LIQUID LIME HEAT EXCHANGER IN VAPOUR COMPRESSION SYSTEM

In this current effort I considered a vapor compression system armed with liquid vapor heat exchanger (lvhe), it is also liquid lime heat exchanger. The goal of liquid lime heat exchanger is to combine the superheating vapor with liquid subcooling. The increment in the refrigeration effect in case of regenerative heat exchanger is obtained at a low temperature correlated to superheating in evaporator.

The diagrammatic of above system is displayed in the figure below

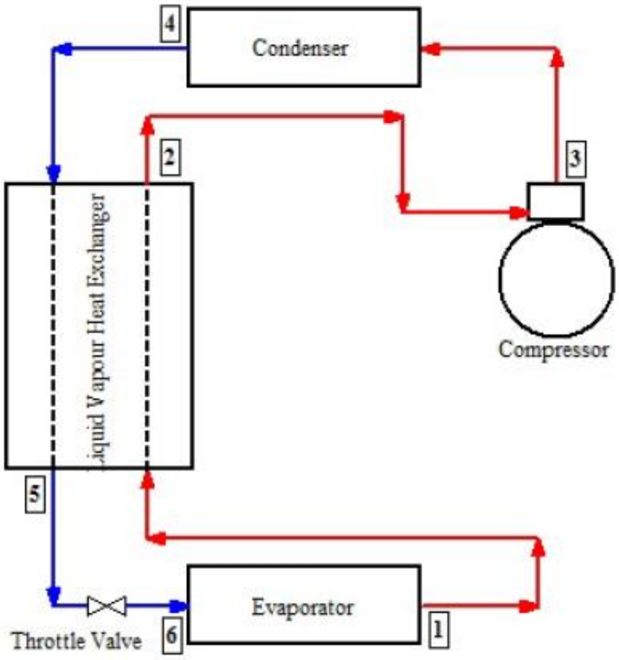


Figure 4.1: Vapor compression system equipped with regenerative heat exchanger. [40]

Thus the given system consists of following processes:

- *Process 1-2:* superheating of saturated vapour refrigerant in lvhe
- *Process 2*-3: actual compression of superheated vapour refrigerant in compressor.
- *Process 3*-4: isobaric heat rejection in condenser.
- *Process 4*-5: sub-cooling of saturated liquid refrigerant in lvhe.
- *Process 5*-6: isenthalpic expansion in expansion device.
- *Process 6*-1: isobaric heat extraction in the evaporator.

The p-h diagram of the above system is expressed in the figure shown below:

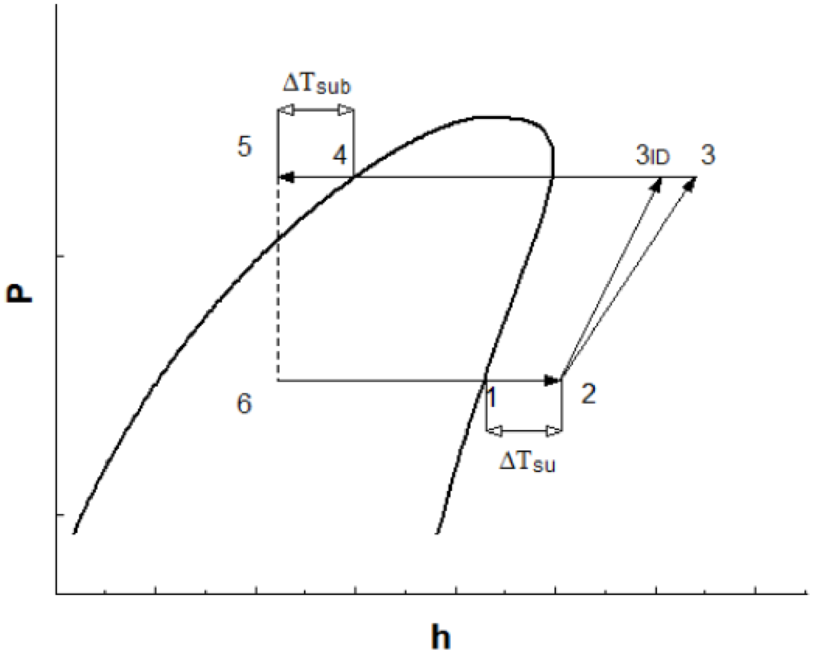


Figure 4.2: Representation of the system on p-h chart.

4.2 ENERGY ANALYSIS

It is associated with work and energy losses. It basically follows the first law of thermodynamics.

We make use of steady state energy equation to find the energy interaction of each and every component of the system.

Steady state as obtained from equation (1),

$$\dot{Q}_i + \dot{W}_i + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{Q}_e + \dot{W}_e + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) \tag{1}$$

Now we apply the steady flow energy equation in each and every component overlooking changes in the kinetic and potential energies, the obtained results are.

- **Evaporator**

  The heat removed in the evaporator:

$$\dot{Q}_{6-1} = \dot{Q}_E = \dot{m}_r(h_1 - h_6) \tag{2}$$

- **Compressor**

  Ideal work input to the compressor:

$$\dot{W}_{Ideal} = \dot{m}_r(h_{3ID} - h_2) \tag{3}$$

  Isentropic efficiency: It is described as the ratio of isentropic/ideal work input to the actual work input.

$$\eta_{isentropic} = \frac{\dot{W}_{ideal}}{\dot{W}_{actual}} \tag{4}$$

  Actual work input can be written in the form of enthalpy as:

$$\dot{W}_{actual} = \dot{m}_r(h_3 - h_2) \tag{5}$$

- **Condenser**

  Heat rejection in the condenser:

$$\dot{Q}_{3-4} = \dot{m}_r(h_3 - h_4) \tag{6}$$

- **Liquid Vapor Heat Exchanger**

  By use of the heat exchanger the superheating of vapor is combined with the liquid subcooling.

  Effectiveness of heat exchanger (ε_{lvhe}) is the ratio of actual heat transfer to the maximum heat transfer taking place in the heat exchanger. This tells about how much percentage increase in heat transfer rate we are able to gain b keeping the the heat exchanger as compared to the case where there is no heat exchanger.

$$\varepsilon_{lvhe} = \frac{h_2 - h_1}{h_4 - h_1} \tag{7}$$

- **Expansion Device**

  The expansion process is known by different names such as throttling, isenthalpic process or constant enthalpy process. Throttling is an irreversible adiabatic process and it always result a decrease in pressure i.e. expansion.

$$h_5 = h_6 \tag{8}$$

Coefficient of performance: obtained from second law of thermodynamics

$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{\dot{Q}_E}{\dot{W}_{actual}} = \frac{\dot{m}_r(h_1 - h_6)}{\dot{W}_{ideal}}\eta_{isentropic}$$

$$= \frac{\dot{m}_r(h_1 - h_6)}{\dot{m}_r(h_3 - h_2)} \tag{9}$$

4.3 EXERGY ANALYSIS

Second law of thermodynamics deduce the conception of exergy. It is the second law which provides the feasibility or the direction of possible energy conversion through the concept of entropy. It is this law which is applied first in the numerical to find out direction of possible conversion and then apply the first law. Other name for exergy is available energy, it is described as the max load of work which is extracted in a cycle from a certain heat input.[41]

This study is an impressive accomplice in the design, escalation, and execution estimation of the systems. This concept provides an idea of how much energy the system is using and the how much is provided. It also provides a platform to inform us about the entropy generated due to the available energy consumption and how much entropy is abandoned in the environment.

Such investigation provides an improved understanding of field of heating, ventilation, and air conditioning and by that it provides us an opportunity to develop the sustainable built climate for tomorrow. [41]

Exergy balance equation for control volume undergoing steady state process is written as:

$$\dot{X}_i + \dot{X}_j^Q = \dot{X}_e + \dot{W}_j + E\dot{D}_j \tag{10}$$

$$\dot{X}_i = \sum_{IN} \dot{m}\, x$$

$$\dot{X}_e = \sum_{OUT} \dot{m}\, x$$

$$\dot{X}_j^Q = \sum \left[\dot{Q}_j \frac{T - T_o}{T} \right]$$

$$x = (h - T_o s) - (h_o - T_o s_o)$$

The first term on both the left side and the right side respectively expresses the physical energy of gush of matter arriving and exiting the control volume respectively. This physical energy does not include kinetic, potential, and chemical energy of the component. The second term on both the right side and left side respectively expresses the thermal exergy flow, which gives exergy transfer rate corresponding to the heat transfer rate $\dot{Q}$ when the temperature at the control surface where heat transfer is occurring is T and exergy associated with work transfer to and from the control region. $E\dot{D}$ represents rate of exergy destruction.

4.3.1 EXERGY DESTRUCTION (ED)

All the practical real life processes are irreversible in nature such as infusion of fluids, heat transfer through a finite temperature difference, free expansion, chemical reaction, etc. and these processes generates entropy. We need to know the destruction of exergy within the devices so that we can improve the efficiency of each and every device. The losses and exergy destruction are inevitable in each device but all we can do improve the efficiency and minimize the losses occurring within the thermal system. The exergy destruction in various devices are shown below:

- **Evaporator**

$$\dot{ED}_E = \dot{X}_6 + \dot{Q}_E\left(1 - \frac{T_o}{T_r}\right) - \dot{X}_1 = \dot{m}_r[(h_6 - h_1) - T_o(s_6 - s_1)] + \dot{Q}_E\left(1 - \frac{T_o}{T_r}\right) \tag{11}$$

- **Compressor**

$$\dot{ED}_{comp} = \dot{X}_2 + \dot{W}_{comp} - \dot{X}_3 = \dot{m}_r[T_o(s_3 - s_2)] \tag{12}$$

- **Condenser**

$$\dot{ED}_c = \dot{X}_3 - \dot{X}_4 = \dot{m}_r[(h_3 - h_4) - T_o(s_3 - s_4)] \tag{13}$$

- **Liquid Vapor Heat Exchanger**

$$\begin{aligned} \dot{ED}_{lvhe} &= (\dot{X}_4 - \dot{X}_5) + (\dot{X}_1 - \dot{X}_2) \\ &= \dot{m}_r\big[(h_4 - h_5) + (h_1 - h_2) - T_o[(s_4 - s_5) + (s_1 - s_2)]\big] \end{aligned} \tag{14}$$

- **Throttle Valve**

$$\dot{ED}_t = \dot{X}_5 - \dot{X}_6 = \dot{m}_r[T_o(s_5 - s_6)] \tag{15}$$

4.3.2 Total Exergy Destruction

This is summation of the exergy destruction of all devices in the system.

$$\dot{ED}_{total} = \dot{ED}_E + \dot{ED}_{comp} + \dot{ED}_c + \dot{ED}_{lvhe} + \dot{ED}_t \tag{16}$$

As discussed earlier, the exergy analysis determines the losses in the system and we can make use of this analysis to improve the efficiency.

4.3.3 Exergetic Efficiency

Exergetic efficiency is described as the ratio of minimal exergy needed to get done a work to the substantial exergy absorbed in carrying out the similar work [41].

$$\eta_{exergetic} = \frac{\text{minimum exergy required to do given task}}{\text{actual exergy consumed}} \tag{17}$$

In the VCR system the ultimate aim is to remove the heat in the evaporator from the area to be refrigerated at temperature T_r and therefore we need minimal exergy which is thermal exergy flow between the area which is refrigerated and the evaporator,

$$\dot{X}_E^Q = \dot{Q}_E \left|\left(1 - \frac{T_o}{T_r}\right)\right| \tag{18}$$

The actual exergy exhausted is the work input of the real compressor, $\dot{W}_{comp}$.

Thus, the exergetic efficiency can be penned as

$$\eta_{exergetic} = \frac{\dot{Q}_E \left|\left(1 - \frac{T_o}{T_r}\right)\right|}{\dot{W}_{comp}} = \frac{COP_{vcr}}{COP_{rev}} \tag{19}$$

Where the COP_{rev} and COP_{vcr} are the coefficient of performance of the reversible system operating between temperature T_o and T_r and of actual operating system respectively.

4.3.4 Exergy Destruction Ratio (EDR)

EDR is the ratio of total exergy destruction in the system to minimum exergy needed to perform a given task.

$$\mathrm{EDR} = \frac{\dot{\mathrm{ED}}_{\mathrm{total}}}{\dot{\mathrm{X}}_{\mathrm{E}}^{\mathrm{Q}}} = \frac{\mathrm{COP}_{\mathrm{vcr}}}{\mathrm{COP}_{\mathrm{rev}}} - 1 \tag{20}$$

EDR can be written in form of exergetic efficiency as shown in equation (21).

$$\mathrm{EDR} = \frac{1}{\eta_{\mathrm{exergetic}}} - 1 \tag{21}$$

4.3.5 Efficiency Defect (δ_j)

The fragment of the input which was destroyed in the devices of the system due to irreversibilities is known as efficiency defect. It provides a link between the irreversibilities of the devices and the consequences it has on the efficiency of the system [41]. It is defined as the ratio of the exergy destruction rate in the j-th device to definite compressor work.

$$\delta_j = \frac{\dot{\mathrm{ED}}_j}{\dot{\mathrm{W}}_{\mathrm{comp}}} \tag{22}$$

- **Evaporator**

$$\delta_e = \frac{\dot{\mathrm{ED}}_{\mathrm{E}}}{\dot{\mathrm{W}}_{\mathrm{comp}}} \tag{23}$$

- **Compressor**

$$\delta_{comp} = \frac{\dot{ED}_{comp}}{\dot{W}_{comp}} \tag{24}$$

- **Condenser**

$$\delta_{c} = \frac{\dot{ED}_{c}}{\dot{W}_{comp}} \tag{25}$$

- **Liquid Vapor Heat Exchanger**

$$\delta_{lvhe} = \frac{\dot{ED}_{lvhe}}{\dot{W}_{comp}} \tag{26}$$

- **Throttle Valve**

$$\delta_{t} = \frac{\dot{ED}_{t}}{\dot{W}_{comp}} \tag{27}$$

CHAPTER 5

RESULT AND DISCUSSION

The energy and exergy analysis of the mathematical computational model was executed using EES software.[42]

The calculation was carried out by assuming the input data given below:

1. Mass flow rate of the refrigerant ($\dot{m}_r$): 1 kg/s
2. Isentropic Efficiency of the compressor (η_{comp}): 75%
3. Effectiveness of liquid vapor heat exchanger (ε_{lvhe}): 0.8
4. Degree of sub-cooling of liquid refrigerant in lvhe (ΔT_{sub}): 5K
5. Difference between space and evaporator temperature ($T_r - T_E$): 15K
6. Evaporator Temperature (T_E): 223 K to 273 K
7. Condenser Temperature (T_c): 313 K to 323 K
8. Ambient Temperature (T_o): 298 K
9. Pressure drop in the devices like evaporator, condenser and heat exchanger is taken as negligible.
10. The value of effectiveness of the heat exchanger is varied from 0 to 1, as at different values its effect is studied on the system.
11. The degree of subcooling is deviated from 0 K to 10 K, as study its consequences on the system at different values.

5.1 MODEL VALIDATION

Yadav et al. [40] carried out the study similar to this, and COP of R134a in that study when varied with evaporator temperature when condenser temperature was 313 K and the COP came out be 1.1 at an evaporator temperature of 223 K. Whereas, at the same condition in this study the COP came out to be 1.13 which is almost similar in trend and thus we can validate our model and perform the study of the other refrigerants.

5.2 RESULTS

A broad exergy analysis has been carried out and the results achieved are arranged in the tabular form, and comparison between the different parameters were calculated, after varying the temperature of evaporator, ambient state, degree of subcooling, and the effectiveness of the heat exchanger at the two distinct values of the temperature of condenser which has been expressed in graphs.

5.2.1 Variation of Evaporator Temperature

The latter tables from table 5.1 to 5.14 display the effect of varying the evaporator temperature on the different system parameters corresponding to condenser temperature of 313 K to 323 K.

Table 5.1: For R134a (T_C=313K)

T_E	T_C	COP	$\eta_{exergetic}$	EDR	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	313	1.13	0.285	4.151	0.2074	0.04795	0.02924	0.2333	0.6651
228	313	1.264	0.2861	4.116	0.2098	0.04406	0.02924	0.2205	0.674
233	313	1.416	0.2854	4.098	0.212	0.04061	0.02919	0.2076	0.6803
238	313	1.589	0.2827	4.098	0.2141	0.03754	0.0291	0.1946	0.6833
243	313	1.79	0.2775	4.122	0.216	0.03483	0.02896	0.1816	0.6824
248	313	2.022	0.2691	4.177	0.2177	0.03245	0.02876	0.1686	0.6767

253	313	2.296	0.257	4.276	0.2193	0.03039	0.02849	0.1556	0.6652
258	313	2.621	0.24	4.443	0.2208	0.02863	0.02813	0.1427	0.6463
263	313	3.014	0.2168	4.725	0.2222	0.02717	0.02767	0.1297	0.6177
268	313	3.496	0.1853	5.233	0.2235	0.02601	0.02707	0.1169	0.5764
273	313	4.102	0.1424	6.304	0.2246	0.02517	0.02628	0.1041	0.5178

Table 5.2: R423A (T_C=313K)

T_E	**T_C**	**COP**	**$\eta_{exergetic}$**	**EDR**	**δ_{comp}**	**δ_c**	**δ_{lvhe}**	**δ_{tv}**	**δ_e**
223	313	0.9959	0.2511	4.602	0.22	0.02297	0.03516	0.2869	0.5904
228	313	1.123	0.2543	4.532	0.2217	0.02084	0.03508	0.2707	0.6042
233	313	1.269	0.2558	4.484	0.2231	0.01904	0.03496	0.2544	0.6155
238	313	1.435	0.2553	4.46	0.2244	0.01754	0.03478	0.2381	0.6238
243	313	1.628	0.2523	4.464	0.2255	0.0163	0.03455	0.2217	0.6284
248	313	2.851	0.2464	4.504	0.2265	0.01532	0.03425	0.2052	0.6284
253	313	2.114	0.2366	4.595	0.2274	0.01457	0.03388	0.1886	0.623
258	313	2.426	0.2222	4.761	0.2281	0.01405	0.03342	0.172	0.6104
263	313	3.803	0.2016	5.055	0.2287	0.01377	0.03285	0.1552	0.5889
268	313	3.264	0.173	5.598	0.2292	0.01374	0.03214	0.1382	0.5554
273	313	4.842	0.1334	6.756	0.2296	0.01399	0.03123	0.1208	0.5057

Table 5.3: R507A (T_C=313K)

T_E	T_C	**COP**	$\eta_{exergetic}$	**EDR**	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	313	0.9421	0.2375	4.819	0.2143	0.03823	0.03214	0.3053	0.5544
228	313	1.064	0.2408	4.743	0.2161	0.0358	0.03181	0.2908	0.5674
233	313	1.202	0.2424	4.69	0.2176	0.03369	0.0314	0.2762	0.578
238	313	1.361	0.2422	4.662	0.2191	0.03187	0.0309	0.2616	0.5855
243	313	1.545	0.2396	4.665	0.2204	0.03034	0.03029	0.2471	0.5895
248	313	1.759	0.2341	4.706	0.2216	0.02906	0.02955	0.2327	0.589
253	313	2.011	0.2251	4.801	0.2227	0.02803	0.02865	0.2184	0.583
258	313	2.311	0.2117	4.975	0.2238	0.02726	0.02754	0.2042	0.5702
263	313	2.674	0.1924	5.283	0.2247	0.02674	0.02616	0.1903	0.5484
268	313	3.12	0.1654	5.854	0.2256	0.02651	0.02442	0.1766	0.5148
273	313	3.68	0.1278	7.071	0.2265	0.0266	0.02217	0.1633	0.465

Table 5.4: R1233zd(E) (T_C=313K)

T_E	T_C	**COP**	$\eta_{exergetic}$	**EDR**	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	313	1.225	0.3088	3.893	0.2119	0.03414	0.0257	0.2097	0.7208
228	313	1.367	0.3094	3.865	0.2143	0.03058	0.02562	0.1963	0.7291
233	313	1.528	0.3081	3.852	0.2166	0.02745	0.0255	0.183	0.7345
238	313	1.712	0.3046	3.856	0.2186	0.02472	0.02533	0.1696	0.7363
243	313	1.924	0.2983	3.882	0.2205	0.02235	0.02511	0.1564	0.7339
248	313	2.17	0.2888	3.936	0.2221	0.02032	0.02483	0.1432	0.7264
253	313	2.459	0.2752	4.031	0.2236	0.01859	0.02449	0.1302	0.7127
258	313	2.802	0.2566	4.188	0.2249	0.01716	0.02407	0.1172	0.691

263	313	3.215	0.2313	4.45	0.2261	0.016	0.02356	0.1044	0.6592
268	313	3.722	0.1973	4.922	0.2271	0.01512	0.02292	0.09183	0.614
273	313	4.358	0.1513	5.912	0.228	0.01453	0.02212	0.0794	0.5506

Table 5.5: R1234ze(E) at (T_C=313 K)

T_E	**T_C**	**COP**	**$\eta_{exergetic}$**	**EDR**	**δ_{comp}**	**δ_c**	**δ_{lvhe}**	**δ_{tv}**	**δ_e**
223	313	1.086	0.2738	4.287	0.2201	0.02265	0.0336	0.261	0.6365
228	313	1.223	0.2769	4.227	0.2216	0.02087	0.0331	0.245	0.6498
233	313	1.379	0.278	4.187	0.2229	0.01922	0.03275	0.2293	0.6598
238	313	1.557	0.2769	4.169	0.2242	0.01774	0.03246	0.2138	0.6661
243	313	1.761	0.273	4.178	0.2254	0.01644	0.03217	0.1984	0.6683
248	313	1.999	0.266	4.22	0.2265	0.01534	0.03186	0.1831	0.6655
253	313	2.278	0.255	4.306	0.2274	0.01447	0.03149	0.168	0.6565
258	313	2.609	0.239	4.461	0.2282	0.01382	0.03103	0.153	0.6399
263	313	3.01	0.2166	4.73	0.2289	0.01342	0.03045	0.1381	0.6135
268	313	3.502	0.1856	5.225	0.2295	0.01326	0.02972	0.1234	0.574
273	313	4.12	0.1431	6.275	0.23	0.01339	0.02878	0.1089	0.5166

Table 5.6: R1234ze(Z) at (T_C=313 K)

T_E	**T_C**	**COP**	**$\eta_{exergetic}$**	**EDR**	**δ_{comp}**	**δ_c**	**δ_{lvhe}**	**δ_{tv}**	**δ_e**
223	313	1.36	0.3428	3.587	0.1984	0.06376	0.02382	0.1663	0.7775
228	313	1.502	0.3399	3.589	0.2014	0.05838	0.02368	0.157	0.7796
233	313	1.663	0.3353	3.602	0.2043	0.0535	0.02351	0.1475	0.7788
238	313	1.846	0.3284	3.629	0.207	0.04908	0.02331	0.1379	0.7748

243	313	2.058	0.319	3.675	0.2095	0.0451	0.02308	0.1281	0.7667
248	313	2.303	0.3064	3.747	0.2118	0.04152	0.02281	0.1183	0.7537
253	313	2.59	0.2899	3.856	0.214	0.03833	0.02249	0.1084	0.7347
258	313	2.931	0.2684	4.024	0.2161	0.03551	0.0221	0.0984	0.7079
263	313	3.342	0.2404	4.294	0.218	0.03304	0.02163	0.08841	0.6713
268	313	3.846	0.2039	4.766	0.2198	0.03093	0.02106	0.07841	0.6214
273	313	4.479	0.1555	5.742	0.2214	0.02919	0.02034	0.06844	0.5536

Table 5.7: R1243f at (T_C=313 K)

T_E	T_C	**COP**	$\eta_{exergetic}$	**EDR**	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	313	1.085	0.2735	4.291	0.2114	0.03896	0.02947	0.2421	0.6516
228	313	1.215	0.2751	4.249	0.2138	0.03526	0.0295	0.229	0.6614
233	313	1.364	0.2751	4.224	0.2159	0.03199	0.02949	0.2158	0.6686
238	313	1.535	0.2731	4.217	0.2178	0.02911	0.02943	0.2025	0.6728
243	313	1.733	0.2686	4.235	0.2196	0.02659	0.02931	0.189	0.6731
248	313	1.962	0.2612	4.285	0.2212	0.0244	0.02914	0.1756	0.6689
253	313	2.233	0.25	4.381	0.2226	0.02251	0.02889	0.1621	0.6589
258	313	2.556	0.234	4.545	0.2239	0.02091	0.02855	0.1486	0.6417
263	313	2.945	0.2119	4.827	0.2251	0.01958	0.0281	0.1352	0.6149
268	313	3.424	0.1815	5.342	0.2261	0.01852	0.02751	0.1217	0.5756
273	313	4.026	0.1398	6.43	0.2271	0.01774	0.02673	0.1084	0.519

Table 5.8: R134a at (T_C=323 K)

T_E	T_C	COP	$\eta_{exergetic}$	EDR	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	323	0.9123	0.23	4.705	0.2011	0.04655	0.03001	0.2677	0.5367
228	323	1.018	0.2305	4.661	0.2033	0.04296	0.03002	0.255	0.543
233	323	1.138	0.2293	4.639	0.2054	0.03977	0.02999	0.2421	0.5466
238	323	1.272	0.2263	4.641	0.2073	0.03696	0.02992	0.2292	0.547
243	323	1.426	0.2211	4.674	0.2091	0.03448	0.0298	0.2162	0.5437
248	323	1.602	0.2131	4.747	0.2107	0.03232	0.02963	0.2032	0.5359
253	323	1.804	0.202	4.877	0.2122	0.03044	0.0294	0.1902	0.5227
258	323	2.04	0.1868	5.094	0.2135	0.02885	0.0291	0.1772	0.5059
263	323	2.317	0.1667	5.46	0.2148	0.02753	0.02871	0.1641	0.4748
268	323	2.646	0.1402	6.118	0.216	0.02647	0.02822	0.1512	0.4362
273	323	3.043	0.1057	7.501	0.217	0.02569	0.02759	0.1382	0.3841

Table 5.9: R423A at (T_C=323 K)

T_E	T_C	COP	$\eta_{exergetic}$	EDR	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	323	0.7654	0.193	5.474	0.214	0.0215	0.03604	0.3313	0.4535
228	323	0.8656	0.1959	5.367	0.2155	0.01959	0.03598	0.3152	0.4653
233	323	0.9787	0.1973	5.292	0.2169	0.01797	0.03588	0.2989	0.4745
238	323	1.107	0.1969	5.25	0.2181	0.01663	0.03573	0.2826	0.4808
243	323	1.253	0.1943	5.249	0.2191	0.01554	0.03552	0.2662	0.4836
248	323	1.421	0.1891	5.297	0.22	0.01468	0.03526	0.2497	0.482
253	323	1.615	0.1807	5.413	0.2208	0.01404	0.03493	0.2332	0.4754
258	323	1.84	0.1685	5.63	0.2215	0.0136	0.03452	0.2167	0.4624

263	323	2.105	0.1514	6.017	0.222	0.01337	0.03403	0.2	0.4417
268	323	2.419	0.1282	6.734	0.2225	0.01335	0.03343	0.1833	0.411
273	323	2.799	0.09718	8.265	0.2229	0.01356	0.03269	0.1664	0.3676

Table 5.10: R507A at (T_C=323 K)

T_E	T_C	**COP**	$\eta_{exergetic}$	**EDR**	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	323	0.6946	0.1751	5.962	0.2074	0.03921	0.03351	0.355	0.4088
228	323	0.7871	0.1782	5.837	0.209	0.03705	0.03317	0.3407	0.4199
233	323	0.8917	0.1798	5.748	0.2105	0.03521	0.03276	0.3263	0.4286
238	323	1.01	0.1797	5.699	0.2118	0.03365	0.03226	0.3119	0.4345
243	323	1.146	0.1776	5.696	0.213	0.03237	0.03167	0.2975	0.437
248	323	1.301	0.1731	5.748	0.2141	0.03134	0.03095	0.2832	0.4354
253	323	1.48	0.1657	5.878	0.2151	0.03056	0.03009	0.2689	0.429
258	323	1.689	0.1547	6.121	0.2161	0.03002	0.02906	0.2548	0.4166
263	323	1.935	0.1392	6.553	0.2169	0.02974	0.02781	0.2408	0.3968
268	323	2.227	0.1181	7.355	0.2177	0.02972	0.02627	0.227	0.3675
273	323	2.581	0.08962	9.065	0.2185	0.03	0.02437	0.2134	0.3261

Table 5.11: R1233zd(E) at (T_C=323 K)

T_E	T_C	**COP**	$\eta_{exergetic}$	**EDR**	δ_{comp}	δ_c	δ_{lvhe}	δ_{tv}	δ_e
223	323	1.019	0.2568	4.286	0.2062	0.03151	0.02568	0.2378	0.5994
228	323	1.134	0.2566	4.253	0.2085	0.02822	0.02561	0.2244	0.6048
233	323	1.263	0.2547	4.239	0.2106	0.02534	0.02549	0.211	0.6071
238	323	1.409	0.2507	4.246	0.2126	0.02284	0.02534	0.1975	0.6059

243	323	1.575	0.2442	4.348	0.2143	0.02068	0.02514	0.1841	0.6006
248	323	1.764	0.2348	4.467	0.2158	0.01883	0.02489	0.1708	0.5905
253	323	1.982	0.2219	4.663	0.2172	0.01726	0.02459	0.1576	0.5744
258	323	2.235	0.2047	4.663	0.2185	0.01596	0.02422	0.1444	0.5512
263	323	2.532	0.1821	4.99	0.2195	0.01491	0.02378	0.1314	0.5191
268	323	2.884	0.1529	5.575	0.2205	0.01409	0.02325	0.1186	0.4759
273	323	3.309	0.1149	6.8	0.2213	0.01352	0.0226	0.1058	0.4181

Table 5.12: R1234ze(E) at (T_C=323 K)

T_E	**T_C**	**COP**	**$\eta_{exergetic}$**	**EDR**	**δ_{comp}**	**δ_c**	**δ_{lvhe}**	**δ_{tv}**	**δ_e**
223	323	0.8594	0.2166	4.952	0.2139	0.0212	0.03423	0.2997	0.5037
228	323	0.9689	0.2193	4.865	0.2153	0.01957	0.03376	0.2836	0.5146
233	323	1.092	0.2201	4.808	0.2166	0.01808	0.03343	0.2678	0.5223
238	323	1.23	0.2188	4.782	0.2178	0.01674	0.03316	0.2521	0.5264
243	323	1.387	0.215	4.791	0.2189	0.01557	0.0329	0.2365	0.5264
248	323	1.567	0.2085	4.844	0.2199	0.01459	0.03262	0.2211	0.5217
253	323	1.774	0.1986	4.955	0.2208	0.01382	0.03228	0.2057	0.5113
258	323	2.015	0.1845	5.155	0.2215	0.01324	0.03118	0.1905	0.4941
263	323	2.298	0.1653	5.505	0.2221	0.01288	0.03137	0.1753	0.4683
268	323	2.635	0.1397	6.146	0.2227	0.01273	0.03075	0.1603	0.4318
273	323	3.042	0.1056	7.506	0.2231	0.01279	0.02998	0.1455	0.3814

Table 5.13: R1234ze(Z) at (T_C=323 K)

T_E	**T_C**	**COP**	**$\eta_{exergetic}$**	**EDR**	**δ_{comp}**	**δ_c**	**δ_{lvhe}**	**δ_{tv}**	**δ_e**
223	323	1.146	0.289	3.886	0.1921	0.06112	0.02386	0.1904	0.6554
228	323	1.261	0.2854	3.89	0.195	0.05603	0.02373	0.1812	0.6545
233	323	1.39	0.2802	3.909	0.1977	0.05142	0.02358	0.1717	0.6509
238	323	1.535	0.2729	3.945	0.2002	0.04724	0.02341	0.162	0.6439
243	323	1.699	0.2634	4.004	0.2026	0.04348	0.02321	0.1522	0.633
248	323	1.886	0.251	4.094	0.2048	0.04009	0.02297	0.1423	0.6175
253	323	2.102	0.2353	4.23	0.2069	0.03706	0.02269	0.1323	0.5963
258	323	2.352	0.2154	4.438	0.2088	0.03437	0.02236	0.1222	0.5682
263	323	2.646	0.1904	4.771	0.2106	0.03199	0.02197	0.1121	0.5315
268	323	2.995	0.1587	5.352	0.2122	0.02992	0.0215	0.102	0.4839
273	323	3.415	0.1186	6.551	0.2138	0.02815	0.02093	0.09186	0.4221

Table 5.14: R1243zf at (T_C=323 K)

T_E	**T_C**	**COP**	**$\eta_{exergetic}$**	**EDR**	**δ_{comp}**	**δ_c**	**δ_{lvhe}**	**δ_{tv}**	**δ_e**
223	323	0.8709	0.2196	4.895	0.2054	0.03735	0.03034	0.2785	0.5232
228	323	0.9747	0.2206	4.84	0.2076	0.03399	0.03039	0.2654	0.5304
233	323	1.092	0.2201	4.807	0.2095	0.03103	0.0304	0.2522	0.5351
238	323	1.225	0.2178	4.8	0.2113	0.02844	0.03035	0.2388	0.5367
243	323	1.376	0.2134	4.825	0.2129	0.02619	0.03026	0.2253	0.5347
248	323	1.55	0.2063	4.891	0.2144	0.02426	0.03012	0.2118	0.5284
253	323	2.751	0.196	5.016	0.2157	0.02261	0.0299	0.1982	0.5167
258	323	2.985	0.1818	5.23	0.2169	0.02124	0.02962	0.1845	0.4984

263	323	2.261	0.1626	5.597	0.218	0.02013	0.02925	0.1709	0.472
268	323	2.589	0.1372	6.263	0.219	0.01928	0.02876	0.1573	0.4352
273	323	2.985	0.1037	7.671	0.2198	0.01869	0.02814	0.1437	0.3848

5.2.2 Variation of Ambient State Temperature (T_o)

Table 5.15: For R134a at (T_C=313 K)

T_o	$\eta_{exergetic}$	**EDR**
298	0.2775	4.122
301	0.2983	3.994
304	0.3191	3.883
307	0.3399	3.785
310	0.3607	3.698
313	0.3815	3.621
316	0.4023	3.552
319	0.4231	3.49
322	0.4439	3.433
325	0.4647	3.382
328	0.4855	3.335

Table 5.16: For R423A at (T_C=313 K)

T_o	$\eta_{exergetic}$	**EDR**
298	0.2523	4.464
301	0.2713	4.315

304	0.2902	4.186
307	0.3091	4.072
310	0.328	3.972
313	0.347	3.882
316	0.3659	3.802
319	0.3848	3.73
322	0.4037	3.664
325	0.4227	3.604
328	0.4416	3.55

Table 5.17: For R507A at (T_C=313 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2396	4.665
301	0.2575	4.504
304	0.2755	4.364
307	0.2935	4.241
310	0.3114	4.133
313	0.3294	4.036
316	0.3474	3.949
319	0.3653	3.871
322	0.3833	3.8
325	0.4013	3.735
328	0.4192	3.676

Table 5.18: For R1233zd(E) at (T_C=313 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2983	3.882
301	0.3207	3.768
304	0.3431	3.67
307	0.3655	3.583
310	0.3878	3.506
313	0.4102	3.438
316	0.4326	3.376
319	0.455	3.321
322	0.4773	3.271
325	0.4997	3.225
328	0.5221	3.184

Table 5.19: For R1234ze(E) at (T_C=313 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.273	4.178
301	0.2935	4.047
304	0.314	3.932
307	0.3344	3.832
310	0.3549	3.743
313	0.3754	3.664
316	0.3959	3.593
319	0.4164	3.529

322	0.4368	3.471
325	0.4573	3.418
328	0.4778	3.37

Table 5.20: For R1234ze(Z) at (T_C=313 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.319	3.675
301	0.3429	3.574
304	0.3669	3.486
307	0.3908	3.409
310	0.4147	3.341
313	0.4386	3.28
316	0.4626	3.225
319	0.4865	3.176
322	0.5104	3.131
325	0.5343	3.091
328	0.5583	3.054

Table 5.21: For R1243zf at (T_C=313 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2686	4.235
301	0.2888	4.1
304	0.3089	3.983

307	0.329	3.88
310	0.3492	3.789
313	0.3693	3.708
316	0.3895	3.635
319	0.4096	3.569
322	0.4298	3.51
325	0.4499	3.455
328	0.4701	3.406

Table 5.22: For R134a at (T_C=323 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2211	4.674
301	0.2377	4.512
304	0.2542	4.372
307	0.2708	4.249
310	0.2874	4.14
313	0.304	4.043
316	0.3206	3.956
319	0.3371	3.877
322	0.3537	3.806
325	0.3703	3.741
328	0.3869	3.682

Table 5.23: For R1233zd(E) at (T_C=323 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2442	4.279
301	0.2625	4.142
304	0.2808	4.022
307	0.2991	3.917
310	0.3174	3.824
313	0.3357	3.741
316	0.354	3.667
319	0.3724	3.6
322	0.3907	3.539
325	0.409	3.484
328	0.4273	3.434

Table 5.24: For R1234ze(E) at (T_C=323 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.215	4.791
301	0.2312	4.622
304	0.2473	4.476
307	0.2634	4.347
310	0.2796	4.233
313	0.2957	4.132
316	0.3118	4.041
319	0.3279	3.959

322	0.3441	3.885
325	0.3602	3.817
328	0.3763	3.755

Table 5.25: For R1234ze(Z) at (T_C=323 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2634	4.004
301	0.2831	3.883
304	0.3029	3.777
307	0.3226	3.685
310	0.3424	3.603
313	0.3622	3.531
316	0.3819	3.465
319	0.4017	3.406
322	0.4214	3.353
325	0.4412	3.305
328	0.4609	3.26

Table 5.26: For R1243zf at (T_C=323 K)

T_o	**$\eta_{exergetic}$**	**EDR**
298	0.2134	4.825
301	0.2294	4.654
304	0.2454	4.506

307	0.2614	4.376
310	0.2774	4.26
313	0.2934	4.156
316	0.3094	4.066
319	0.3254	3.983
322	0.3414	3.908
325	0.3574	3.839
328	0.3734	3.777

Table 5.27: For R423A at (T_C=323 K)

$\mathbf{T_o}$	$\boldsymbol{\eta_{exergetic}}$	**EDR**
298	0.1943	5.249
301	0.2089	5.052
304	0.2235	4.882
307	0.238	4.732
310	0.2526	4.6
313	0.2672	4.482
316	0.2818	4.376
319	0.2963	4.28
322	0.3109	4.194
325	0.3255	4.115
328	0.3401	4.043

Table 5.28: For R507A at (T_C=323 K)

T_o	$\eta_{exergetic}$	EDR
298	0.1776	5.696
301	0.1909	5.472
304	0.2042	5.278
307	0.2176	5.108
310	0.2309	4.957
313	0.2442	4.823
316	0.2575	4.703
319	0.2708	4.594
322	0.2842	4.496
325	0.2975	4.406
328	0.3108	4.324

5.2.3 Variation of Effectiveness (ε_{lvhe}):

Table 5.29: For R134a at (T_C=313 K)

ε_{lvhe}	COP	$\eta_{exergetic}$	EDR
0	0.7513	0.1165	8.865
0.1	1.401	0.2172	5.075
0.2	1.574	0.244	4.593
0.3	1.656	0.2568	4.398
0.4	1.705	0.2644	4.292
0.5	1.737	0.2693	4.226
0.6	1.76	0.2729	4.18

0.7	1.777	0.2755	4.147
0.8	1.79	0.2775	4.121
0.9	1.801	0.2792	4.101
1	1.809	0.2805	4.085

Table 5.30: For R1233zd(E)a at (T_C=313 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.8649	0.1341	7.791
0.1	1.568	0.2431	4.608
0.2	1.734	0.2688	4.233
0.3	1.809	0.2804	4.086
0.4	1.852	0.2871	4.007
0.5	1.88	0.2914	3.958
0.6	1.899	0.2944	3.924
0.7	1.914	0.2967	3.9
0.8	1.925	0.2984	3.881
0.9	1.933	0.2998	3.867
1	1.941	0.3009	3.855

Table 5.31: For R1234ze(Z)a at (T_C=313 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.9811	0.1521	6.95
0.1	1.674	0.2596	4.359

0.2	1.846	0.2862	4.018
0.3	1.927	0.2988	3.877
0.4	1.975	0.3062	3.8
0.5	2.006	0.3111	3.751
0.6	2.029	0.3145	3.718
0.7	2.045	0.3171	3.693
0.8	2.058	0.3191	3.674
0.9	2.069	0.3207	3.66
1	2.077	0.322	3.648

Table 5.32: For R1234ze(E)a at (T_C=313 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.738	0.1144	9.012
0.1	1.395	0.2163	5.093
0.2	1.56	0.2419	4.627
0.3	1.638	0.2539	4.441
0.4	1.683	0.2609	4.34
0.5	1.713	0.2655	4.276
0.6	1.734	0.2688	4.233
0.7	1.749	0.2712	4.201
0.8	1.761	0.2731	4.177
0.9	1.771	0.2746	4.158
1	1.779	0.2758	4.143

Table 5.33: For R1243zf at (T_C=313 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.7521	0.1166	8.855
0.1	1.373	0.2129	5.164
0.2	1.533	0.2377	4.696
0.3	1.61	0.2496	4.506
0.4	1.655	0.2565	4.402
0.5	1.684	0.2611	4.337
0.6	1.705	0.2644	4.292
0.7	1.721	0.2668	4.259
0.8	1.733	0.2687	4.234
0.9	1.743	0.2702	4.215
1	1.751	0.2714	4.199

Table 5.34: For R423A at (T_C=313 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.6825	0.1058	9.689
0.1	1.28	0.1984	5.489
0.2	1.435	0.2225	4.97
0.3	1.509	0.234	4.76
0.4	1.552	0.2407	4.647
0.5	1.581	0.2451	4.575
0.6	1.601	0.2483	4.526
0.7	1.616	0.2506	4.49

0.8	1.628	0.2524	4.463
0.9	1.637	0.2539	4.441
1	1.645	0.255	4.424

Table 5.35: For R507A at (T_C=313 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.6022	0.09336	10.89
0.1	1.172	0.1817	5.93
0.2	1.334	0.2068	5.294
0.3	1.414	0.2192	5.035
0.4	1.461	0.2265	4.894
0.5	1.493	0.2314	4.805
0.6	1.515	0.235	4.743
0.7	1.532	0.2376	4.698
0.8	1.546	0.2396	4.664
0.9	1.556	0.2413	4.637
1	1.565	0.2426	4.615

Table 5.36: For R134a at (T_C=323 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.5875	0.09108	10.63
0.1	1.105	0.1714	5.885
0.2	1.247	0.1933	5.274
0.3	1.315	0.2039	5.026

0.4	1.355	0.2101	4.891
0.5	1.382	0.2143	4.806
0.6	1.401	0.2172	4.748
0.7	1.415	0.2194	4.705
0.8	1.426	0.2211	4.673
0.9	1.435	0.2225	4.647
1	1.442	0.2236	4.627

Table 5.37: For R1233zd(E) at (T_C=323 K)

ε_{lvhe}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	0.7052	0.1093	8.939
0.1	1.28	0.1985	5.149
0.2	1.417	0.2197	4.701
0.3	1.479	0.2293	4.524
0.4	1.515	0.2348	4.429
0.5	1.538	0.2384	4.37
0.6	1.554	0.2409	4.33
0.7	1.566	0.2428	4.301
0.8	1.575	0.2442	4.278
0.9	1.583	0.2454	4.261
1	1.589	0.2463	4.247

Table 5.38: For R1234ze(Z) at (T_C=323 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.9447	0.1465	6.8
0.1	1.397	0.2165	4.762
0.2	1.528	0.2369	4.395
0.3	1.593	0.2469	4.237
0.4	1.631	0.2529	4.149
0.5	1.657	0.2569	4.092
0.6	1.675	0.2597	4.053
0.7	1.689	0.2618	4.024
0.8	1.7	0.2635	4.002
0.9	1.708	0.2648	3.984
1	1.715	0.2659	3.97

Table 5.39: For R1234ze(E) at (T_C=323 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.5703	0.08842	10.94
0.1	1.089	0.1689	5.965
0.2	1.222	0.1895	5.369
0.3	1.286	0.1993	5.129
0.4	1.323	0.2051	4.999
0.5	1.347	0.2089	4.918
0.6	1.365	0.2116	4.862
0.7	1.377	0.2136	4.821

0.8	1.387	0.2151	4.79
0.9	1.395	0.2163	4.765
1	1.402	0.2173	4.746

Table 5.40: For R1243zf at (T_C=323 K)

$\boldsymbol{\varepsilon_{lvhe}}$	**COP**	$\boldsymbol{\eta_{exergetic}}$	**EDR**
0	0.5853	0.09075	10.67
0.1	1.08	0.1675	6.01
0.2	1.211	0.1878	5.414
0.3	1.274	0.1975	5.172
0.4	1.311	0.2033	5.039
0.5	1.336	0.2071	4.955
0.6	1.353	0.2098	4.898
0.7	1.366	0.2119	4.856
0.8	1.377	0.2134	4.824
0.9	1.385	0.2147	4.798
1	1.391	0.2157	4.778

Table 5.41: For R423A at (T_C=323 K)

$\boldsymbol{\varepsilon_{lvhe}}$	**COP**	$\boldsymbol{\eta_{exergetic}}$	**EDR**
0	0.515	0.07985	12.06
0.1	0.9759	0.1513	6.599
0.2	1.099	0.1703	5.917
0.3	1.158	0.1795	5.641

0.4	1.193	0.1849	5.491
0.5	1.216	0.1885	5.396
0.6	1.232	0.191	5.331
0.7	1.244	0.1929	5.283
0.8	1.254	0.1944	5.247
0.9	1.261	0.1956	5.219
1	1.268	0.1965	5.196

Table 5.42: For R507A at (T_C=323 K)

ε_{lvhe}	**COP**	$\eta_{exergetic}$	**EDR**
0	0.4296	0.0666	14.35
0.1	0.8526	0.1322	7.48
0.2	0.9775	0.1516	6.588
0.3	1.04	0.1613	6.222
0.4	1.078	0.1671	6.022
0.5	1.103	0.171	5.895
0.6	1.121	0.1739	5.807
0.7	1.135	0.176	5.743
0.8	1.146	0.1777	5.694
0.9	1.155	0.179	5.655
1	1.162	0.1801	5.624

5.2.4 Variation with degree of Subcooling (ΔT_{sub})

Table 5.43: For R134a at (T_C=313 K)

ΔT_{sub}	**COP**	$\eta_{exergetic}$	**EDR**
0	1.787	0.2771	4.127
1	1.787	0.2771	4.127
2	1.788	0.2771	4.126
3	1.788	0.2772	4.125
4	1.789	0.2773	4.124
5	1.79	0.2775	4.122
6	1.791	0.2776	4.12
7	1.792	0.2778	4.118
8	1.793	0.278	4.116
9	1.794	0.2782	4.113
10	1.796	0.2784	4.11

Table 5.44: For R1233zd(E) at (T_C=313 K)

ΔT_{sub}	**COP**	$\eta_{exergetic}$	**EDR**
0	1.92	0.2977	3.89
1	1.921	0.2978	3.888
2	1.921	0.2979	3.887
3	1.922	0.298	3.885
4	1.923	0.2982	3.884
5	1.924	0.2983	3.882
6	1.925	0.2985	3.88

7	1.927	0.2987	3.878
8	1.928	0.2989	3.876
9	1.929	0.2991	3.874
10	1.93	0.2993	3.872

Table 5.45: For R1234ze(Z) at (T_C=313 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	2.073	0.3214	3.653
1	2.069	0.3208	3.658
2	2.066	0.3203	3.663
3	2.063	0.3199	3.667
4	2.06	0.3194	3.672
5	2.058	0.319	3.675
6	2.055	0.3186	3.679
7	2.053	0.3182	3.683
8	2.051	0.3179	3.686
9	2.048	0.3176	3.689
10	2.047	0.3173	3.691

Table 5.46: For R1234ze(E) at (T_C=313 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	1.741	0.2699	4.218
1	1.743	0.2703	4.213
2	1.748	0.271	4.204
3	1.752	0.2716	4.196
4	1.757	0.2723	4.187
5	1.761	0.273	4.178
6	1.766	0.2737	4.169
7	1.77	0.2744	4.16
8	1.775	0.2751	4.151
9	1.779	0.2759	4.142
10	1.784	0.2766	4.133

Table 5.47: For R1243zf at (T_C=313 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	1.721	0.2669	4.258
1	1.723	0.2672	4.254
2	1.725	0.2675	4.25
3	1.728	0.2678	4.245
4	1.73	0.2682	4.241
5	1.733	0.2686	4.235
6	1.735	0.269	4.23
7	1.738	0.2694	4.224

8	1.741	0.2699	4.219
9	1.744	0.2703	4.213
10	1.747	0.2708	4.206

Table 5.48: For R423A at (T_C=313 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	1.596	0.2475	4.538
1	1.602	0.2484	4.524
2	1.609	0.2494	4.509
3	1.615	0.2504	4.494
4	1.621	0.2514	4.479
5	1.628	0.2523	4.464
6	1.634	0.2533	4.449
7	1.64	0.2543	4.435
8	1.647	0.2553	4.42
9	1.653	0.2563	4.406
10	1.66	0.2573	4.391

Table 5.49: For R507A at (T_C=313 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	1.518	0.2354	4.736
1	1.523	0.2362	4.722
2	1.529	0.237	4.708
3	1.534	0.2378	4.694

4	1.54	0.2387	4.68
5	1.545	0.2396	4.665
6	1.551	0.2404	4.65
7	1.557	0.2413	4.636
8	1.562	0.2422	4.621
9	1.568	0.2431	4.607
10	1.574	0.244	4.592

Table 5.50: For R134a at (T_C=323 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	1.414	0.2192	4.71
1	1.416	0.2195	4.704
2	1.418	0.2199	4.697
3	1.421	0.2203	4.689
4	1.423	0.2207	4.682
5	1.426	0.2211	4.674
6	1.429	0.2215	4.666
7	1.432	0.2219	4.658
8	1.434	0.2224	4.649
9	1.437	0.2229	4.641
10	1.44	0.2233	4.632

Table 5.51: For R1233zd(E) at (T_C=323 K)

ΔT_{sub}	**COP**	$\eta_{exergetic}$	**EDR**
0	1.564	0.2425	4.305
1	1.566	0.2428	4.3
2	1.568	0.2432	4.295
3	1.571	0.2435	4.29
4	1.573	0.2438	4.285
5	1.575	0.2442	4.279
6	1.577	0.2445	4.274
7	1.579	0.2449	4.268
8	1.582	0.2452	4.263
9	1.584	0.2456	4.257
10	1.586	0.246	4.252

Table 5.52: For R1234ze(Z) at (T_C=323 K)

ΔT_{sub}	**COP**	$\eta_{exergetic}$	**EDR**
0	1.706	0.2646	3.988
1	1.705	0.2643	3.992
2	1.703	0.264	3.995
3	1.701	0.2638	3.998
4	1.7	0.2636	4.001
5	1.699	0.2634	4.004
6	1.698	0.2632	4.006
7	1.697	0.2631	4.008

8	1.696	0.2629	4.01
9	1.695	0.2628	4.011
10	1.694	0.2627	4.013

Table 5.53: For R1234ze(E) at (T_C=323 K)

ΔT_{sub}	**COP**	$\eta_{exergetic}$	**EDR**
0	1.359	0.2107	4.88
1	1.363	0.2114	4.866
2	1.369	0.2123	4.847
3	1.375	0.2132	4.828
4	1.381	0.2141	4.809
5	1.387	0.2151	4.791
6	1.393	0.216	4.772
7	1.399	0.2169	4.754
8	1.405	0.2178	4.736
9	1.411	0.2187	4.719
10	1.417	0.2196	4.701

Table 5.54: For R1243zf at (T_C=323 K)

ΔT_{sub}	**COP**	$\eta_{exergetic}$	**EDR**
0	1.356	0.2103	4.889
1	1.36	0.2109	4.876
2	1.364	0.2115	4.864
3	1.368	0.2121	4.851

4	1.372	0.2127	4.838
5	1.376	0.2134	4.825
6	1.381	0.214	4.811
7	1.385	0.2147	4.798
8	1.389	0.2154	4.785
9	1.393	0.216	4.771
10	1.398	0.2167	4.758

Table 5.55: For R423A at (T_C=323 K)

ΔT_{sub}	**COP**	**$\eta_{exergetic}$**	**EDR**
0	1.213	0.1881	5.406
1	1.221	0.1893	5.375
2	1.229	0.1906	5.343
3	1.237	0.1918	5.311
4	1.245	0.1931	5.279
5	1.253	0.1943	5.249
6	1.261	0.1956	5.218
7	1.269	0.1968	5.189
8	1.277	0.198	5.16
9	1.285	0.1992	5.132
10	1.293	0.2004	5.104

Table 5.56: For R507A at (T_C=323 K)

ΔT_{sub}	COP	$\eta_{exergetic}$	EDR
0	1.101	0.1707	5.906
1	1.11	0.1721	5.861
2	1.119	0.1735	5.818
3	1.128	0.1749	5.776
4	1.137	0.1762	5.735
5	1.146	0.1776	5.696
6	1.154	0.1789	5.657
7	1.163	0.1803	5.619
8	1.171	0.1816	5.582
9	1.179	0.1828	5.546
10	1.188	0.1841	5.512

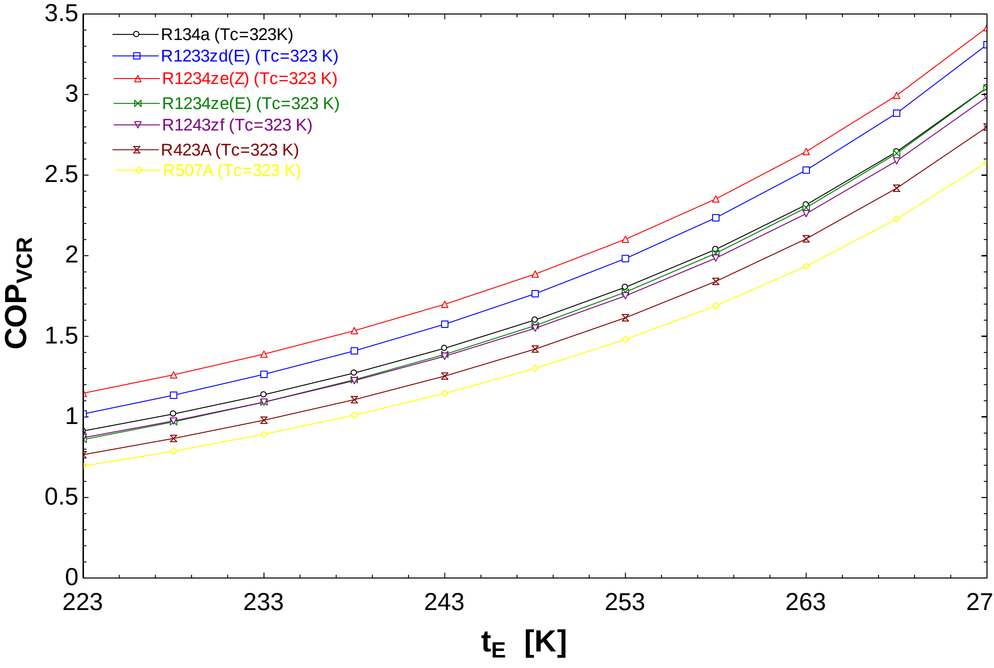


Figure 5.1: Variation in COP with evaporator temperature at (Tc=323 K)

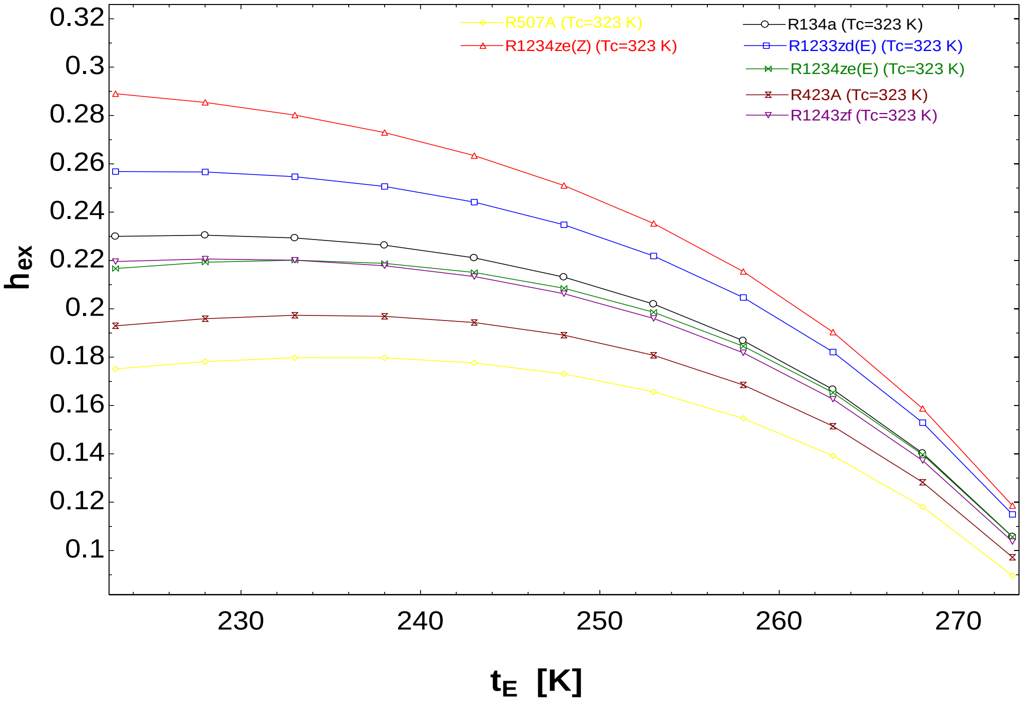


Figure 5.2: Variation of Exergetic efficiency with evaporator temperature at (Tc=323 K)

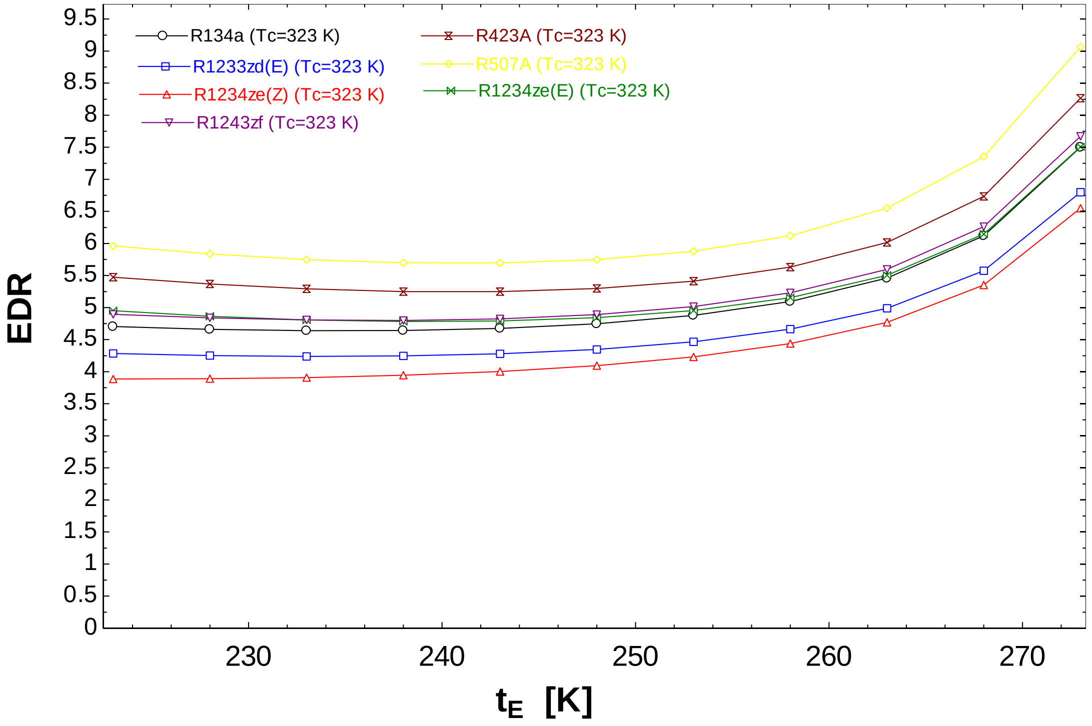


Figure 5.3: Variation in EDR with evaporator temperature at (Tc=323 K)

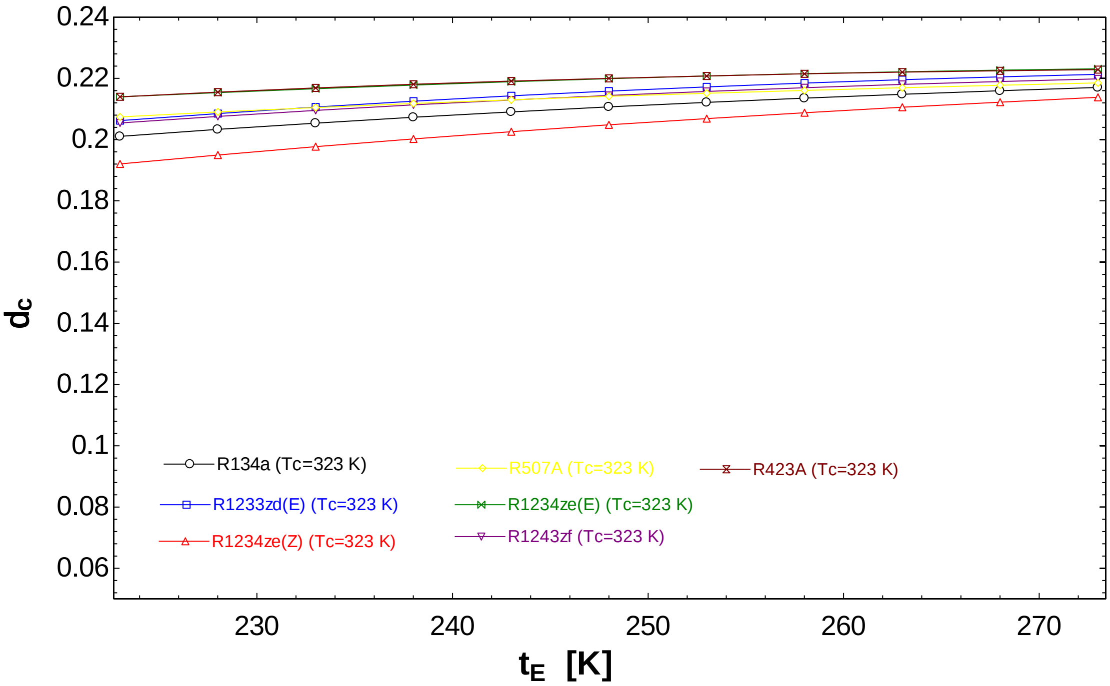


Figure 5.4: Variation in efficiency defect in compressor with evaporator temperature at (Tc=323 K)

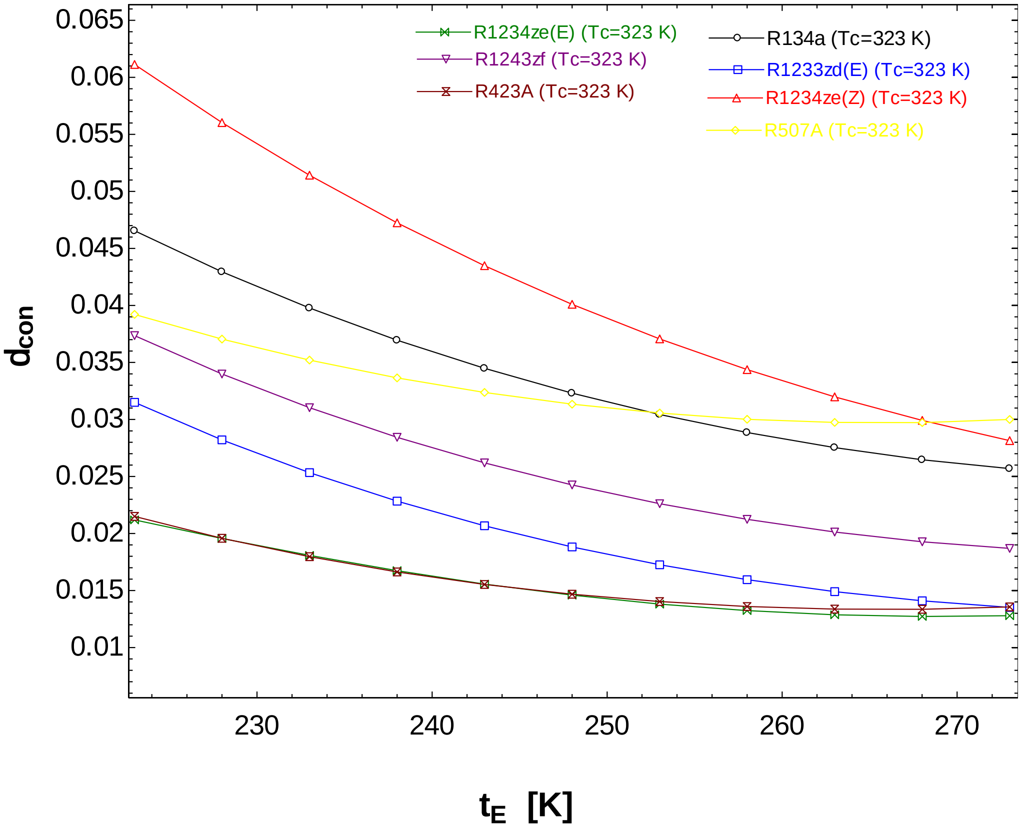


Figure 5.5: Variation in efficiency defect in condenser wrt evaporator temperature at (Tc=323 K)

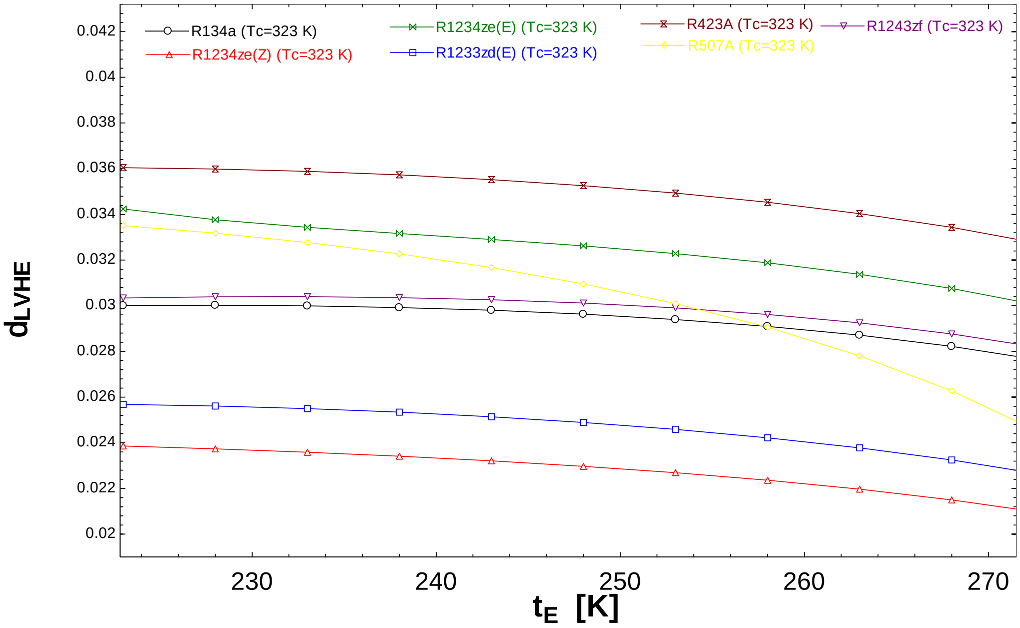


Figure 5.6: Variation in efficiency defect in heat exchanger wrt evaporator temperature at (Tc=323 K)

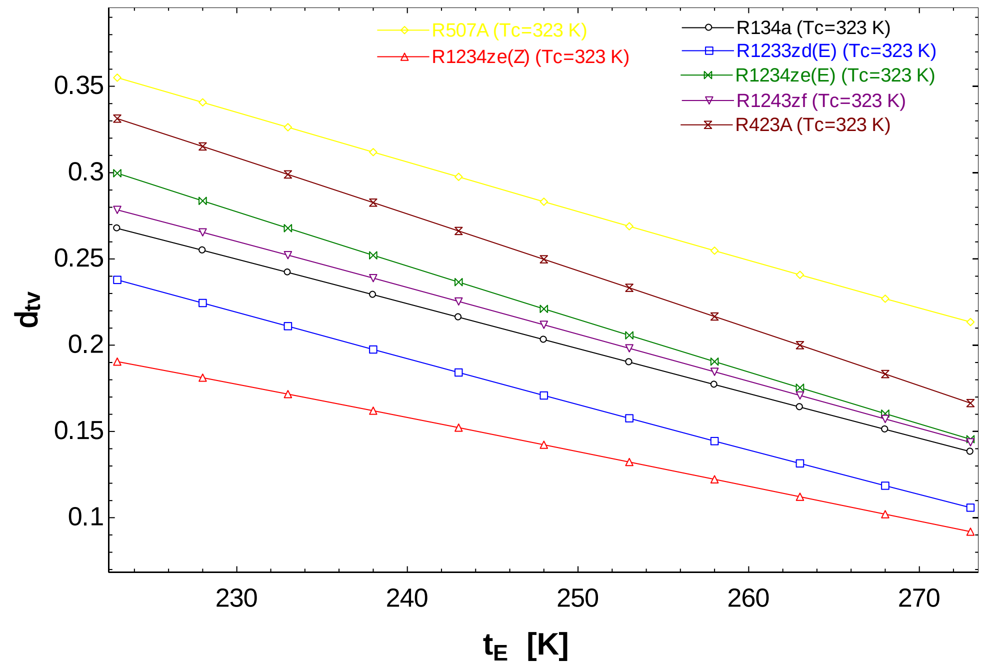


Figure 5.7: Variation in efficiency defect in throttle valve with evaporator temperature at (Tc=323 K)

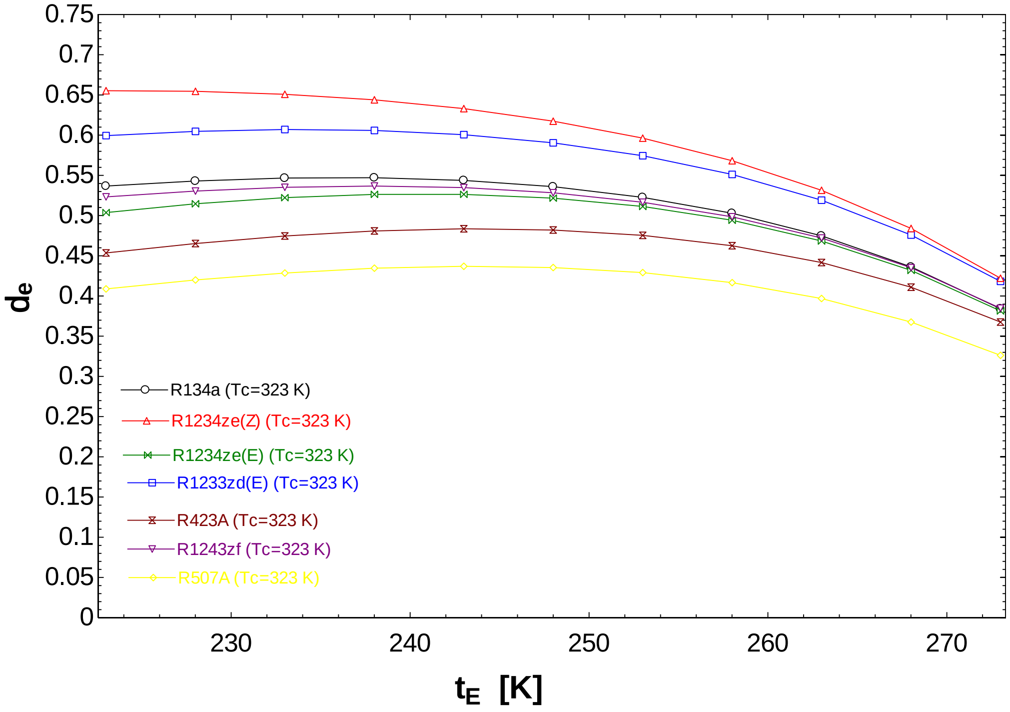


Figure 5.8: Variation in efficiency defect in evaporator valve wrt evaporator temperature (Tc=323 K)

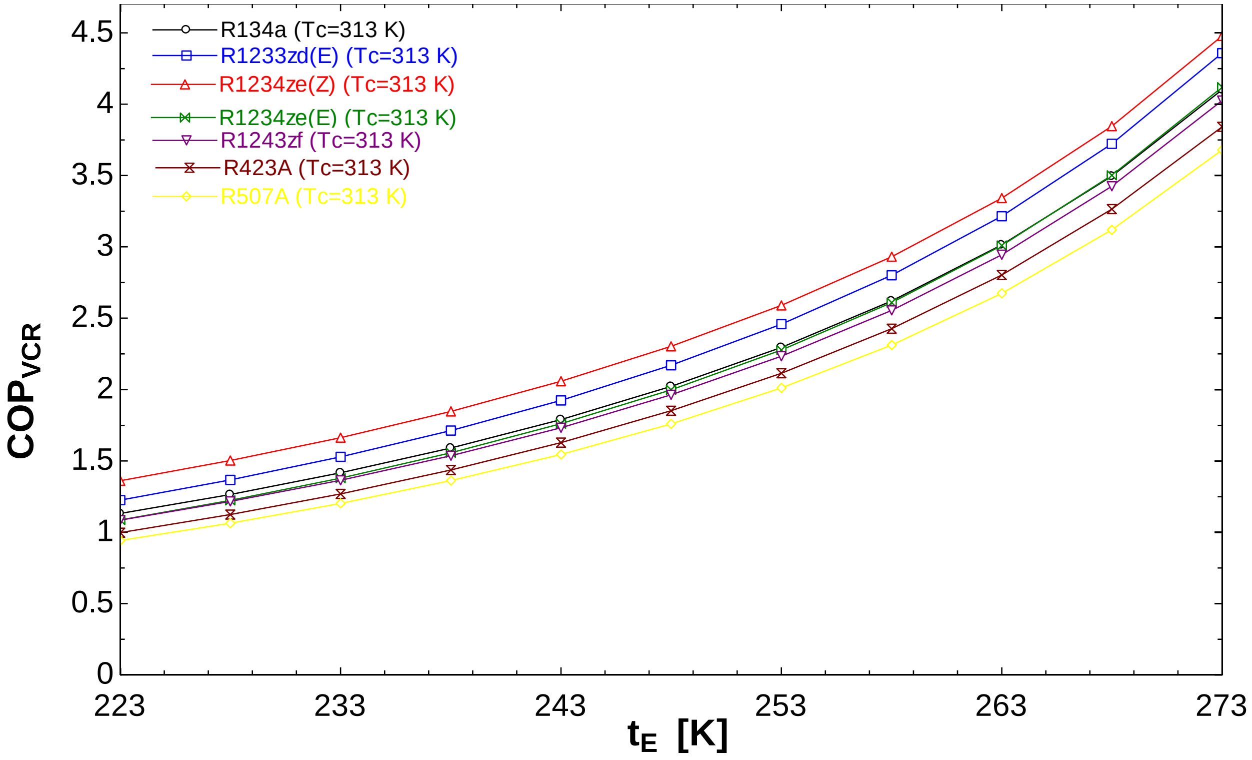


Figure 5.9: Variation in COP with evaporator temperature at (T_C=313 K)

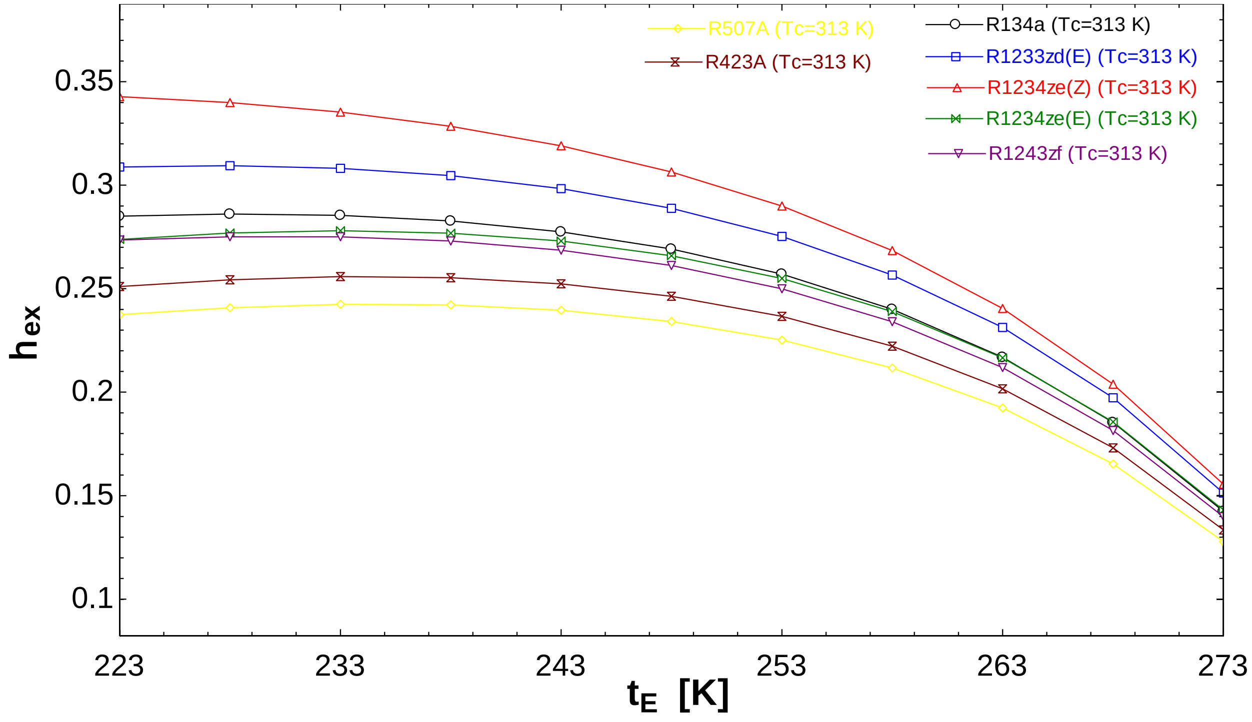


Figure 5.10: Variation in exergetic efficiency with evaporator temperature at (T_C=313 K)

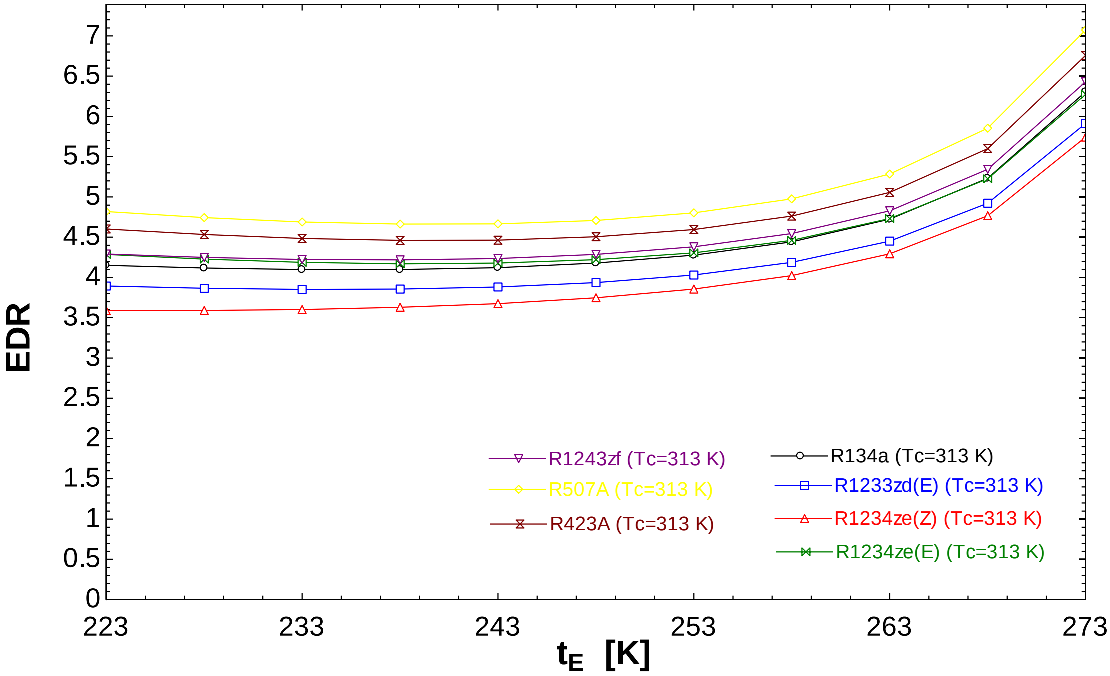


Figure 5.11: Variation in EDR with evaporator temperature at (T_C=313 K)

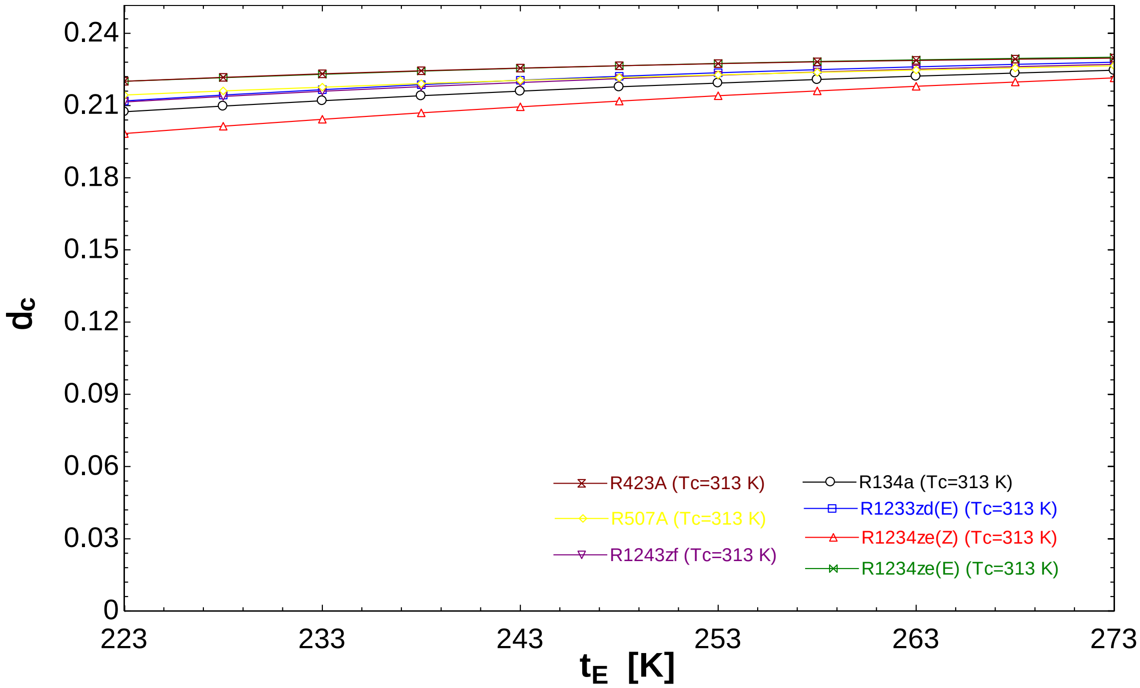


Figure 5.12: Variation in efficiency defect in compressor with evaporator temperature at (T_C=313 K)

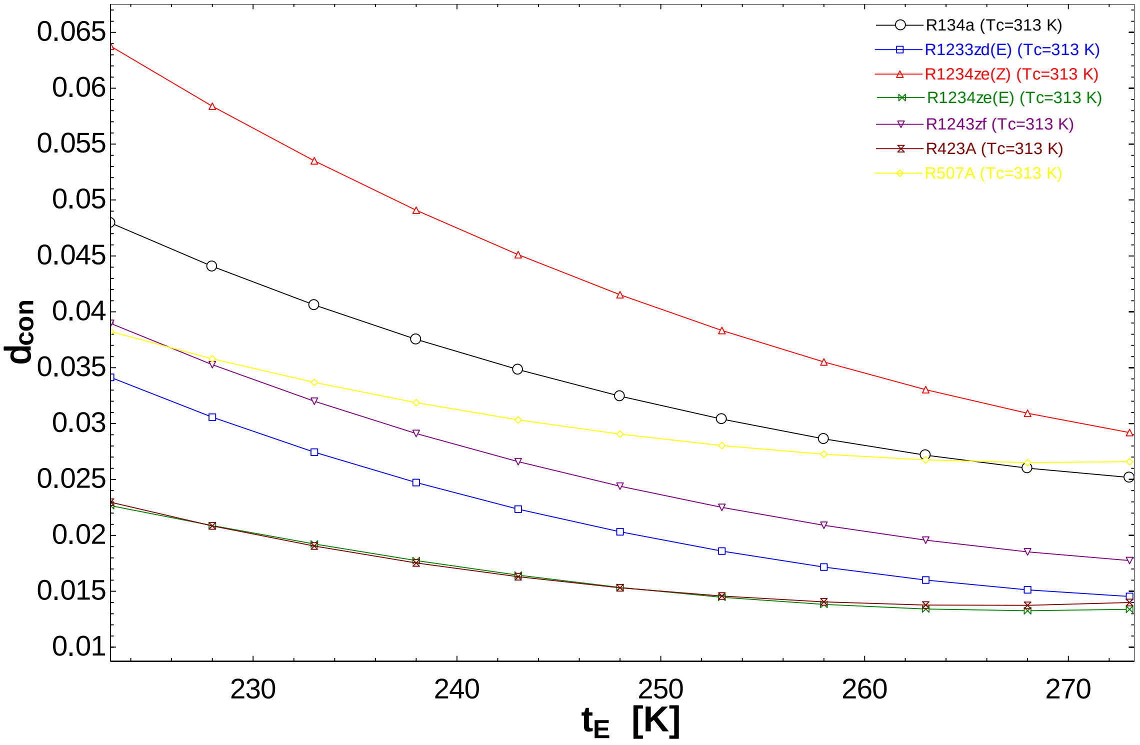


Figure 5.13: Variation in efficiency defect in condenser with evaporator temperature at (T_C=313 K)

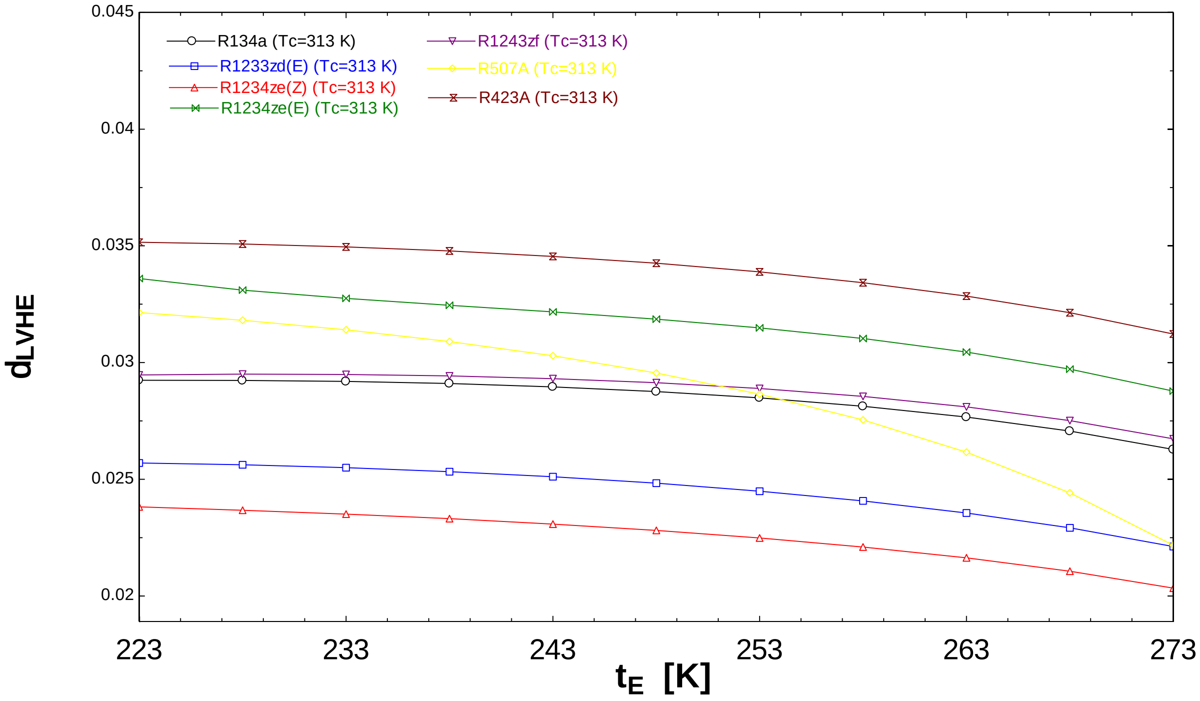


Figure 5.14: Variation in efficiency defect in lvhe with evaporator temperature at (T_C=313 K)

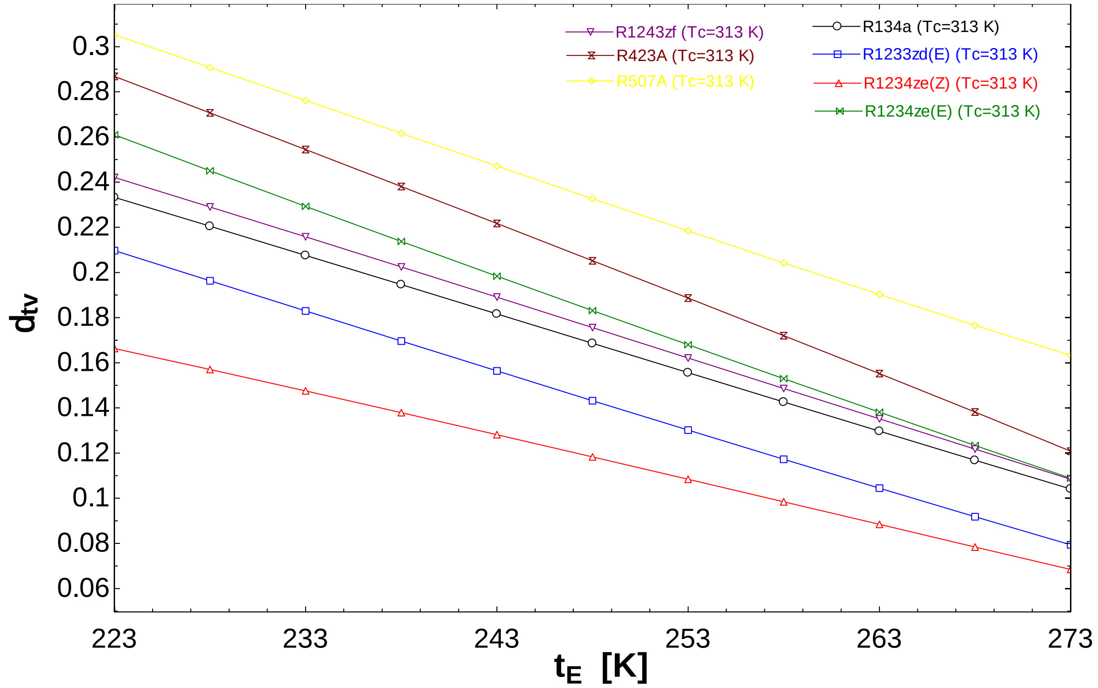


Figure 5.15: Variation in efficiency defect in throttle valve with evaporator temperature at (T_C=313 K)

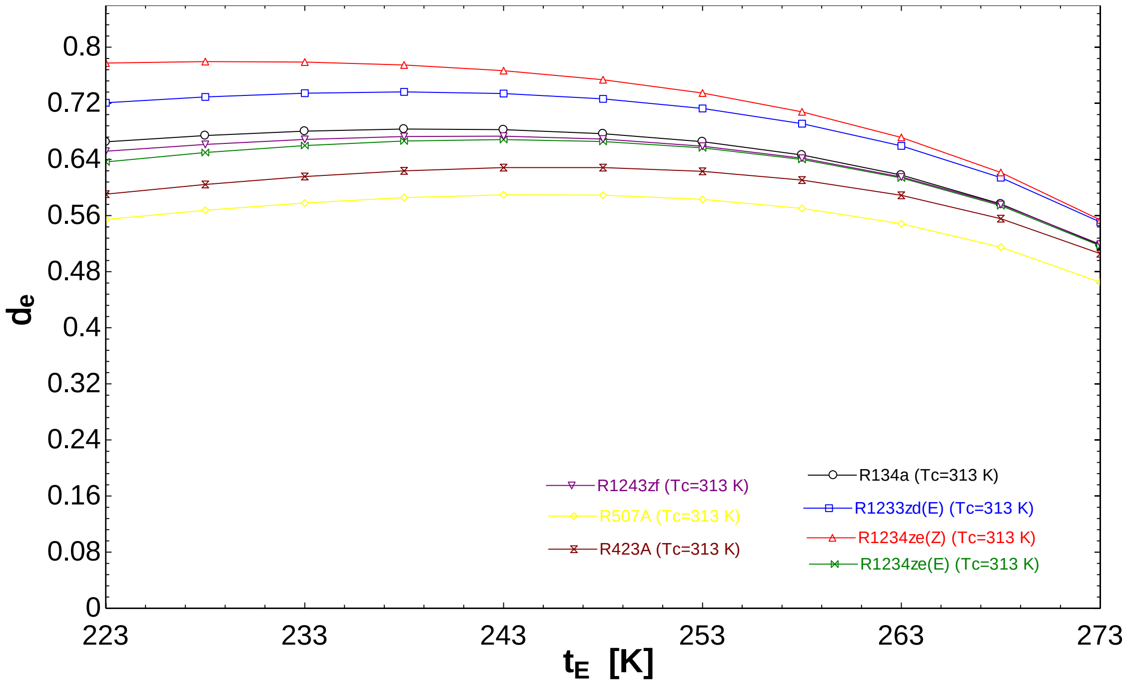


Figure 5.16: Variation in efficiency defect in evaporator with evaporator temperature at (T_C=313 K)

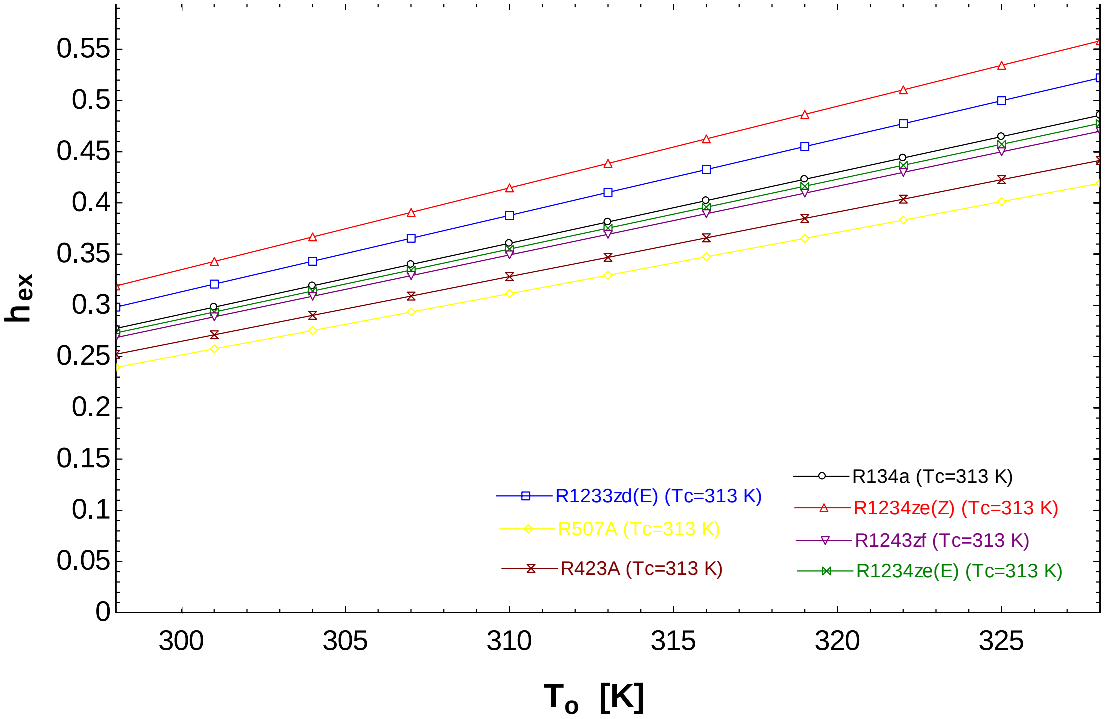


Figure 5.17: Variations in exergetic efficiency with ambient temperature at (T_C=313 K)

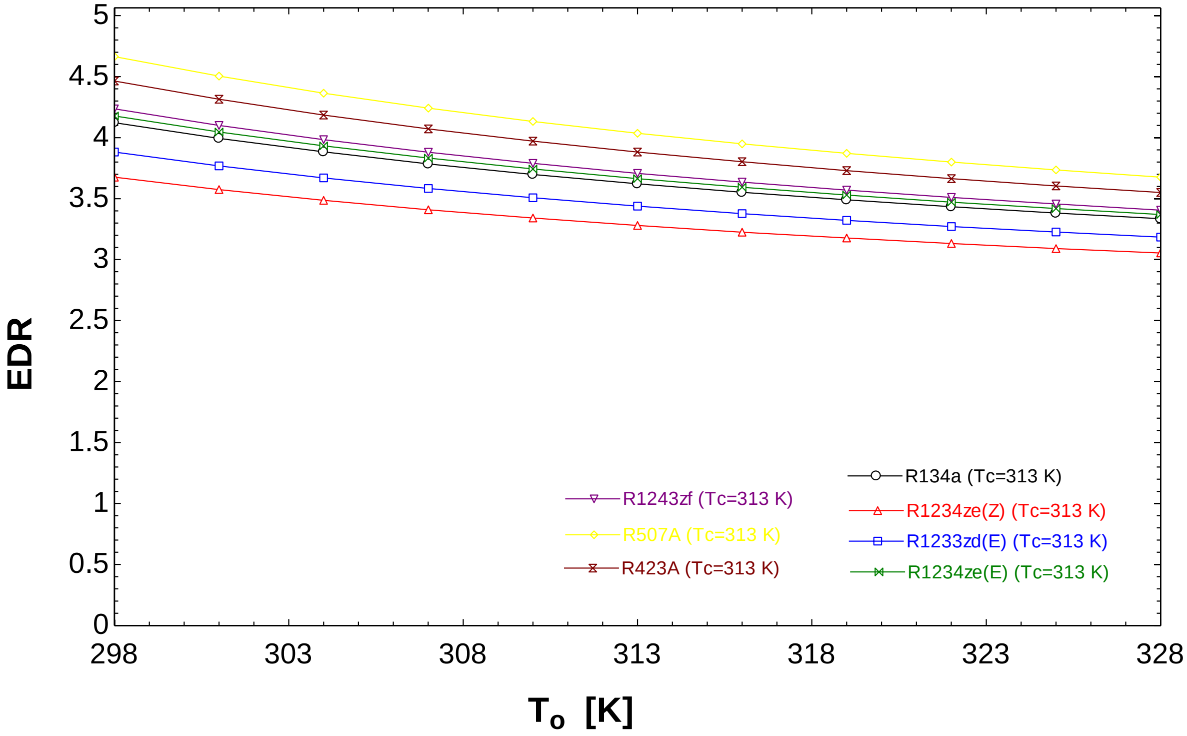


Figure 5.18: Variations in EDR with ambient temperature at (T_C=313 K)

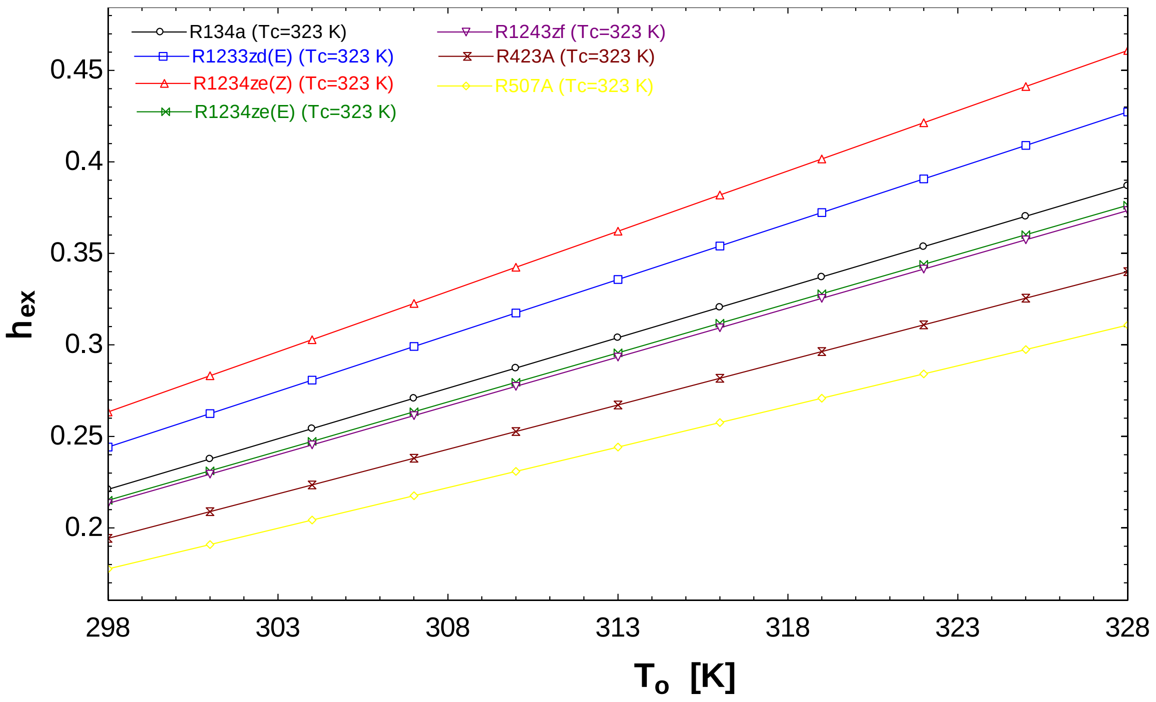


Figure 5.19: Variations in exergetic efficiency with ambient temperature at (T_C=323 K)

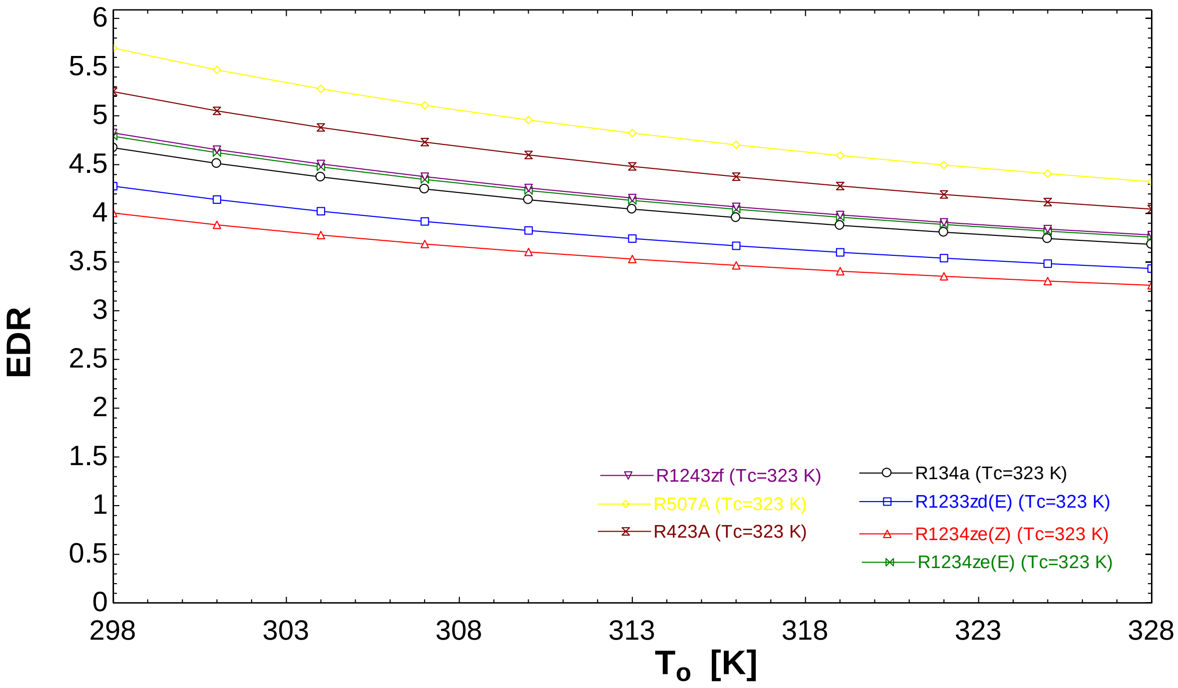


Figure 5.20: Variations in EDR with ambient temperature at (T_C=323 K)

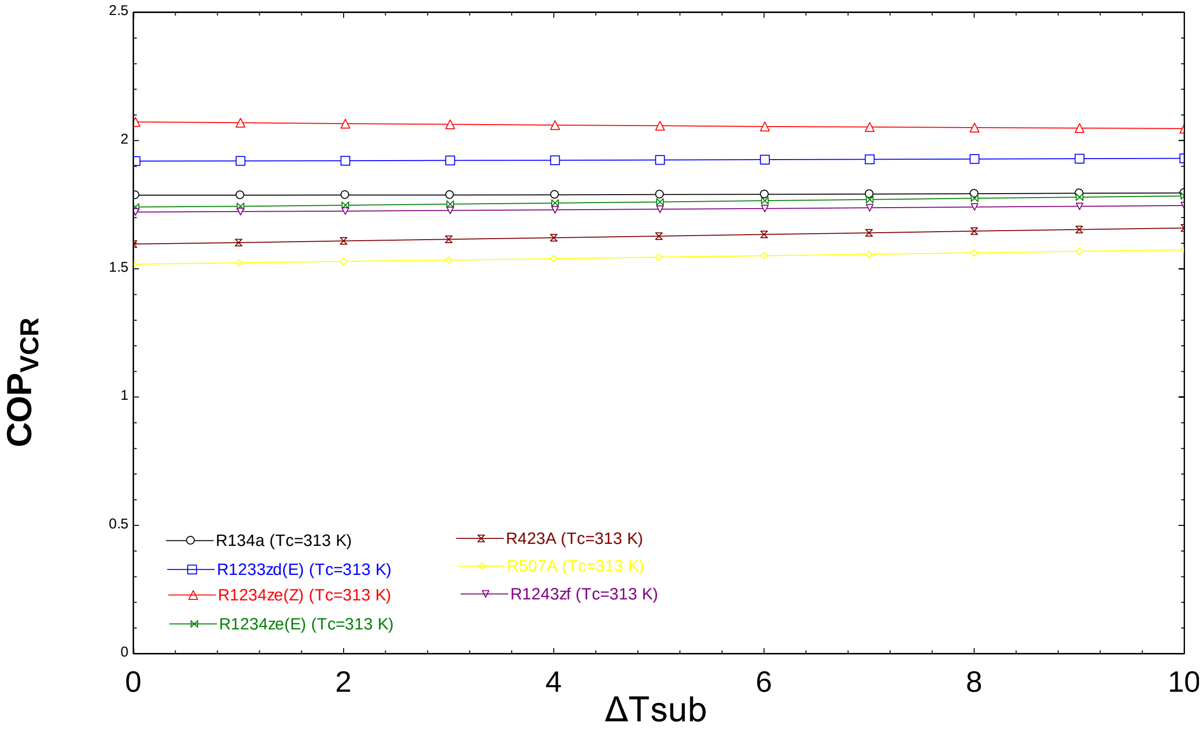


Figure 5.21: Variation in COP with degree of subcooling at (T_C=313 K)

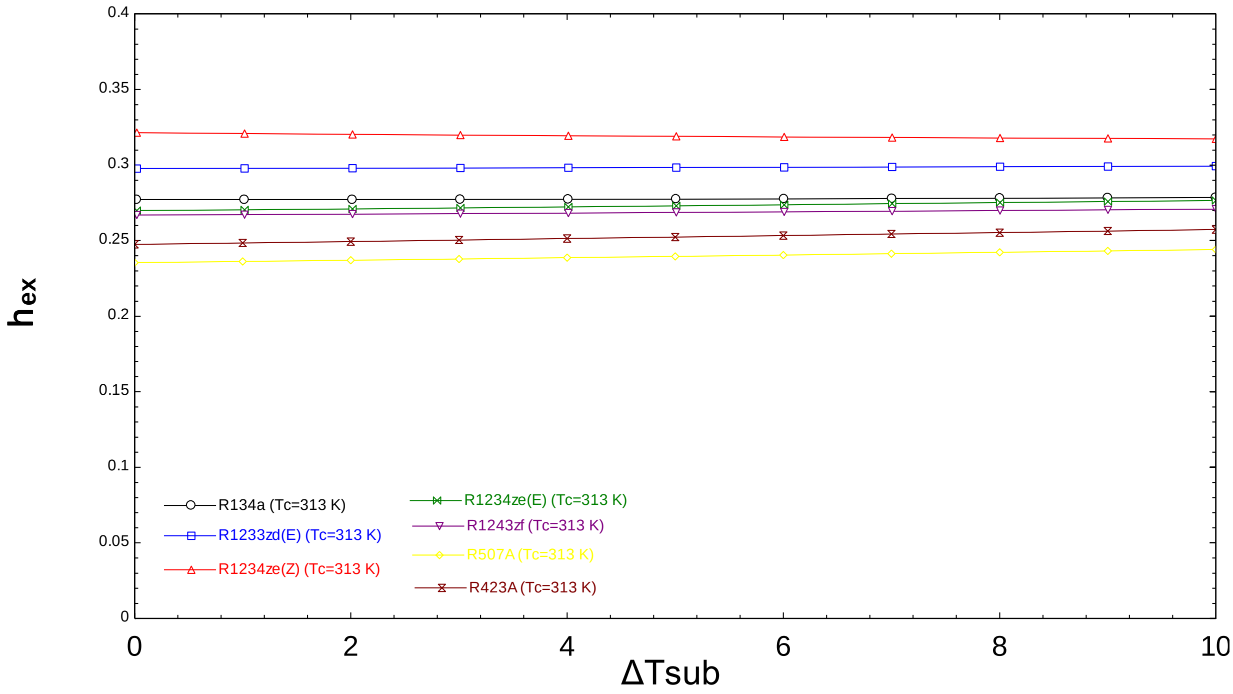


Figure 5.22: variation in exergetic efficiency with degree of subcooling at (T_C=313 K)

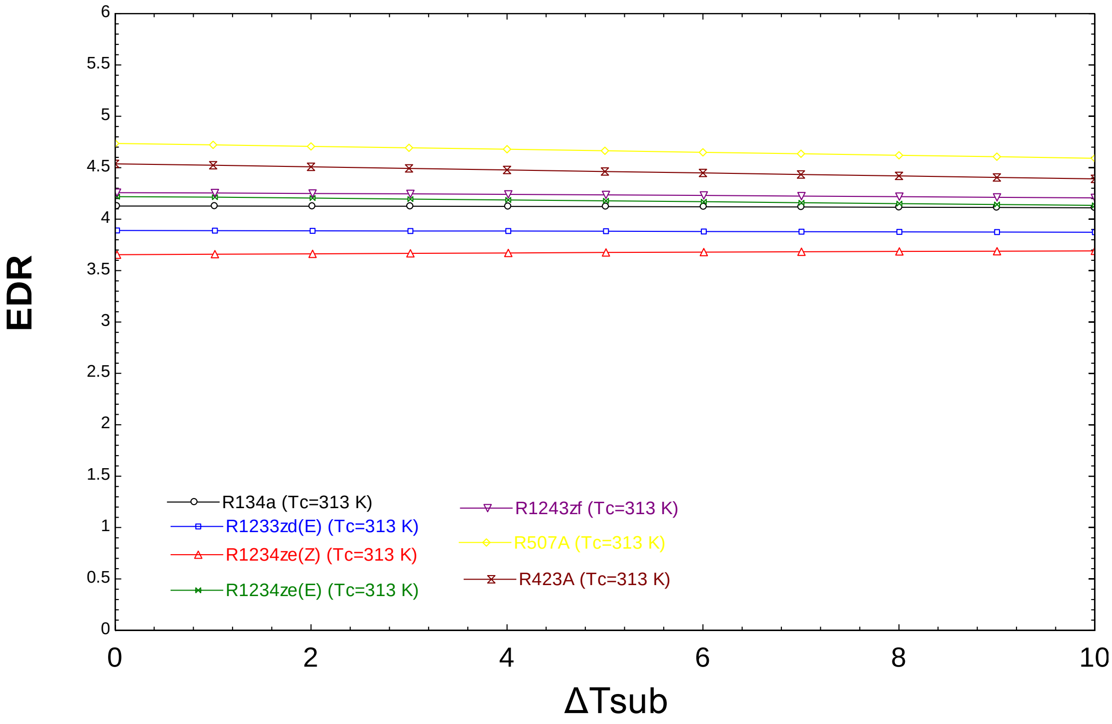


Figure 5.23: Variation in EDR with degree of subcooling at (T_C=313 K)

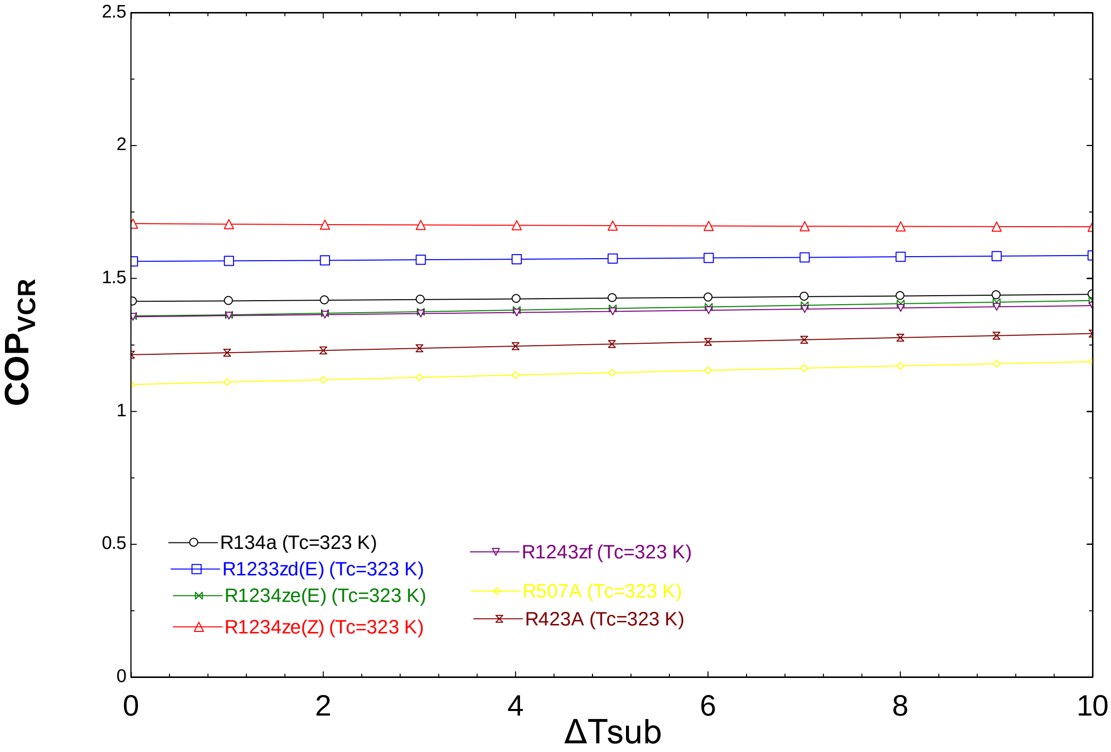


Figure 5.24: Variation in COP with degree of subcooling at (T_C=323 K)

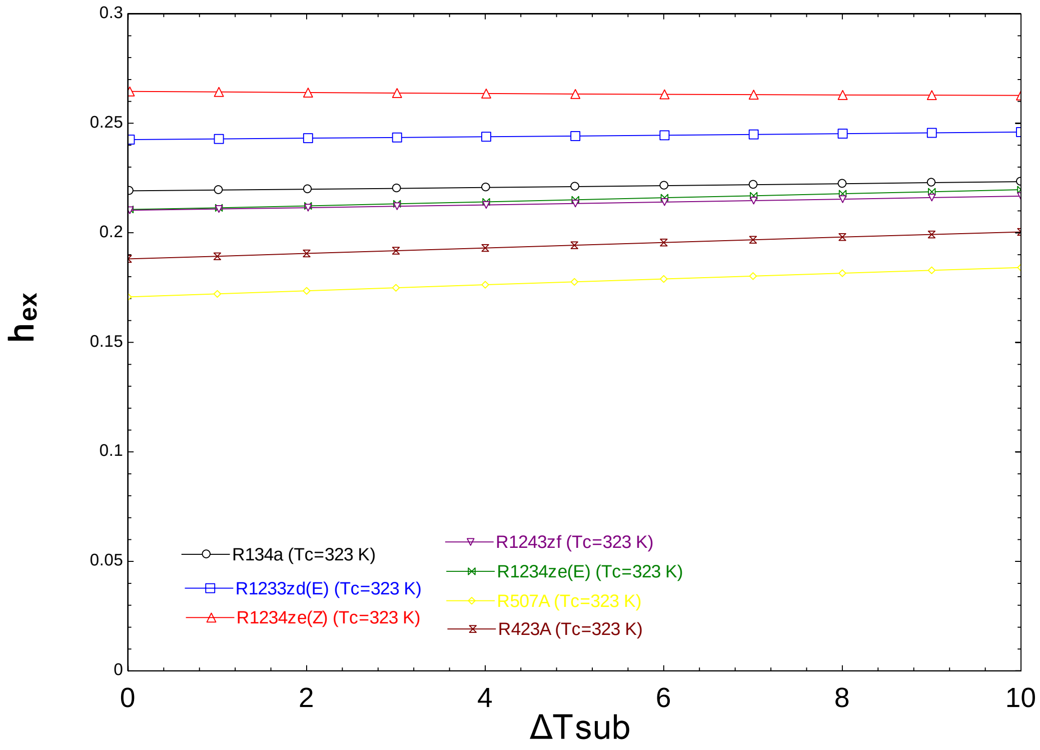


Figure 5.25: Variation in exergetic efficiency with degree of subcooling at (T_C=323 K)

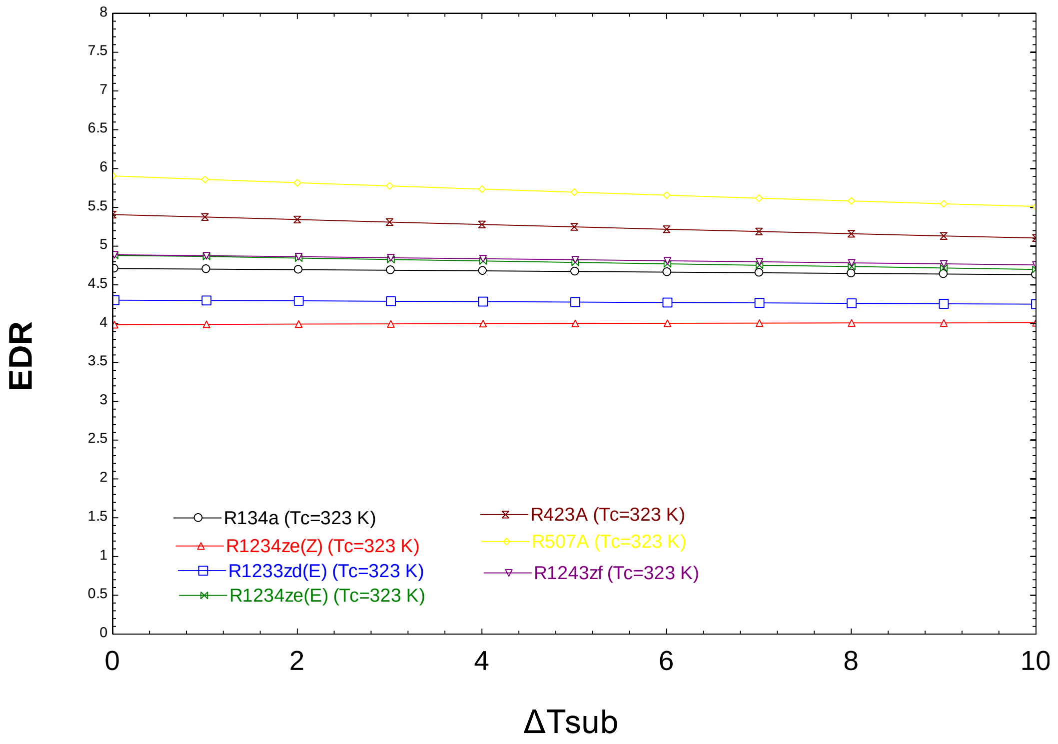


Figure 5.26: Variation in EDR with degree of subcooling at (T_C=323 K)

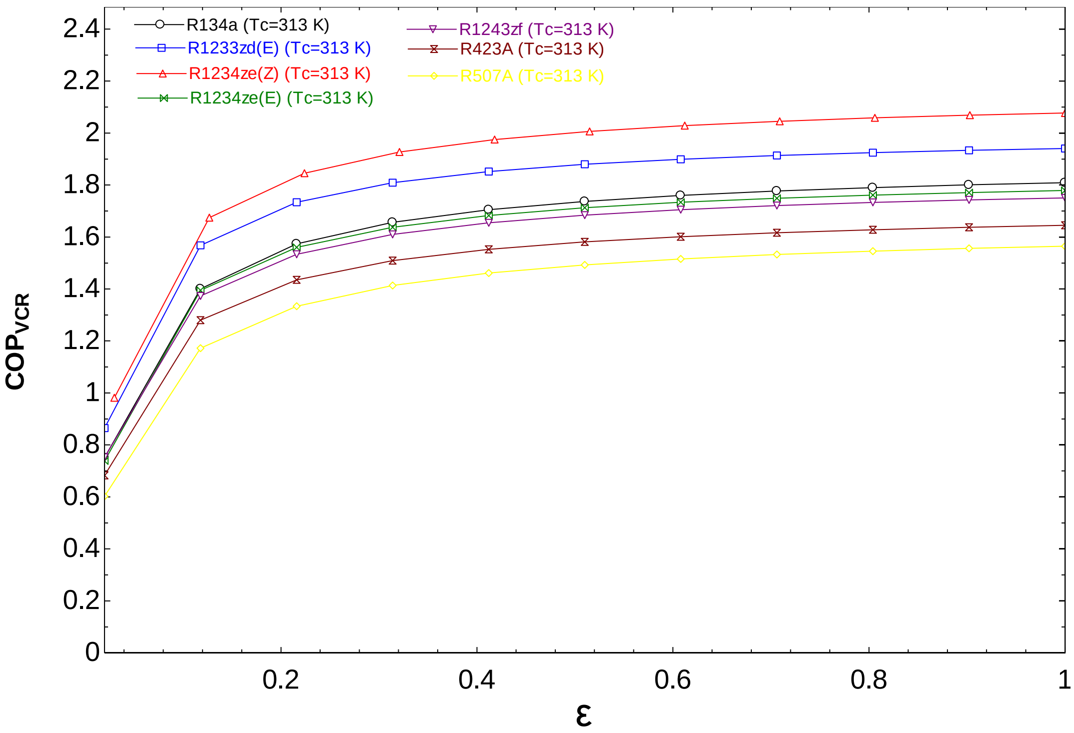


Figure 5.27: Variation in COP with effectiveness of heat exchanger at (T_C=313 K)

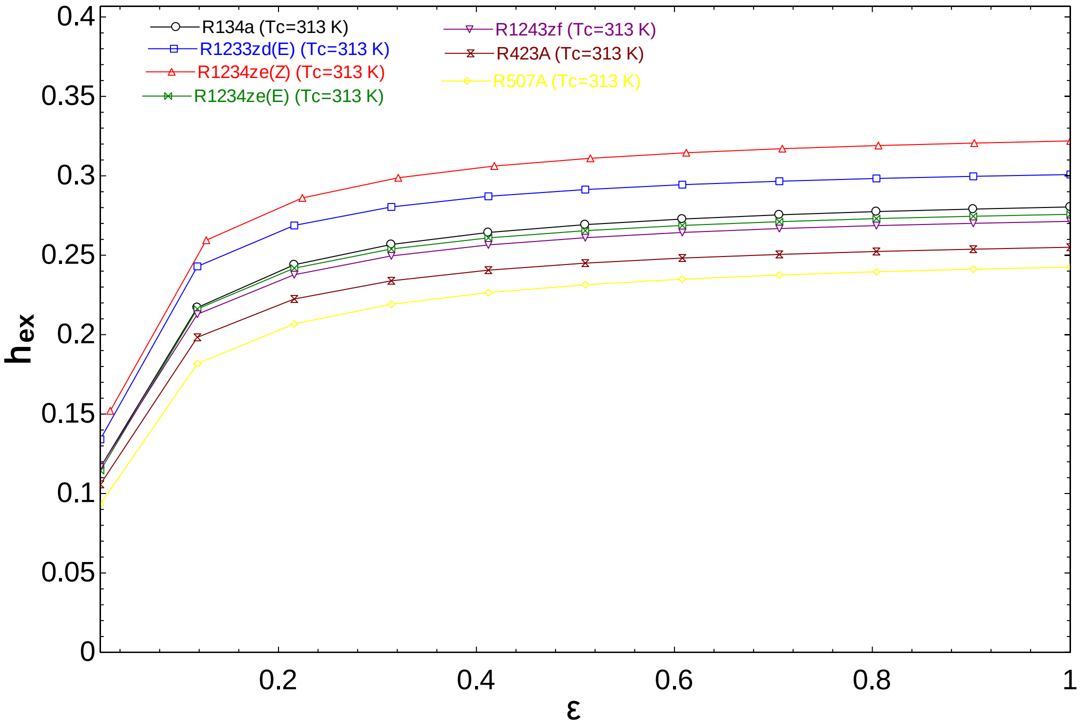


Figure 5.28: Variation in exergetic efficiency with effectiveness of heat exchanger at (T_C=313 K)

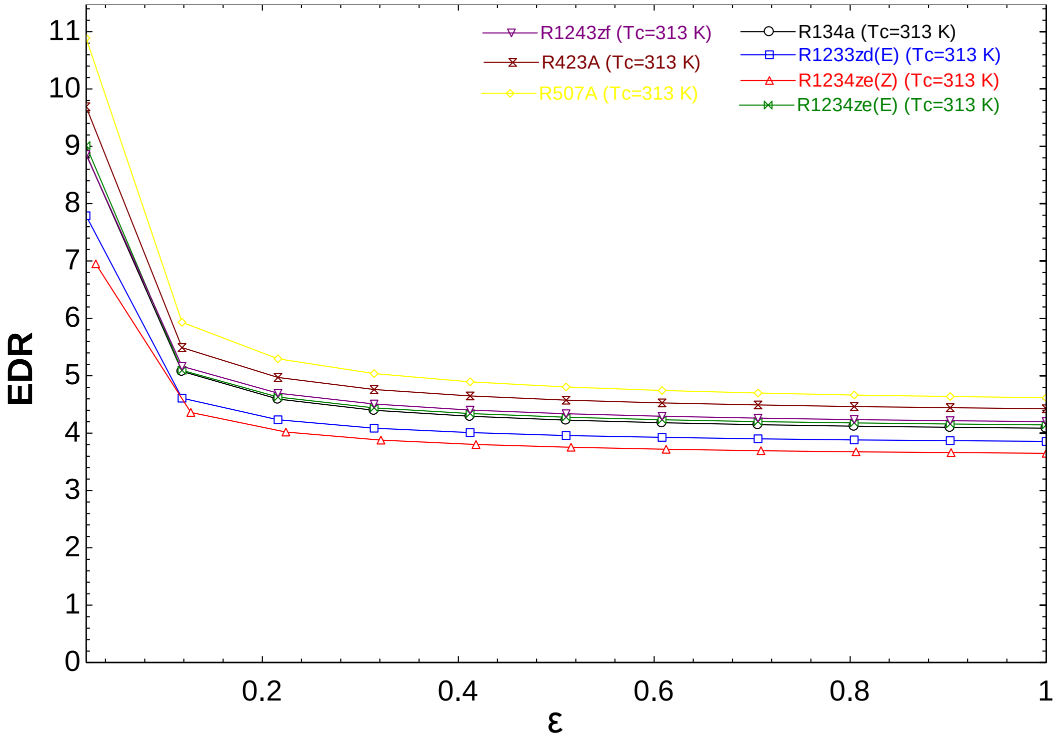


Figure 5.29: Variation in EDR with effectiveness of heat exchanger at (T_C=313 K)

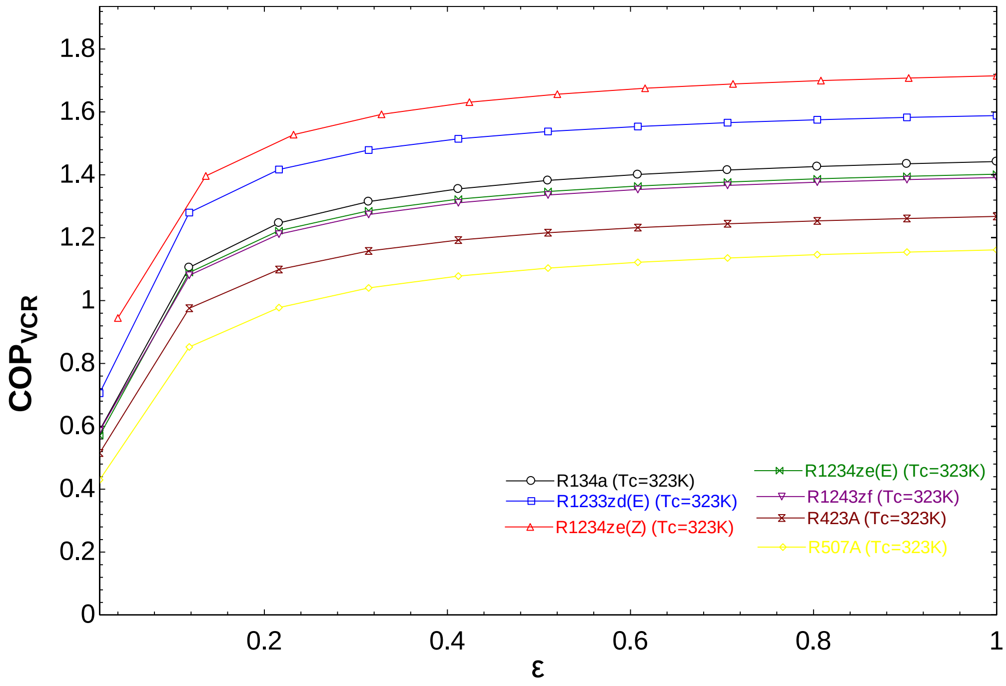


Figure 5.30: Variation in COP with effectiveness of heat exchanger at (T_C=323 K)

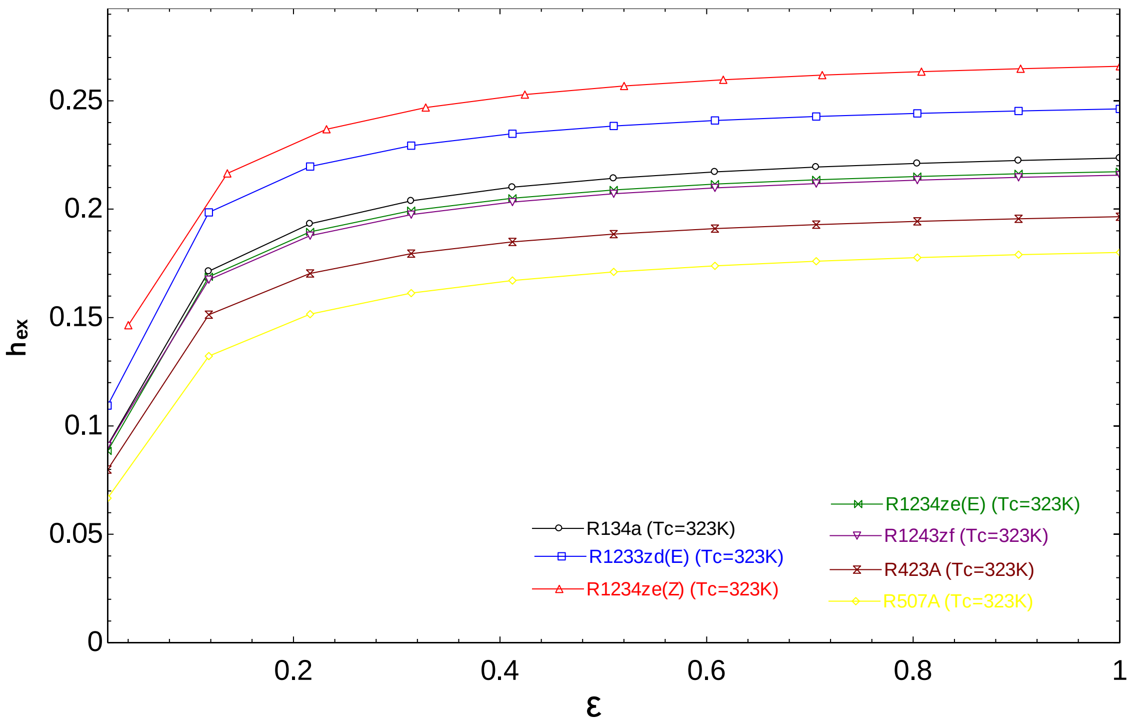


Figure 5.31: Variation in exergetic efficiency with effectiveness of heat exchanger at (T_C=323 K)

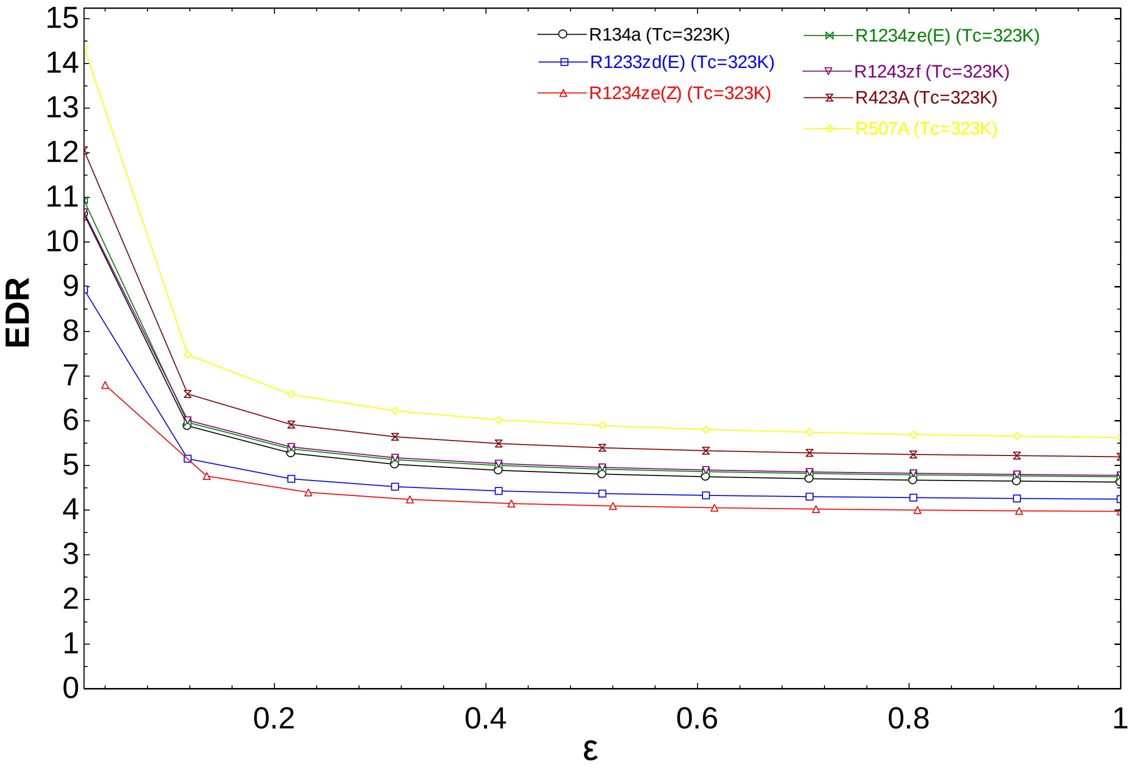


Figure 5.32: Variation in EDR with effectiveness of heat exchanger at (T_C=323 K)

5.3 Discussion

Figures 5.1 of variation of COP with evaporator temperature at condenser temperature of 323 K and it can be implied that when the temperature of the evaporator in elevated, then the pressure ratio decline which lead to the reduction of compressor work and elevation in the cooling effect and hence the performance is increased. Refrigerant R1234ze(Z) has the highest performance out of all the seven refrigerants compared. Decreasing order of COP in this graph is R1234ze(Z) (min COP=1.146 and max COP=3.415), R1233zd(E) (min COP=1.019 and max COP=3.309), R134a (min COP=0.9123 and max COP=3.043), R1234ze(E) (min COP=0.8594 and max COP=3.042), R1243zf (min COP=0.8709 and max COP=2.985), R423A (min COP=0.7654 and max COP=2.799), R507A (min COP=0.6946 and max COP=2.581). Here the minimum and maximum is calculated at the evaporator temperature of 223 K and 273 K respectively.

Figure 5.2 of variation of exergetic efficiency with evaporator temperature at condenser temperature of 323 K. Initially the exergetic efficiency is increased and then eventually decreased. There are basically two parameters to look out for while comparing exergetic efficiency they are thermal exergy flow in the evaporator i.e. $\dot{Q}_e \left|\left(1-\frac{T_o}{T_r}\right)\right|$ and the other is the work of the compressor. As the temperature of the evaporator increases the cooling effect $\dot{Q}_e$ increases the $\left|\left(1-\frac{T_o}{T_r}\right)\right|$ term is decreased as the T_r reaches to T_o, and the work done by the compressor is lessen as there is increase in evaporator temperature. These two parameters effects simultaneously to elevate the exegetic efficiency when it reaches at its maximum point and evaporator temperature achieved is optimum beyond this temperature the effect of the parameters helps in reduction of exergetic efficiency. Refrigerant R1234ze(Z) has the highest exergetic efficiency out of all the seven refrigerants compared. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.1186 and max=0.289), R1233zd(E) (min=0.1149 and max =0.2568), R134a (min =0.1057 and max=0.23), R1243zf (min=0.1037 and max=0.2196), R1234ze(E) (min=0.1056 and max=0.2166), R423A (min=0.09718 and max=0.193), R507A (min=0.08962 and max=0.1751). Here the minimum and maximum is calculated at the evaporator temperature of 223 K and 273 K respectively.

Figures 5.3 of variation of exergy destruction ratio (EDR) with evaporator temperature at condenser temperature of 323 K and it can be implied that the behavior of the graph is exact opposite of the behavior of the exergetic efficiency graph. Refrigerant R507A has the highest exergy destruction ratio (EDR) out of all the seven refrigerants compared.

Figures 5.4 to 5.8 and figure 5.12 to 5.16 represents variations of efficiency defect in compressor, condenser, liquid vapor heat exchanger, throttle valve and evaporator. This concept helps in finding the component in which the losses are maximum. Liquid vapor heat exchanger has the lowest efficiency defect therefore it is the most efficient part of the system. In the ascending order of efficiency defect the component are arranged as liquid vapor heat exchanger, condenser, throttle valve, compressor and evaporator. From refrigerants point of view in condenser and evaporator, the minimal efficiency defect in the condenser is for refrigerant R423A and minimal efficiency defect in evaporator is for refrigerant R507A when the condenser temperature is at 313 K. When condenser temperature is at 323 K then the minimal efficiency defect in the condenser is for refrigerant R1234ze(E) and minimal efficiency defect in evaporator is for refrigerant R507A.

Figures 5.9 of variation of COP with evaporator temperature at condenser temperature of 313 K and it can be implied that when the temperature of the evaporator in elevated, then the pressure ratio decline which lead to the reduction of compressor work and elevation in the cooling effect and hence the performance is increased. Refrigerant R1234ze(Z) has the highest performance out of all the seven refrigerants compared. Decreasing order of COP in this graph is R1234ze(Z) (min COP=1.36 and max COP=4.479), R1233zd(E) (min COP=1.1225 and max COP=4.4.358), R134a (min COP=1.13 and max COP=4.102), R1234ze(E) (min COP=1.086 and max COP=4.12), R1243zf (min COP=1.085 and max COP=4.086), R423A (min COP=0.9959 and max COP=4.842), R507A (min COP=0.9421 and max COP=3.68). Here the minimum and maximum is calculated at the evaporator temperature of 223 K and 273 K respectively.

Figure 5.10 of variation of exergetic efficiency with evaporator temperature at condenser temperature of 313 K. Initially the exergetic efficiency is increased and then eventually decreased. There are basically two parameters to look out for while comparing exergetic efficiency they are thermal exergy flow in the evaporator i.e. $\dot{Q}_e \left|\left(1-\frac{T_o}{T_r}\right)\right|$ and the other is the work of the compressor. As the temperature of the evaporator increases the cooling effect $\dot{Q}_e$ increases the $\left|\left(1-\frac{T_o}{T_r}\right)\right|$ term is decreased as the T_r reaches to T_o, and the work done by the compressor is lessen as there is increase in evaporator temperature. These two parameters effects simultaneously to elevate the exegetic efficiency when it reaches at its maximum point and evaporator temperature achieved is optimum beyond this temperature the effect of the parameters helps in reduction of exergetic efficiency. Refrigerant R1234ze(Z) has the highest exergetic efficiency out of all the seven refrigerants compared. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.1555 and max=0.3428), R1233zd(E) (min=0.1513 and max =0.3088), R134a (min =0.1424 and max=0.285), R1234ze(E) (min=0.1431 and max=0.2738), R1243zf (min=0.1398 and max=0.2375), R423A (min=0.1334 and max=0.2511), R507A (min=0.1278 and max=0.2375). Here the minimum and maximum is calculated at the evaporator temperature of 223 K and 273 K respectively.

Figures 5.11 of variation of exergy destruction ratio (EDR) with evaporator temperature at condenser temperature of 323 K and it can be implied that the behavior of the graph is exact opposite of the behavior of the exergetic efficiency graph. Refrigerant R507A has the highest exergy destruction ratio (EDR) out of all the seven refrigerants compared.

Figures 5.17 represents the variation of exergetic efficiency with the ambient temperature. From the figure we can imply that the exergetic efficiency elevates as there is elevation in the ambient temperature. This happens as the cooling effect and the work done by the compressor remains constant and there is change in this term $\left|\left(1 - \frac{T_o}{T_r}\right)\right|$

As there is elevation in the ambient temperature then the irreversibility because of the finite temperature difference as a result of this exergetic efficiency increases. R1234ze(Z) has the highest exergetic efficiency when condenser temperature is at 313 K. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.319 and max=0.5583), R1233zd(E) (min=0.2983 and max=0.5221), R134a (min=0.2775 and max=0.4855), R1234ze(E) (min=0.273 and max =0.4778), R1243zf (min=0.2686 and max=0.4701), R423A (min=0.2523 and max=0.4416), R507A (min=0.2396 and max=0.4192). Here the minimum and maximum is calculated at the ambient temperature of 298 K and 328 K respectively.

Figures 5.18 represents the variation of EDR with the ambient temperature. From the figure we can imply that the EDR lessens as there is elevation in the ambient temperature. This happens as the cooling effect and the work done by the compressor remains constant and there is change in this term $\left|\left(1 - \frac{T_o}{T_r}\right)\right|$

As there is elevation in the ambient temperature then the irreversibility because of the finite temperature difference as a result of this EDR lessens. R507A has highest EDR.

Figures 5.19 represents the variation of exergetic efficiency with the ambient temperature. From the figure we can imply that the exergetic efficiency elevates as there is elevation in the ambient temperature. This happens as the cooling effect and the work done by the compressor remains constant and there is change in this term $\left|\left(1 - \frac{T_o}{T_r}\right)\right|$

As there is elevation in the ambient temperature then the irreversibility because of the finite temperature difference as a result of this exergetic efficiency increases. R1234ze(Z) has the highest exergetic efficiency in this graph. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.2634 and max=0.4609), R1233zd(E) (min=0.2442 and max=0.4273), R134a (min=0.2211 and max=0.3869), R1234ze(E) (min=0.215 and max =0.3763), R1243zf (min=0.2134 and max=0.3734), R423A (min=0.1943 and max=0.3401), R507A (min=0.1776 and max=0.3108). Here the minimum and maximum is calculated at the ambient temperature of 298 K and 328 K respectively.

Figures 5.20 represents the variation of EDR with the ambient temperature. From the figure we can imply that the EDR lessens as there is elevation in the ambient temperature. This happens as the cooling effect and the work done by the compressor remains constant and there is change in this term $\left|\left(1 - \frac{T_o}{T_r}\right)\right|$

As there is elevation in the ambient temperature then the irreversibility because of the finite temperature difference as a result of this EDR lessens. R507A has highest EDR in this graph.

From figures 5.21 we can imply that due to subcooling the refrigerant entering into the expansion valve will be at lower temperature. Hence after expansion through the expansion valve the refrigerant entering into evaporator will be at very low temperature (compared to refrigerant which is passing through a simple refrigeration cycle) so the refrigeration effect of the system is increased. From the figures we can imply that R1234ze(Z) has highest COP. Decreasing order of COP in this graph is R1234ze(Z) (min COP=2.047 and max COP=2.073), R1233zd(E) (min COP=1.92 and max COP=1.93), R134a (min COP=1.787 and max COP=1.796), R1234ze(E) (min COP=1.741 and max COP=1.784), R1243zf (min COP=1.721 and max COP=1.747), R423A (min

COP=1.596 and max COP=1.66), R507A (min COP=1.518 and max COP=1.574). Here the minimum and maximum is calculated at the degree of subcooling of 0 K and 10 K respectively.

From figures 5.22 we can imply that due to subcooling the refrigerant entering into the expansion valve will be at lower temperature. Hence after expansion through the expansion valve the refrigerant entering into evaporator will be at very low temperature (compared to refrigerant which is passing through a simple refrigeration cycle) so the refrigeration effect of the system is increased, which in effect increases the exergetic efficiency. R1234ze(Z) has highest exergetic efficiency. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.3173 and max=0.3214), R1233zd(E) (min=0.2977 and max =0.2993), R134a (min =0.2771 and max=0.2784), R1234ze(E) (min=0.2699 and max=0.2766), R1243zf (min=0.2669 and max=0.2694), R423A (min=0.2475 and max=0.2573), R507A (min=0.2354 and max=0.244). Here the minimum and maximum is calculated at the degree of subcooling of 0 K and 10 K respectively.

From figures 5.23 we can imply that due to subcooling the refrigerant entering into the expansion valve will be at lower temperature. Hence after expansion through the expansion valve the refrigerant entering into evaporator will be at very low temperature (compared to refrigerant which is passing through a simple refrigeration cycle) so the refrigeration effect of the system is increased, which in effect increases the exergetic efficiency and as the exergetic efficiency increases the EDR elevates. R507A has highest EDR in this graph.

From figures 5.24 we can imply that due to subcooling the refrigerant entering into the expansion valve will be at lower temperature. Hence after expansion through the expansion valve the refrigerant entering into evaporator will be at very low temperature (compared to refrigerant which is passing through a simple refrigeration cycle) so the refrigeration effect of the system is increased. From the figures we can imply that R1234ze(Z) has highest COP. Decreasing order of COP in this graph is R1234ze(Z) (min COP=1.694 and max COP=1.706), R1233zd(E) (min COP=1.564 and max COP=1.586), R134a (min COP=1.414 and max COP=1.44), R1234ze(E) (min COP=1.359 and max COP=1.417), R1243zf (min COP=1.356 and max COP=1.398), R423A (min COP=1.213and max COP=1.293), R507A (min COP=1.101 and max COP=1.188). Here the minimum and maximum is calculated at the degree of subcooling of 0 K and 10 K respectively.

From figures 5.25 we can imply that due to subcooling the refrigerant entering into the expansion valve will be at lower temperature. Hence after expansion through the expansion valve the refrigerant entering into evaporator will be at very low temperature (compared to refrigerant which is passing through a simple refrigeration cycle) so the refrigeration effect of the system is increased, which in effect increases the exergetic efficiency. R1234ze(Z) has highest exergetic efficiency. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.2627 and max=0.2646), R1233zd(E) (min=0.2425 and max =0.246), R134a (min =0.2192 and max=0.2233), R1234ze(E) (min=0.2107 and max=0.2196), R1243zf (min=0.2103 and max=0.2167), R423A (min=0.1881 and max=0.2004), R507A (min=0.1707 and max=0.1841). Here the minimum and maximum is calculated at the degree of subcooling of 0 K and 10 K respectively.

From figures 5.26 we can imply that due to subcooling the refrigerant entering into the expansion valve will be at lower temperature. Hence after expansion through the expansion valve the refrigerant entering into evaporator will be at very low temperature (compared to refrigerant which is passing through a simple refrigeration cycle) so the refrigeration effect of the system is increased, which in effect increases the exergetic efficiency and as the exergetic efficiency increases the EDR elevates. R507A has highest EDR in this graph.

Figures 5.27 show the result of varying the effectiveness of the heat exchanger on the COP. From the figure we can depict that the COP elevates. This happens as the effectiveness is incremented subsequently the degree of subcooling is elevated simultaneously there is superheating of the suction vapor happens this makes an increment in the refrigerant effect which is why the COP is incremented. Out of all the seven refrigerants compared R1234ze(Z) has the highest COP. Decreasing order of COP in this graph is R1234ze(Z) (min COP=1.674 and max COP=2.077), R1233zd(E) (min COP=1.568 and max COP=1.941), R134a (min COP=1.401 and max COP=1.809), R1234ze(E) (min COP=1.395 and max COP=1.779), R1243zf (min COP=1.373 and max COP=1.751), R423A (min COP=1.28 and max COP=1.645), R507A (min COP=1.172 and max COP=1.565). Here the minimum and maximum is calculated at the effectiveness of 0.1 and 1 respectively.

Figures 5.28 show the result of varying the effectiveness of the heat exchanger on the exergetic efficiency. From the figure we can depict that the exergetic efficiency elevates. This happens as the effectiveness is incremented subsequently the degree of subcooling is elevated simultaneously there is superheating of the suction vapor happens this makes an increment in the refrigerant effect which is why the exergetic efficiency is incremented. Out of all the seven refrigerants compared R1234ze(Z) has the highest exergetic efficiency. R1234ze(Z) has highest exergetic efficiency. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.2596 and max=0.322), R1233zd(E) (min=0.2431 and max =0.3009), R134a (min =0.2172 and max=0.2805), R1234ze(E) (min=0.2163 and max=0.2758), R1243zf (min=0.2129 and max=0.2714), R423A (min=0.1984 and max=0.255), R507A (min=0.1714 and max=0.2236). Here the minimum and maximum is calculated at the effectiveness of 0.1 and 1 respectively.

Figures 5.29 show the result of varying the effectiveness of the heat exchanger on the EDR. From the figure we can depict that the exergetic efficiency and COP elevates. This happens as the effectiveness is incremented subsequently the degree of subcooling is elevated simultaneously there is superheating of the suction vapor happens this makes an increment in the refrigerant effect which is why the exergetic efficiency is incremented and as a result of that EDR lessens. Out of all the seven refrigerants compared R507Ahas the highest EDR in this graph.

Figures 5.30 show the result of varying the effectiveness of the heat exchanger on the COP. From the figure we can depict that the COP elevates. This happens as the effectiveness is incremented subsequently the degree of subcooling is elevated simultaneously there is superheating of the suction vapor happens this makes an increment in the refrigerant effect which is why the COP is incremented. Out of all the seven refrigerants compared R1234ze(Z) has the highest COP. Decreasing order of COP in this graph is R1234ze(Z) (min COP=0.9447 and max COP=1.715), R1233zd(E) (min COP=1.7052 and max COP=1.589), R134a (min COP=0.5875 and max COP=1.442), R1234ze(E) (min COP=0.5703 and max COP=1.402), R1243zf (min COP=0.5853 and max COP=1.391), R423A (min COP=0.515 and max COP=1.268), R507A (min COP=0.4296 and max COP=1.162). Here the minimum and maximum is calculated at the effectiveness of 0.1 and 1 respectively.

Figures 5.31 show the result of varying the effectiveness of the heat exchanger on the exergetic efficiency. From the figure we can depict that the exergetic efficiency elevates. This happens as the effectiveness is incremented subsequently the degree of subcooling is elevated simultaneously there is superheating of the suction vapor happens this makes an increment in the refrigerant effect which is why the exergetic efficiency is incremented. Out of all the seven refrigerants compared R1234ze(Z) has the highest exergetic efficiency. Decreasing order of exergetic efficiency in this graph is R1234ze(Z) (min=0.2165 and max=0.2659), R1233zd(E) (min=0.1985 and max =0.2463), R134a (min =0.1714 and max=0.2236), R1234ze(E) (min=0.1689 and max=0.2173), R1243zf (min=0.1675 and max=0.2157), R423A (min=0.1513 and max=0.1965), R507A (min=0.1322 and max=0.1801). Here the minimum and maximum is calculated at the effectiveness of 0.1 and 1 respectively.

Figures 5.32 show the result of varying the effectiveness of the heat exchanger on the EDR. From the figure we can depict that the exergetic efficiency and COP elevates. This happens as the effectiveness is incremented subsequently the degree of subcooling is elevated simultaneously there is superheating of the suction vapor happens this makes an increment in the refrigerant effect which is why the exergetic efficiency is incremented and as a result of that EDR lessens. Out of all the seven refrigerants compared R507Ahas the highest EDR in this graph.

Chapter 6

CONCLUSION

By carrying out this comprehensive energy and exergy analysis of refrigerants R134a, R423A, R507A, R1233zd(E), R1234ze(Z), R1234ze(E) and R1243zf in simple vapor compression cycle with heat exchanger the specified conclusions are epitomized beneath.

1. Among the refrigerants studied R1234ze(Z) gives highest COP which is increased by 16-31.15 % when the condenser temperature is decreased.
2. Among the refrigerants studied R1234ze(Z) gives highest exergetic efficiency which is increased by 18.6-31.11 % when the condenser temperature is decreased.
3. In this setup we found out that evaporator is the worst device and liquid vapor heat exchanger is the best device. The minimal efficiency defect in the condenser is for R423A and minimal efficiency defect in evaporator is for R507A, when condenser temperature is 313 K and when temperature is 323 K minimal efficiency defect in the condenser is for R1234ze(E) and minimal efficiency defect in evaporator is for R507A.
4. As there is elevation in ambient temperature the effect of this is that exergetic efficiency increases and EDR lessens. R507A has highest EDR when condenser temperature is increased.
5. R1234ze(Z) gives the highest COP as well as exergetic efficiency when the condenser temperature is increased. But this result is reversed in case of EDR, here the EDR is lessened and R507A has highest EDR at low condenser temperature when the effectiveness is varied from 0 to 1.

Henceforth, from the meticulous investigation carried out R1234ze(Z) performs better than all of the refrigerants used. Hence, R1234ze(Z) can replace R134a in this system with minor modifications as it performs better and beholds eco-friendly properties such as low GWP and low ODP.

REFERENCES

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[1] Esbrı´, J. N., Mendoza-Miranda, J. M., Mota-Babiloni, A., Barraga´n-Cervera, A., & Belman-Flores, J. M. (2013). Experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system. *International Journal of Refrigeration, 36,* 870-880.

[2] Mohanraj, M., Jayaraj, S., & Muraleedharan, C. (2009). Environment friendly alternatives to halogenated refrigerants-A Review. *International Journal of Greenhouse Gas Control, 3*(1), 108-119.

[3] A Brief Analysis of the Kyoto Protocol. (1997). *IX.* Kyoto: Global Environmental Change Report.

[4] Directive 2006/40/EC of the European Parliament and of the Council. (2006). Official Journal of the European Union.

[5] Minor, B., & Spatz, M. (2008). HFO-1234yf Low GWP Refrigerant Update. *International Refrigeration and Air Conditioning*.

[6] Zilio, C., Brown, J. S., & Cavallini, A. (2009). Simulation of R-1234yf performance in a typical automotive system. *Proceedings of the 3rd Conference on Thermophysical Properties and Transfer Processes of Refrigerants, Boulder, CO*, Paper No. 128.

[7] Nielsen, O. J., Javadi, M. S., Andersen, M. S., Hurley, M. D., Wallington, T. J., & Singh, R. (2007). Atmospheric chemistry of CF3CF@CH2: Kinetics and mechanisms of gas-phase reactions with Cl atoms, OH radicals, and O3. *Chemical Physics Letters, 439*, 18-22.

[8] Mota-Babiloni, A., Navarro-Esbrí, J., F. M., Cervera, Á. B., Peris, B., & Verdú, G. (2016). A review of refrigerant R1234ze(E) recent investigations. *Applied Thermal Engineering, 95*, 211-222.

[9] Arora, A., & Kaushik, S. C. (2008). Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A. *International Journal of Refrigeration, 31*, 998-1005.

[10] Liu, X., Wang, T., & He, M. (2019). Investigation on the condensation process of HFO refrigerants by molecular dynamics simulation*. Journal of Molecular Liquids, 288,* 111034.

[11] Llopis, R., Torrella, E., Cabello, R., & Sánchez, D. (2010). Performance evaluation of R404A and R507A refrigerant mixtures in an experimental double-stage vapour compression plant. *Applied Energy, 87*, 1546–1553

[12] Nawaz, K., Shen, B., Elatar, A., Baxter, V., & Abdelaziz, O. (2017). R-1234yf and R-1234ze(E) as low-GWP refrigerants for residential heat pump water heaters. *International Journal of Refrigeration, 82*, 348-365.

[13] Mancuhan, E. (2019). A comprehensive comparison between low and medium temperature application refrigerants at a two-stage refrigeration system with flash intercooling. Thermal Science and Engineering Progress, 13, 100357.

[14] Giuffrida, A. (2018). A theoretical study on the performance of a scroll expander in an organic Rankine cycle with hydrofluoroolefins (HFOs) in place of R245fa. Energy, 161, 1172-1180.

[15] Bobbo, S., Nicola, G. D., Zilio, C., Brown, J. S., & Fedele, L. (2018). Low GWP halocarbon refrigerants: A review of thermophysical properties. *International Journal of Refrigeration, 90,* 181–201.

[16] Nagata, R., Kondou, C., & Koyama, S. (2016). Comparative assessment of condensation and pool boiling heat transfer on horizontal plain single tubes for r1234ze(e), r1234ze(z), and r1233zd(e). *International Journal of Refrigeration, 63,* 157-170.

[17] Zhang, J., Kærn, M. R., Ommen, T., Elmegaard, B., & Haglind, F. (2019). Condensation heat transfer and pressure drop characteristics of R134a, R1234ze(E), R245fa and R1233zd(E) in a plate heat exchanger. *International Journal of Heat and Mass Transfer, 128*, 136–149.

[18] Mota-Babiloni, A., Navarro-Esbrí, J., Mendoza-Miranda, J. M., & Peris, B. (2017). Experimental evaluation of system modifications to increase R1234ze(E) cooling capacity. *Applied Thermal Engineering, 111*, 786–792.

[19] Kou, L., Yang, Z., Tang, X., Zhang, W., & Lu, J. (2019). Experimental measurements and correlation of isothermal vapor-liquid equilibria for HFC-32 +HFO-1234ze (E) and HFC-134a + HFO-1234ze (E) binary systems. *The Journal of Chemical Thermodynamics.*

[20] Devecioğlu, A. G., & Oruç, V. (2018). Improvement on the energy performance of a refrigeration system adapting a plate-type heat exchanger and low-GWP refrigerants as alternatives to R134a. *Energy, 155*, 105-116.

[21] Fukuda, S., Kondou, C., Takata, N., & Koyama, S. (2014). Low GWP refrigerants R1234ze(E) and R1234ze(Z) for high temperature heat pumps. *International Journal of Refrigeration, 40*, 161-173.

[22] Mikielewicz, D., & Wajs, J. (2019). Performance of the very high-temperature heat pump with low GWP working fluids. *Energy, 182*, 460-470.

[23] Wu, D., Hu, B., & Wang, R. Z. (2018). Performance simulation and exergy analysis of a hybrid source heat pump system with low GWP refrigerants. *Renewable Energy, 116*, 775-785.

[24] Calm, J. M., & Hourahan, G. C. (2001). Refrigerant data summary. *Engineered Systems, 18*(11), 74-88.

[25] Goetzler, W., Sutherland, T., Rassi, M., & Burgos, J. (n.d.). Research & Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants. *Energy Efficiency & Renewable Energy*.

[26] Montreal protocol on substances that deplete the ozone layer(report of the technology and economic assessment panel). (2016). *United Nations Environment Programme*.

[27] Fact Sheet No.16 Refrigerents Blend. (n.d.). UNEP Compliance Assistance Programme.

[28] Whitman, B., Johnson, B., & Tomczyck, J. (2005). *Refrigeration and Air Conditioning Technology.* USA: Delmar Cengage Learning.

[29] Lavelle, J. (2006). Understanding Refrigerant Blend Performance. *RSES*, 29-33.

[30] Fisher, D. A., Hales, C. H., Filkin, D. L., Ko, M. K., Sze, N. D., Connell, P. S., . . . Stordal, F. (1990). Model calculations of the relative effects of CFCs and their replacements on stratospheric ozone. *Nature, 344*(6266), 508-512.

[31] Susan, S., & L., A. D. (1992). Time-dependent ozone depletion potentials for short- and long-term forecasts. *Nature, 357*(6373), 33-37.

[32] Abas, N., Kalair, A., Khan, N., & Kalair, A. R. (2017). Review of GHG emissions in Pakistan compared to SAARC countries. *Renewable and Sustainable Energy Reviews, 80,* 990-1016.

[33] Devottaa, S. (2014). Refrigerant Selection – Global Environment, Thermodynamics, Safety and Efficiency. *Indian Chemical Engineer, 56*(3), 294-312.

[34] Solstice, H. (n.d.). R1233zd(E).

[35] Honeywell R1234ze, The Environmental Alternative to Traditional Refrigerants, 2014).

[36] Kayukawa, Y., Tanaka, K., Kano, Y., & Fujita, Y. (2012). Experimental evaluation of the fundamental properties for low-GWP refrigerant HFO-1234ze(Z). *In: Proceedings of the International Symposium on New Refrigerants and Environmental Technology*.

[37] Lai, N. A. (2014). Thermodynamic properties of HFO-1243zf and their application in study on a refrigeration cycle. *Applied Thermal Engineering, 70*(1), 1-6.

[38] Lemmon, E. W., Huber, M. L., & McLinden, M. O. (2013). NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1.

[39] Cengel, Y. A., & Boles , M. A. (n.d.). *Thermodynamics: An Engineering Approach.* McGraw Hill Education.

[40] Ansari, N. A., Yadav, B., & Kumar, J. (2013). Theoretical Exergy Analysis of HFO-1234yf and HFO-1234ze as an Alternative Replacement of HFC-134a in Simple Vapour Compression Refrigeration System. *International Journal of Scientific & Engineering Research, 4*(8).

[41] Dincer, I., & Cengel, Y. A. (2001). Energy, Entropy and Exergy Concepts and Their Roles in. *Entropy, 3*, 116-149.

[42] Klein, S. A., & Alvarado, F. L. (2012). EES—Engineering Equation Solver Version 9.223. *F Chart Software*.