



## ORIGINAL ARTICLE

# Methods for improving thermodynamic performances using exergy evaluation in modified VCRS using HFO refrigerants for reducing global warming

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### Abstract

Methods for improving thermodynamic performances in vapour compression refrigeration system using different load conditions have been discussed and numerical computation was carried out by using eight ultra-low HFO refrigerants and low GWP HFC refrigerants. It was found that modified vapour compression refrigeration system-1 using R1234ze(Z) gives highest thermodynamic first and second law performances and lowest 3.25% using R1234yf as compared with HFC-134a. The first law efficiency (COP) and exergetic efficiency using R-1225ye(Z), R1243zf, and R1234ze(E) is nearly same with slightly variation which can be negligible as compared with R134a. The performance improvement is maximum is 4.2% by using HFO 1234ze(Z). The power required to run whole system using 4.03% lower using HFO 1234ze(Z) and 3.62% higher by using R1234yf refrigerant for replacing HFC-134a. ©2021 ijrei.com. All rights reserved

## 1. Introduction

Refrigeration is a technology which absorbs heat at low temperature and provides temperature lower than the surrounding temperature, by rejecting heat to the surrounding at higher temperature. The simple vapour compression system which consists of four major components compressor, expansion valve, condenser and evaporator in which total cooling load is carried at one temperature by single evaporator but in many applications like large hotels, food storage and food processing plants, food items are stored in different compartment and at different temperatures

At the present time, the most of the energy utilize in cooling and air conditioning in industrial as well as for domestic applications, in addition to energy consumption, using of refrigerants in cooling and air conditioning having high GWP and ODP which are responsible for increasing global warming

and ozone depletion.

## 2. Methods for improving thermodynamic performances of Vapour compression refrigeration systems

Simple vapour compression system which consists of four major components compressor, expansion valve, condenser and evaporator in which total cooling load is carried at one temperature by single evaporator but in many applications like large hotels, food storage and food processing plants, food items are stored in different compartment and at different temperatures. Therefore, there is need of multi evaporator vapour compression refrigeration system. The systems under vapour compression technology consume enormous amount of electricity, this problem can be solved by improving performance of system.

Thermodynamic performances of systems based on vapour

compression refrigeration technology can be improved by following [1]:

- COP means coefficient of performance known as first law efficiency. The performance of refrigerator is defined, is the ratio of refrigeration effect to the net work input given to the system. The COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. by adopting multi-stage expansion with flash chamber where the flash vapour is removed after each stage of expansion as a consequence there will be increasing.
- cooling capacity and reduce the size of the evaporator. Because throttling process in VCR is an irreversible expansion process due to internal irreversibility. The expansion process is one of the main factors responsible for exergy loss in cycle thermodynamic performance, since the entering portion of the refrigerant flashing to vapour in evaporator which will not only reduce the cooling capacity but also increase the size of evaporator.
- The Work input can also be reduced by replacing multi-stage compression or compound compression with single stage compression.
- Refrigeration effect can also be increased by passing the refrigerant through subcooler after condenser by sub cooling to evaporator.

Vapour compression refrigeration system based applications make use of refrigerants which are responsible for greenhouse gases, global warming and ozone layer depletion. Montreal protocol was signed on the issue of substances that are responsible for depleting Ozone layer and discovered how much consumption and production of ozone depletion substances took place during certain time period for both developed and developing countries. Another protocol named as Kyoto aimed to control emission of greenhouse gases in 1997. The relationship between ozone depletion potential and global warming potential is the major concern in the field of GRT (green refrigeration technology) Kyoto proposed new refrigerants having lower value of ODP and GWP. Internationally a program being pursued to phase out refrigerants having high chlorine content for the sake of global environmental problems. Due to presence of high chlorine content, high global warming potential and ozone depletion potential after 90's CFC and HCFC refrigerants have been restricted. Thus, HFC refrigerants are used nowadays, showing much lower global warming potential value, but still high with respect to non-fluorine refrigerants. Lots of research work has been done for replacing "old" refrigerants with "new" refrigerants [2].

The primary requirements of ideal refrigerants are having good physical and chemical properties. Due to good physical and chemical properties such as non-corrosiveness, non-toxicity, non-flammability, low boiling point, Chlorofluorocarbons (CFCs) have been used over the last many decades, but hydro

chloro fluorocarbons (HCFCs) and Chlorofluorocarbons (CFCs) having large amount of ozone depletion potential, so after 90s the chlorine content as well as high global warming potential are almost prohibited and searching for low GWP refrigerants. The existing low GWP refrigerants can be divided into two categories: pure refrigerants and mixed refrigerants.

The pure refrigerants can be divided into three types: (i) HFCs with medium and low GWP, such as R32, R152a, R161, etc.; (ii) natural refrigerants, which include carbon dioxide (R744), ammonia (R717), water (R718), hydrocarbons such as propane (R290) and (iii) HFOs and HCFOs, such as R1234yf, R1234ze(E), R1234ze(Z), R1336mzz(Z), R1233zd(E), etc.;

Some HFO refrigerants are nonflammable, nontoxic. Moreover, the range of standard boiling point, critical temperature and critical pressure is wide, which can basically meet the requirements of different types of refrigeration systems, so they can be used as the replacements for HFC refrigerants. Few alternative HFO and HCFO refrigerants for replacing R134a are given below.

### 2.1 HFOs refrigerants

The HFOs refrigerants have ultra-low GWP values are less than three and can be used as long-term substitutes of HFC refrigerants from the perspective of environmental protection. For comparing with HFO refrigerants, the relative cooling capacity and COP of following alternative refrigerants of R134a, nearly similar of R1243zf, R1225ye(Z) and R1234ze(E). R1234ze(E) has the lowest relative capacity. The COP values of these substitutes are slightly lower and higher than that of R134a.

### 2.2 R1234ze(E) refrigerant

R1234ze(E) also belongs to A2L refrigerant. Its physical properties are closed to that of R134a, but its unit price is lower than that of R1234yf. It has good mutual solubility with mineral oil, PAG, POE, etc. The heat transfer coefficient of evaporation is the same as that of R134a, and the heat transfer coefficient of condensation is lower than that of R134a, but higher than that of R1234yf. It can be used as a substitute of R134a in centrifugal water chiller, and can also be used in subcritical medium and high temperature heat pump and water heater. Compared with R134a, it has nearly similar COP and smaller heating capacity per unit volume. Therefore, a larger displacement compressor is required, otherwise the heating time will be prolonged. The improvement direction of the adaptation system is to improve the condensation heat transfer performance, increase the sub-cooling (regeneration), and add the ejector. It can be used in the double cycle chiller; Industrial high-temperature heat pump has a wide range of applications.

### 2.3 R1234yf refrigerant

R1234yf belongs to A2L refrigerant. Its basic physical properties are close to that of R134a, and the latent heat of gasification is lower than that of R134a. It is mainly used in the replacement of R134a in vehicle air conditioning, and also in residential heat pump water heater. Although under the same working condition, the discharge temperature of R1234yf is lower than that of R134a and the reliability of R1234yf compressor is better under low temperature condition. It is compatible with carbon steel, stainless steel, copper and brass, plastic and rubber. R1234yf as an alternative to R134a has been applied to household refrigerators. The optimal charge is 92.2 g, which is 7.8% lower than R134a. It also showed that the energy consumption can be reduced by about 4%. In addition, its TEWI value is 1.07% higher than R134a. The performances of R1234yf and R134a were compared and analyzed on the bench test instrument of heat pump under the condition of automobile air conditioning and the results showed that the COP of R1234yf is 0.8% to 2.7% lower than R134a, the cooling capacity is reduced by about 4%, and the charge amount can be reduced by 10% to 11%. Because of its excellent environmental protection characteristics, it can be used as a long term alternative for replacing high GWP R-134a.

### 2.4 R1234ze(Z) refrigerant

R1234ze(Z) belongs to A1 refrigerant and its physical properties are closed to R245fa, which can be used as the substitute of R245fa and R123. Therefore, it is suitable for high temperature industrial centrifugal heat pump and waste heat recovery system. It has good solubility with mineral oil, and other common lubricants. It does not react with steel, iron, rubber plastic and other materials. Therefore, it has good material compatibility. In addition, its thermal conductivity is much higher than the common working fluid of medium temperature refrigeration and high temperature heat pump.

### 2.5 R1233zd(E) refrigerant

R1233zd(E) is a class A1 refrigerant with has a high critical temperature and standard boiling point, although it contains a chlorine atom, and its ODP and GWP are negligible due to its short atmospheric lifetime. The physical properties of R1233zd(E) are closed to that of R245fa. R1233zd(E) can be used as an alternative refrigerant for R245fa in centrifugal chiller, low temperature heat recovery system, high temperature heat pump system and heat pump water heater. R1233zd(E) refrigerant is best suited for two-stage centrifugal chiller.

### 2.6 R1336mzz(Z) refrigerant

R1336mzz(Z) is a class A1 refrigerant which has high critical

temperature of 444.13K (171.35 °C) and standard boiling point of 306.4K (33.453 °C). It shows a very high chemical stability at high temperature. Due to these advantages, it is appropriate for low, medium and high temperature heat pump, centrifugal water chiller, positive displacement chiller and industrial process air conditioning system. When the temperature is higher than 100 °C, the performance of R1336mzz(Z) would significantly better than that of R245fa; in the industrial field, it can also be used in the heat recovery of ORC. Most of the study has been carried out for the performance evaluation of vapour compression refrigeration system using energetic analysis, but with the help of first law analysis irreversibility destruction or losses in components of system unable to determined. Therefore, exergetic analysis is the advanced approach for thermodynamic analysis which gives an additional practical view of the processes. The utility of second law analysis on vapour compression refrigeration systems is well defined because it gives the idea for improvements in efficiency due to modifications in existing design in terms of reducing exergy destructions in the components. In addition to this second law analysis also provides new thought for development in the existing system. The thermodynamic performance has been compared on a domestic refrigerator which is originally designed to work with R134a [3]. Using R290/R600a mixture and found that R290/R600a hydrocarbon mixture showed higher COP (i.e. first law efficiency) and exergetic efficiency (i.e. second law efficiency) than using R134a. they also found the highest irreversibility in the compressor as compared to condenser, expansion valve and evaporator. The numerical analysis of vapour compression refrigeration system using R134a, R143a, R152a, R404A, R410A, R502 and R507A was performed and found the significant effect of evaporator temperature, degree of subcooling at condenser outlet, superheating of evaporator outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature on COP (i.e. first law efficiency) and exergetic efficiency and also found that R134a has the better performance than using R407C in all respect [4].

The energy and exergy analysis of vapour compression refrigeration system carried out by using of exergy-enthalpy diagram [5]. Analytically plant irreversibility using R22 refrigerant of two stage vapour compression refrigeration plant and found significant effect of change in evaporator and condenser temperatures and suggested that there is need for optimizing the conditions imposed upon the condenser and evaporator [6]. The thermodynamic analysis for finding the effect of operating parameters on COP, work input and cooling capacity of single-stage vapour compression refrigeration system and found great influence on energetic parameters due change in suction pressure, condensing and evaporating temperatures [7]. The effect of condensing pressure, evaporating pressure and degree of superheating was experimentally investigated on single stage vapour compression refrigeration system using R22, R134a and R407C [7,8] and found that the mass flow rate is greatly

affected by change in suction conditions of compressor results on refrigeration capacity because refrigeration capacity depended on mass flow rate through evaporator. Also found that for higher compression ratio R22 gives lower COP than R407C.

The experimental study on the vapour compression refrigeration system designed for R404A and found that the mixture of HFC-161 gives higher thermodynamic performances than using R404A at lower and higher evaporative temperature respectively. Also presented energy analysis for replacement of R502 by mixture of HFC-161 [9]. The experimental performance of vapour compression refrigeration system, using R401A, R290 and R134A and compared with R12 and found similar performance using R134a in comparison with R12. Also concluded that the R134A can be replaced in the same system without any medication in the system components and found best results, using R290 [10]. The experimental investigation on domestic refrigerator under different environmental temperatures using mixture of R290 and R600a in the ratio of 45.2: 54.8 by weight showing up to 3.6% greater COP of system than using R134a. Also discharge temperature of compressor with mixture of R290 and R600a is lower in the range of 8.5-13.4K than same compressor with R134a [11]. The experimental investigation vapour compression refrigeration system having rotor compressor with mixture of R32/R125/R161 under different working conditions and found higher COP, less pressure ratio and slightly high discharge compressor temperature without any modification in the same system using R407c and concluded that the mixture of R32/R125/R161 could be replacement of R407C [12]. The exergy analysis on vapour compression refrigeration cycle by considering the effect of condensing and evaporating temperatures and computed COP, second law efficiency and exergy losses and found by increasing condenser and evaporator temperatures, first law efficiency(COP) and exergy efficiency increases but total exergy losses of system decrease [13]. The exergy analysis of domestic vapour compression refrigeration system using R12 and R413A and concluded that the thermodynamic performances in terms of power consumption, irreversibility and exergetic efficiency of R413A is better than R12. Therefore, R12 can be replaced by using R413A in domestic vapour compression refrigeration system [14]. Use of hydrocarbons and mixture of hydrocarbons and R134a in vapour compression refrigeration system and found that compressor shows much higher exergy destruction as compared to rest of components of vapour compression refrigeration system and this exergy destruction can be minimized by using of nano fluid and nano lubricants in compressor [15]. The experimental investigation of domestic refrigerator using hydrocarbons (isobutene and butane) and carried out energy and exergy analysis. Also found that the energy efficiency ratio of hydrocarbons as comparable with R134a but exergetic efficiency and sustainability index of hydrocarbons much higher than that of R134a at considered

evaporator temperature and found that the compressors shows highest system defect among other components of considered vapour compression refrigeration system [16]. Effect of subcooling, superheating and compression ratio of single stage vapour compression refrigeration system using R22, R134a, R717, R507a, R404a refrigerants [17]. The comparative analysis of R32, R152a and R134a refrigerants in vapour compression refrigerator carried out and concluded that the R32 shows lowest performance whereas R134a and R152a showing nearly same performance but best performance as compared to R32 [18]. The thermodynamic analysis of cascade heat exchanger R744-R717 cascade refrigeration system and optimized operating parameters (i.e. condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature difference) using regression analysis was carried out [19]

Based on the literature it was observed that researchers have gone through detailed first law analysis in terms of coefficient of performance and second law analysis in term of exergetic efficiency of simple vapour compression refrigeration system with single evaporator. Researchers did not go through the irreversibility analysis or second law analysis of: simple VCR with flash intercooler, flash chamber, water intercooler, liquid sub cooler and stages in compression (double stage and triple stage) and multiple evaporators systems with multi-stage expansion and compound compression in vapour compression refrigeration systems. This paper mainly deals with the methods for improving thermal performance of vapour compression refrigeration systems (both single and multiple evaporator system) by improving:

- First law efficiency (coefficient of performance)
- Second law efficiency (exergetic efficiency)
- Reduction of system defect in components of system which results into reduction of work input.
- Detailed analysis of some vapour compression refrigeration systems using HFO ecofriendly refrigerants.

### 3. Thermodynamic analysis of multi evaporator systems

Energy analysis is concerned with the conservation of energy but it gives no information on how, where, and how much the system performance is degraded or evaluation of actual irreversibility losses occurred in system.

Therefore, exergy analysis which is based on first law and second law of thermodynamic is a powerful tool in the design, optimization, and performance evaluation of energy systems. Exergy analysis (second law analysis) helps in identifying the thermal losses and energy transfer for the processes. As per earlier research, exergetic efficiency, energetic efficiency and irreversibility in each component of VCR system is not same for different refrigerants. In this paper numerical models have been developed for the comparison of performance parameters of system (system-1 & system-2) based on selected refrigerants by using EES software.

### 3.1 Description of system

System-1 consist of compressors (Comp<sub>1</sub>, Comp<sub>2</sub>, Comp<sub>3</sub>), throttle valves (tv<sub>1</sub>, tv<sub>2</sub>, tv<sub>3</sub>), condenser and evaporators(EP<sub>1</sub>,

EP<sub>2</sub>, EP<sub>3</sub>). The main components of system-1 are compressors (Comp<sub>1</sub>\*, Comp<sub>2</sub>\*, Comp<sub>3</sub>\*), throttle valves (tv<sub>1</sub>\*, tv<sub>2</sub>\*, tv<sub>3</sub>\*), condenser and evaporators(EP<sub>1</sub>\*, EP<sub>2</sub>\*, EP<sub>3</sub>\*), intercooler, and flash chambers as shown in Fig. 1.

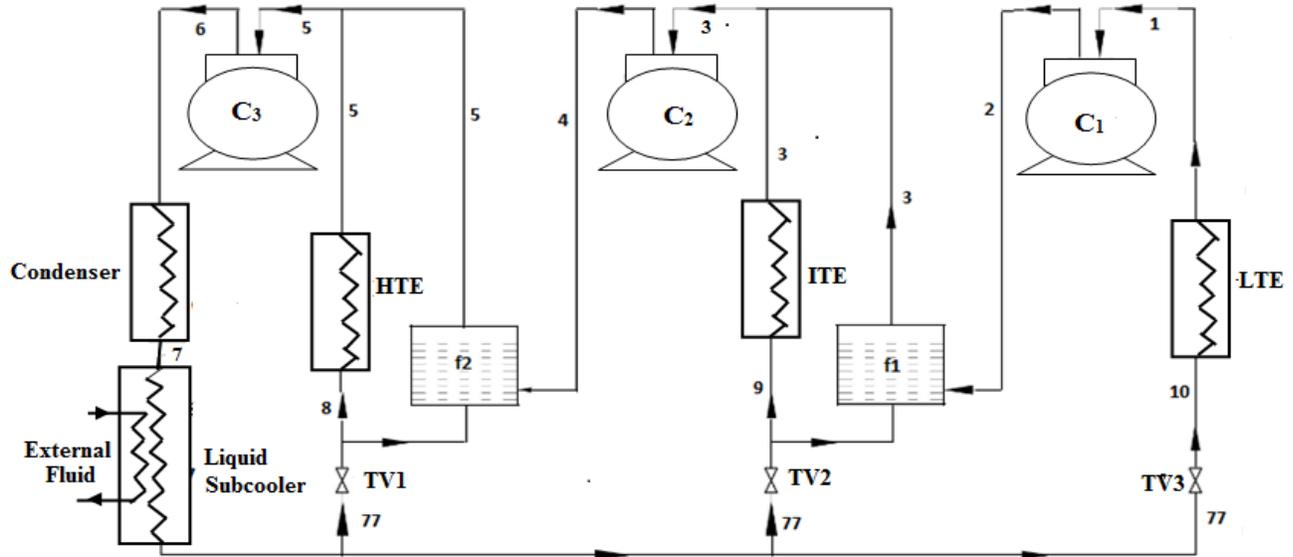


Figure 1: Schematic diagram of modified vapour compression refrigeration system using multiple evaporators with compound compression, flash intercooler and multiple throttle valve

### 3.2 Energy and Exergy analysis

For carrying out energetic and exergetic analysis, computational model of modified vapour compression refrigeration system has been developed and impact of chosen HFO refrigerants on the system has been analyzed using EES software. In this investigation following assumptions are made:

- Load on the low, intermediate and high temperature evaporators are 10TR, 20 TR and 30 TR respectively.
- Dead state temperature (T<sub>0</sub>): 25 °C
- Difference between evaporator and space temperature (T<sub>r</sub>-T<sub>e</sub>):5 °C.
- Adiabatic efficiency of compressor: 76%.
- Dead state enthalpy (Φ<sub>0</sub>) and entropy (s<sub>0</sub>) of the refrigerants have been calculated corresponding to the dead state temperature (T<sub>0</sub>) of 25 °C.
- Variation in kinetic and potential energy is negligible.
- Expansion process is adiabatic
- Temperature of low, intermediate and high temperature evaporators are -10 °C,0 °C and 10 °C respectively.
- Condenser temperature: 40 °C
- Degree of sub cooling: 10 °C

Exergy at any state is given as

$$X = (\Phi - \Phi_0) - T_0(s - s_0) \quad (1)$$

### 3.3 Energy analysis

First law of thermodynamic gives the idea of energy balance of system.

Mass flow analysis of system-1

$$\dot{m}_{c1} = \dot{m}_{e1} = \frac{\dot{Q}_{e1}}{(\Phi_1 - \Phi_{10})} \quad (2)$$

$$\dot{m}_{e2} = \frac{\dot{Q}_{e2}}{(\Phi_3 - \Phi_9)} \quad (3)$$

$$\dot{m}_{f1} = \frac{\dot{m}_{c1}(\Phi_2 - \Phi_3)}{(\Phi_3 - \Phi_9)} \quad (4)$$

$$\dot{m}_{c2} = \dot{m}_{c1} + \dot{m}_{e2} + \dot{m}_{f1} \quad (5)$$

$$\dot{m}_{e3} = \frac{\dot{Q}_{e3}}{(\Phi_5 - \Phi_8)} \quad (6)$$

$$\dot{m}_{f2} = \frac{\dot{m}_{c2}(\Phi_4 - \Phi_5)}{(\Phi_5 - \Phi_8)} \quad (7)$$

$$\dot{m}_{c3} = \dot{m}_{c2} + \dot{m}_{e3} + \dot{m}_{f2} \quad (8)$$

Energy consumption for sytem-1

$$P_{c1} = \frac{\dot{m}_{c1}(\Phi_2 - \Phi_1)}{60} \quad (9)$$

$$P_{c2} = \frac{\dot{m}_{c2}(\Phi_4 - \Phi_3)}{60} \quad (10)$$

$$P_{c3} = \frac{\dot{m}_{c3}(\Phi_6 - \Phi_5)}{60} \quad (11)$$

Energetic efficiency of system-1

$$COP = \frac{\dot{Q}_e}{P_c * 60} \quad (12)$$

3.4 Rate of exergy loss due to irreversibility ( $T_o\dot{S}_{gen}$ ) in various components of system-1

The concept of exergy was given by second law of thermodynamics, which always decreases due to thermodynamic irreversibility. Exergy is defined as the measure of usefulness, quality or potential of a stream to cause change and an effective measure of the potential of a substance to impact the environment.

Compressors

$$(T_o\dot{S}_{gen})_{c1} = \dot{W}_{c1} + m_{c1}(X_2 - X_1) \quad (13)$$

$$(T_o\dot{S}_{gen})_{c2} = \dot{W}_{c2} + m_{c2}(X_4 - X_3) \quad (14)$$

$$(T_o\dot{S}_{gen})_{c3} = \dot{W}_{c3} + m_{c3}(X_6 - X_5) \quad (15)$$

$$\dot{\Psi}_c = (T_o\dot{S}_{gen})_{c1} + (T_o\dot{S}_{gen})_{c2} + (T_o\dot{S}_{gen})_{c3} \quad (16)$$

Evaporators

$$(T_o\dot{S}_{gen})_{e1} = \dot{m}_{e1}(X_1 - X_{10}) - \dot{Q}_{e1} \left(1 - \frac{T_o}{T_{r1}}\right) \quad (17)$$

$$(T_o\dot{S}_{gen})_{e2} = \dot{m}_{e2}(X_3 - X_9) - \dot{Q}_{e2} \left(1 - \frac{T_o}{T_{r2}}\right) \quad (18)$$

$$(T_o\dot{S}_{gen})_{e3} = \dot{m}_{e3}(X_5 - X_8) - \dot{Q}_{e3} \left(1 - \frac{T_o}{T_{r3}}\right) \quad (19)$$

$$\dot{\Psi}_e = (T_o\dot{S}_{gen})_{e1} + (T_o\dot{S}_{gen})_{e2} + (T_o\dot{S}_{gen})_{e3} \quad (20)$$

Condenser

$$\begin{aligned} \dot{\Psi}_{cond} &= (T_o\dot{S}_{gen})_{cond} \\ &= \dot{m}_{c3}(X_6 - X_7) - \dot{Q}_e \left(1 - \frac{T_o}{T_r}\right) \end{aligned} \quad (21)$$

Throttle Valves

$$(T_o\dot{S}_{gen})_{tv1} = \dot{m}_{e1}(X_{77} - X_{10}) \quad (22)$$

$$(T_o\dot{S}_{gen})_{tv2} = (\dot{m}_{e2} + \dot{m}_{f1})(X_{77} - X_9) \quad (23)$$

$$(T_o\dot{S}_{gen})_{tv3} = (\dot{m}_{e3} + \dot{m}_{f2})(X_{77} - X_8) \quad (24)$$

$$\begin{aligned} \dot{\Psi}_{tv} &= (T_o\dot{S}_{gen})_{tv1} + (T_o\dot{S}_{gen})_{tv2} \\ &\quad + (T_o\dot{S}_{gen})_{tv3} \end{aligned} \quad (25)$$

Liquid subcooler

$$\dot{\Psi}_{lsc} = (T_o\dot{S}_{gen})_{sc} = \dot{m}_{c3}(X_7 - X_{77}) \quad (26)$$

Flash intercoolers

$$(T_o\dot{S}_{gen})_{f1} = \dot{m}_{f1}(X_9 - X_3) + \dot{m}_{c1}(X_2 - X_3) \quad (27)$$

$$(T_o\dot{S}_{gen})_{f2} = \dot{m}_{f2}(X_8 - X_5) + \dot{m}_{c1}(X_4 - X_5) \quad (28)$$

$$\dot{\Psi}_f = (T_o\dot{S}_{gen})_{f1} + (T_o\dot{S}_{gen})_{f2} \quad (29)$$

3.5 Total irreversibility destruction in system-1

$$\sum \dot{\Psi}_k = \dot{\Psi}_e + \dot{\Psi}_c + \dot{\Psi}_{cond} + \dot{\Psi}_{tv} + \dot{\Psi}_{lsc} + \dot{\Psi}_f \quad (30)$$

$$\dot{m}_{c1} = \dot{m}_{e1} = \frac{\dot{Q}_{e1}}{(\Phi_{1'} - \Phi_{12'})} \quad (31)$$

$$\dot{m}_{e2} = \frac{\dot{Q}_{e2'}}{(\Phi_{3'} - \Phi_{10'})} + \dot{m}_{c1} \left(\frac{x_{10'}}{1 - x_{10'}}\right) \quad (32)$$

$$\dot{m}_{f1} = \frac{\dot{m}_{c1}(\Phi_{2'} - \Phi_{3'})}{(\Phi_{3'} - \Phi_{10'})} \quad (33)$$

$$\dot{m}_{c2} = \dot{m}_{c1} + \dot{m}_{e2} + \dot{m}_{f1} \quad (34)$$

$$\dot{m}_{e3} = \frac{\dot{Q}_{e3'}}{(\Phi_{5'} - \Phi_{8'})} + \dot{m}_{c2} \left(\frac{x_{8'}}{1 - x_{8'}}\right) \quad (35)$$

$$\dot{m}_{f2} = \frac{\dot{m}_{c2}(\Phi_{4'} - \Phi_{5'})}{(\Phi_{5'} - \Phi_{8'})} \quad (36)$$

Power required for running the compressors

$$P_{c1} = \frac{\dot{m}_{c1}(\Phi_{2'} - \Phi_{1'})}{60} \quad (37)$$

$$P_{c2} = \frac{\dot{m}_{c2}(\Phi_{4'} - \Phi_{3'})}{60} \quad (38)$$

$$P_{c3} = \frac{\dot{m}_{c3}(\Phi_{6'} - \Phi_{5'})}{60} \quad (39)$$

$$\text{Energetic efficiency} = \frac{\dot{Q}_{e'}}{P_c * 60} \quad (40)$$

Exergetic efficiency

$$= \frac{\text{Exergy of cooling load of evaporators}}{\text{Compressors work}} = \frac{\dot{E}P}{\dot{W}} \quad (41)$$

Exergetic efficiency of system - 1

$$= \frac{(\dot{Q}_{e1} + \dot{Q}_{e2} + \dot{Q}_{e3}) - T_o \left(\frac{\dot{Q}_{e1}}{T_{r1}} + \frac{\dot{Q}_{e2}}{T_{r2}} + \frac{\dot{Q}_{e3}}{T_{r3}}\right)}{P_c * 60} \quad (42)$$

Exergetic efficiency of system - 2

$$= \frac{(\dot{Q}_{e1'} + \dot{Q}_{e2'} + \dot{Q}_{e3'}) - T_o \left(\frac{\dot{Q}_{e1'}}{T_{r1'}} + \frac{\dot{Q}_{e2'}}{T_{r2'}} + \frac{\dot{Q}_{e3'}}{T_{r3'}}\right)}{P_{c'} * 60} \quad (43)$$

**4. Results and Discussion**

Following four modified vapour compression refrigeration systems using different four type of load conditions have been considered for numerical computations and their specifications are shown in Table-1. The performance parameters are evaluated by considering following operating conditions of the systems.

- Adiabatic efficiency of each compressor ( $\eta_c$ ): 75%.
- Negligible pressure drop in pipelines
- Negligible change in potential and kinetic energy
- Expansion of refrigerant in expansion valves is isenthalpic
- Condenser temperature ( $T_{cond}$ ): 313K
- Dead state temperature ( $T_0$ ): 298K
- Dead state enthalpy ( $\psi_0$ ) and entropy ( $s_0$ ) of the refrigerants have been calculated corresponding to the dead state temperature ( $T_0$ ) of 298K.

*4.1 Effect of ultra-low GWP and zero ODP ecofriendly HFO&HCFO refrigerants*

Table-2 shows the thermodynamic performances of modified vapour compression refrigeration system using following ecofriendly ultra-low GWP refrigerants for replacing R-134a.

it is observed that R-1234ze(Z), R1224yd(Z), R1233zd(E), R1336mzz(Z) gives better thermodynamic first and second law performances in terms of coefficient of performance (energy performance) and second law (exergetic) performances. However, R1225ye(Z), R1243zf and R134aze(Z) gives similar thermodynamic performances with slightly varying considered negligible variations. Similarly, R1234yf gives around 2.9% lower thermodynamic performances. Table-(3-5) shows the performance of same system with different loading conditions. similar trends were observed by using HFO refrigerants.

*Table 1: Modified vapour compression refrigeration system (system-1, 2, 3, and 4) using multiple evaporators at the different temperatures with compound compression, multiple expansion valves and flash inter cooler*

Input value	Value
Cooling Load on First Evaporator( $Q_{Eva_1}$ ) (KW)	105
Cooling Load on second Evaporator( $Q_{Eva_2}$ ) (KW)	35
Cooling Load on second Evaporator( $Q_{Eva_2}$ ) (KW)	70
Isentropic Efficiency of first compressor(Comp_Eff_1)	75%
Isentropic Efficiency of second compressor (Comp_Eff_2)	75%
Isentropic Efficiency of third compressor(Comp_Eff_3)	75%
Temperature of first evaporator (°K)	263
Temperature of second evaporator (°K)	278
Temperature of third evaporator (°K)	283

*Table 2: Energy performance parameters of modified vapour compression refrigeration system(system-1) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)*

Performance Parameters	R1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	HFO-1336 mzz(Z)	R-1225 ye(Z)	R-1243 zf	R1234 ze(E)	R1234 yf
COP	4.548	4.498	4.529	4.477	4.334	4.35	4.378	4.235
EDR	1.878	1.09	1.89	1.92	1.996	1.986	1.968	2.055
Exergetic efficiency	0.3431	0.3394	0.3417	0.3318	0.327	0.3282	0.3303	0.3195
Total Compressor Work “kW”	46.17	46.69	46.37	46.90	48.45	48.28	47.96	49.58
Mass flow rate in First Compressor ‘kg/sec’	0.5846	0.7569	0.6393	0.7472	0.8840	0.6815	0.7529	0.878
Mass flow rate in second Compressor ‘kg/sec’	0.7825	1.009	0.8536	0.993	1.180	0.911	1.004	1.169
Mass flow rate in third Compressor ‘kg/sec’	1.166	1.498	1.269	1.468	1.751	1.355	1.488	1.731
First Compressor Work “kW”	3.209	3.303	3.257	3.364	3.483	3.443	3.450	3.616
Second Compressor Work “kW”	4.169	4.272	4.218	4.335	4.492	4.448	4.444	4.646
Third Compressor Work “kW”	38.79	35.11	38.90	39.2	40.48	40.39	40.07	41.32
Exergy of Fuel “kW”	46.17	46.17	46.17	46.17	46.17	46.17	46.17	46.17
Exergy of Product “kW”	15.84	15.84	15.84	15.84	15.84	15.84	15.84	15.84

*Table 3: Energy performance parameters of vapour compression refrigeration system (system-2) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 70 kW, second evaporator load is 105 kW, third evaporator load is 35 kW)*

Performance Parameters	R1234 ze(Z)	R1224 yd(Z)	R1233 zd(E)	HFO1336 mzz(Z)	R1225 ye(Z)	R1243 zf	R1234 ze(E)	R1234 yf
COP	4.558	4.508	4.539	4.488	4.345	4.360	4.389	4.247
EDR	1.876	1.904	1.888	1.917	1.993	1.983	1.965	2.051
Exergetic efficiency	0.3433	0.3396	0.3419	0.3381	0.3273	0.3284	0.3306	0.3199
Total Compressor Work “kW”	46.08	46.58	46.27	46.190	48.33	48.16	47.84	49.45
Mass flow rate in First Compressor ‘kg/sec’	0.3897	0.5046	0.4262	0.4981	0.5894	0.4543	0.502	0.5853
Mass flow rate in second compressor ‘kg/sec’	0.9679	1.248	1.056	1.228	1.458	1.126	1.24	1.444
Mass flow rate in third compressor ‘kg/sec’	1.166	1.498	1.268	1.468	1.751	1.354	1.488	1.730
First Compressor Work “kW”	2.410	2.202	2.171	2.243	2.322	2.295	2.30	2.411

Second Compressor Work “kW”	5.157	5.282	5.217	5.359	5.551	5.498	5.492	5.74
Third Compressor Work “kW”	38.78	39.10	38.88	39.19	48.33	40.37	40.05	41.30
Exergy of Fuel“kW”	46.08	46.58	46.27	46.19	40.46	48.16	47.84	49.45
Exergy of Product “kW”	15.84	15.84	15.84	15.84	15.84	15.84	15.84	15.84

Table 4: Energy performance parameters of vapour compression refrigeration system(system-3) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R1234 ze(Z)	R1224 yd(Z)	R1233 zd(E)	HFO 1336 mzz(Z)	R1225 ye(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R134a
COP	4.382	4.381	4.380	4.371	4.213	4.261	4.237	4.114	4.252
EDR	1.988	1.864	1.834	1.954	1.847	1.878	1.944	1.927	1.935
Exergetic efficiency	0.3492	0.3445	0.3484	0.3448	0.337	0.3338	0.3340	0.3212	0.3342
Total Compressor Work “kW”	50.45	47.92	47.37	49.75	47.59	48.15	49.57	49.25	49.39
Mass flow rate in First Compressor	0.878	0.7569	0.5846	0.8840	0.639	0.7422	0.6815	0.7529	0.6816
Mass flow rate in second Compressor	1.454	1.256	0.9737	1.467	1.062	1.235	1.133	1.248	1.136
Mass flow rate in third Compressor	1.740	1.505	1.172	1.760	1.275	1.476	1.362	1.496	1.369
First Compressor Work “kW”	3.583	3.303	3.209	3.483	3.257	3.364	3.443	3.45	3.412
Second Compressor Work “kW”	5.726	5.315	5.188	5.587	5.249	5.393	5.533	5.528	5.490
Third Compressor Work “kW”	41.14	39.3	38.95	40.68	39.08	39.40	40.59	40.27	40.49
Exergy of Fuel“kW”	50.45	47.92	47.37	49.75	47.59	48.15	49.57	49.25	49.39
Exergy of Product “kW”	16.51	16.51	16.51	16.51	16.51	16.51	16.51	16.51	16.51

Table-5:Energy performance parameters of vapour compression refrigeration system (system-4) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	HFO-1336 mzz(Z)	R-1225 ye(Z)	R-1243 zf	R1234 ze(E)	R1234 yf
COP	4.956	4.909	4.939	4.892	4.739	4.752	4.787	4.634
EDR	2.028	2.053	2.038	2.064	2.14	2.132	2.111	2.195
Exergetic efficiency	0.3259	0.3258	0.3257	0.3256	0.3224	0.3135	0.3132	0.3116
Total Compressor Work “kW”	42.38	42.78	42.52	42.92	44.31	44.19	43.87	45.28
Mass flow rate in First Compressor‘kg/sec’	0.1949	0.2223	0.2131	0.2491	0.2947	0.2272	0.2510	0.2927
Mass flow rate in secondCompressor‘kg/sec’	0.5796	0.7473	0.6321	0.735	0.8729	0.6741	0.7426	0.8645
Mass flow rate in thirdCompressor‘kg/sec’	1.149	1.475	1.250	1.446	1.723	1.334	1.465	1.702
First Compressor Work “kW”	1.07	1.101	1.086	1.121	1.161	1.148	1.15	1.205
Second Compressor Work “kW”	3.088	3.163	3.124	3.209	3.323	3.291	3.288	3.436
Third Compressor Work “kW”	38.22	38.52	38.31	38.61	39.83	39.75	39.43	40.64
Exergy of Fuel“kW”	42.38	42.78	42.52	42.92	44.31	44.19	43.87	45.28
Exergy of Product “kW”	13.81	13.81	13.81	13.81	13.81	13.81	13.81	13.81

Table 6: Energy performance parameters of modified vapour compression refrigeration system (system-1) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R134a	R-152a	R-245fa	R-32
COP	4.365	4.462	4.514	4.215
EDR	1.977	1.924	1.896	2.075
Exergetic efficiency	0.3293	0.3366	0.3406	0.318
Total Compressor Work “kW”	48.11	47.07	46.52	49.83
Mass flow rate in First Compressor ‘kg/sec’	0.6816	0.4196	0.6489	0.4051
Mass flow rate in second Compressor ‘kg/sec’	0.9134	0.5647	0.8660	0.5506
Mass flow rate in third Compressor ‘kg/sec’	1.362	0.8446	1.286	0.8335
First Compressor Work “kW”	3.412	3.241	3.288	3.296
Second Compressor Work “kW”	4.413	4.217	4.251	4.308
Third Compressor Work “kW”	40.29	39.61	38.98	42.22
Exergy of Fuel“kW”	48.11	47.07	46.52	49.83
Exergy of Product “kW”	15.84	15.84	15.84	15.84

Table 7: Energy performance parameters of vapour compression refrigeration system(system-2) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 70 kW, second evaporator load is 105 kW, third evaporator load is 35 kW)

Performance Parameters	R134a	R-152a	R-245fa	R-124
COP	4.39	4.493	4.545	4.458
EDR	1.975	1.922	1.894	1.941
Exergetic efficiency	0.33	0.3372	0.3412	0.3346
Total Compressor Work “kW”	48.0	46.97	46.42	47.338
Mass flow rate in First Compressor	0.4544	0.2797	0.4326	0.2701
Mass flow rate in second Compressor	1.129	0.6984	1.071	0.6809
Mass flow rate in third Compressor	1.362	0.8457	1.286	0.8332
First Compressor Work “kW”	2.275	2.161	2.192	2.253
Second Compressor Work “kW”	5.455	5.216	5.257	5.395
Third Compressor Work “kW”	40.27	39.60	38.97	39.69
Exergy of Fuel“kW”	48.0	46.97	46.42	47.34
Exergy of Product “kW”	15.84	15.84	15.84	15.84

Table 8 Energy performance parameters of vapour compression refrigeration system(system-3) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R134a	R-152a	R-245fa	R-124	R32
COP	4.252	4.349	4.398	4.311	4.111
EDR	1.935	1.88	1.854	1.901	2.027
Exergetic efficiency	0.334	0.342	0.346	0.339	0.323
Total Compressor Work “kW”	49.39	48.29	47.75	48.71	51.08
Mass flow rate in First Compressor‘kg/sec’	0.6816	0.4196	0.6489	0.8488	0.4051
Mass flow rate in second compressor ‘kg/sec’	1.136	0.7027	1.078	1.409	0.6850
Mass flow rate in third compressor ‘kg/sec’	1.369	0.850	1.293	1.689	0.8376
First Compressor Work “kW”	3.412	3.241	3.288	3.329	3.296
Second compressor Work “kW”	5.490	5.247	5.289	5.431	5.36
Third compressor Work “kW”	40.49	39.81	39.17	39.9	42.43
Exergy of Fuel“kW”	49.39	48.29	47.75	48.71	51.08
Exergy of Product “kW”	16.51	16.51	16.51	16.51	16.51

#### 4.2 Effect of low GWP and zero ODP ecofriendly HFC refrigerants

The performance parameters of modified vapour compression refrigeration have been computed using low GWP HFO refrigerants as shown in tables-6 to table-9 respectively and it was found that using low GWP R1234ze(Z) is suitable for replacing R134a

#### 4.3 Comparison of thermodynamic performances using HFO refrigerants with R134a for replacing HFC-134a refrigerants

The performance parameters of modified vapour compression refrigeration have been computed using low GWP HFO refrigerants as shown in tables-10 to Tables-12 respectively and it was found that using low GWP R1234ze(Z) is suitable

for replacing R134a gives 4.192% improvement in first law efficiency while by using R-1224yd(Z) gives 3.94% improvement and by using R-1233zd(E) gives 3.75% COP improvement for replacing R134a and R1234yf gives 2.978% to 3.257% lower performance as compared to R134a. However coefficient of performance (COP) using R-1225ye(Z), R1243zf, and R1234ze(E) is nearly same with slightly variation in COP which can be considerable as negligible. Similarly, by using R1234ze(Z), the exergetic efficiency improvement is 4.488%, and by using R1224yd(Z), the improvement is 3.082% while using R1234yf gives 5.485% decrement in exergetic efficiency. However, exergetic efficiency using R-1225ye(Z), R1243zf, and R1234ze(E) is nearly same with slightly variation which can be considerable as negligible. Similarly, power required to run whole system is 4.0324% lower using HFO 1234ze(Z), 3.617% lower using R-1233 zd(E)refrigerant.

Table 9 Energy performance parameters of vapour compression refrigeration system (system-4) using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R134a	R-152a	R-245fa	R-32
COP	4.767	4.859	4.925	4.578
EDR	2.124	2.078	2.043	2.246
Exergetic efficiency	0.31344	0.3195	0.32586	0.3011
Total Compressor Work “kW”	44.06	43.22	42.38	45.87
Mass flow rate in First Compressor ‘kg/sec’	0.2272	0.1399	0.2163	0.135
Mass flow rate in second Compressor ‘kg/sec’	0.676	0.4182	0.6412	0.4077
Mass flow rate in third Compressor ‘kg/sec’	1.341	0.8333	1.267	0.8208
First Compressor Work “kW”	1.137	1.08	1.096	1.099
Second Compressor Work “kW”	3.266	3.123	3.148	3.19
Third Compressor Work “kW”	39.65	39.02	38.39	41.58
Exergy of Fuel “kW”	44.06	43.22	42.38	45.87
Exergy of Product “kW”	13.81	13.81	13.81	13.81

Table 10(a): percentage improvement in first law efficiency (i.e. COP) of modified VCRS using HFO refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	HFO-1336 mzz(Z)
System-1	4.19244	3.943	3.75	3.566
System-2	3.827	2.688	3.394	2.232
System-3	3.057	3.034	3.01	2.447
System-4	3.965	2.979	3.6082	2.6222

Table 10(b): percentage improvement in first law efficiency (i.e. COP) of modified VCRS using HFO refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R-1225 ye(Z)	R1243 zf	R1234 ze(E)	R1234 yf
System-1	-0.710	-0.434	0.298	-2.978
System-2	-1.025	-0.6833	-0.0228	-3.257
System-3	-0.917	0.2117	-0.353	-3.245
System-4	-0.5873	-0.3147	0.4196	-2.874

Table 11(a): percentage improvement in exergetic efficiency of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	HFO-1336 mzz(Z)
System-1	4.488	3.082	4.249	3.085
System-2	4.03	2.909	3.606	2.455
System-3	4.488	3.082	4.249	3.085
System-4	3.98	3.957	3.925	3.893

Table 11(b): percentage improvement in exergetic efficiency of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R-1225 ye(Z)	R1243 zf	R1234 ze(E)	R1234 yf
System-1	-0.8181	-0.485	0.182	-5.485
System-2	-0.8181	-0.485	0.182	-5.485
System-3	0.8370	-0.1197	0.0598	-3.89.
System-4	2.872	0.032	-0.064	-0.57

Table 12(a): percentage decrement in power required to run whole system of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	HFO-1336 mzz(Z)
System-1	-4.0324	-2.951	-3.617	-2.515
System-2	-4.0	-2.958	-3.604	-3.77
System-3	-4.1304	-2.976	-4.0899	0.7289
System-4	-3.813	-2.905	-3.495	-2.58

Table 12(b): Percentage decrement in power required to run whole system of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R-1225 ye(Z)	R1243 zf	R1234 ze(E)	R1234 yf
System-1	-	0.3533	-0.3117	3.0555
System-2	-	0.333	-0.333	3.021
System-3	0.837	-0.1197	0.0598	-3.89.
System-4	0.567	0.295	-0.431	2.769

#### 4.4 Effect of Low GWP HFC Refrigerants

The performance parameters of modified vapour compression refrigeration have been computed using low GWP HFC refrigerants are shown in Table-13 to Table-15 respectively and it was found that using low GWP R152a is suitable for replacing R134a gives 2.2% improvement in first law efficiency while by using R245fa gives 3.41% improvement and by using R32 gives 3.436% lower COP Similarly by using R152a , the exergetic efficiency improvement is 2.217%, and by using R-1233zd(E) the improvement is 4.249% while using HFO-1336mzz(Z) gives 3.085% improvement in exergetic efficiency Similarly power required to run whole system using R152a is 2.16% lower, 3.3% by using R-245fa and 2.515% lower and 3.575% higher by using HFC -32 refrigerant for replacing HFC-134a.

Table 13: percentage improvement in first law efficiency (i.e. COP) of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R-152a	R-245fa	R-32
System-1	2.22%	3.4135	-3.436
System-2	2.346%	3.453	-3.533
System-3	2.281	3.434	-3.316
System-4	1.93	3.314	-3.965

Table 14: percentage improvement in exergetic efficiency of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R-152a	R-245fa	R-32
System-1	2.217	3.432	-3.43
System-2	2.182	3.39	-3.53
System-3	2.395	3.593	-3.293
System-4	1.933	3.9433	-3.937

Table 15: percentage decrement in power required to run whole system of modified VCRS using HFC refrigerants as compared to HFC-134a for replacement purpose

Performance Parameters	R-152a	R-245fa	R-32
System-1	-2.16	-3.305	3.575
System-2	-2.16	-3.305	3.575
System-3	-2.227	-3.32	3.42
System-4	-1.9065	-3.813	4.108

## 5. Conclusions

Following conclusions were drawn from present investigation.

- Modified vapour compression refrigeration system-1 using R1234ze(Z) gives best (highest) thermodynamic first and second law performances and lowest 3.25% using R1234yf as compared with HFC-134a
- The first law efficiency (COP) and exergetic efficiency using R-1225ye(Z), R1243zf, and R1234ze(E) is nearly same with slightly variation which can be negligible as compared with R134a. The performance improvement is maximum is 4.2% by using HFO 1234ze(Z)
- The power required to run whole system using 4.0324% lower using HFO 1234ze(Z) and 3.617% higher by using R1234yf refrigerant for replacing HFC-134a.

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