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Research Article

Theoretical investigation of low GWP refrigerant mixtures as an alternative to R-134A in a domestic refrigerator

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ABSTRACT

In India most of the domestic refrigerators use Tetrafluoroethane, (CF_3CH_2F) i.e., R134a as a refrigerant from Halofluorocarbon (HFC) group. This refrigerant though have a zero-ozone depletion potential (ODP) but has high global warming potential (GWP). When it is released into the atmosphere so many environmental issues like acid rains, global warming, etc., result. Therefore, HFC group refrigerants should be banned in the coming years based on the Kyoto Protocol. So, in the present research work, theoretical analysis was carried out to investigate the properties of different low GWP refrigerants and their mixtures from different groups in the perspective of the replacement of R-134a in a domestic refrigerator. The most promising direct substitutes identified from this work are three refrigerants namely R513A, R513B and R515A. The results revealed that COP and the Exergetic efficiency of refrigerant R513A and R513B are on par with R134a with a slight difference of 5.6%, which decreases with the increase in evaporator temperature. The total efficiency defect is more for R513A, R513B followed by R515A and R134a, with a negligible difference. So, it is concluded that refrigerants R513A & R513B can be directly used as an alternative to R134a, but when using the R515A system needs some modifications.

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INTRODUCTION

The problem of ozone layer depletion was identified first in the 1970s. A rapid decrease in the total volume of ozone at about 4% per decade has been observed in the Earth's stratosphere, which is quite large when looking at a global scale. By the advice of the scientific community, the Montreal Protocol came into force on January 1, 1989. It mainly focuses on the substances that diminish the ozone layer. It has been ratified by all the countries of the world by prescribing timed targets to reduce the use of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) since 1 mole of CFC can deplete 1,00,000 ozone molecules. It was decided in 1994 to reduce the use of CFCs and halogens to 80% of the 1986 levels and the

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target fixed was to reduce up to 50% from 1999 onwards. Several amendments have been made to the original treaty and now the list of compounds harmful to the ozone layer has been expanded to include the use and production of carbon tetrachloride, trichloroethane, methyl bromide, and hydro-fluoro-bromo-carbons.

Third-generation refrigerants have been developed with a focus only on the aspect that they should not have any effect on the ozone layer. The representative of these classes of refrigerants is hydrofluorocarbons (HFCs), which are a class of synthetic organic compounds that mainly contain fluorine, hydrogen, and carbon. Examples of this type of compound include difluoroethane (R152a), tetrafluoroethane (R134a), etc. In addition to the property of its benign nature on the ozone layer, the development of HFC refrigerants has led to the development of chemical research in the field of fluorocarbon-free chemicals that have been recognized as the next generation of refrigerants. Since HFC refrigerants do not affect the ozone layer, they have replaced CFCs as refrigerants in most applications like refrigerators, air conditioners. The application of R12, which is used in vehicle air conditioning, has been replaced by R134a. But recent research on the behavior of refrigerants in the atmosphere has revealed that HFCs, although they do not affect the ozone layer, are themselves evolved as a potent greenhouse gas. In 2006, the European Parliament decided to phase out the use of HFC refrigerant gases from 2017 onwards. In addition to the European Union, the US has also decided to limit the use of R134a from 2016 to meet the Kyoto Protocol requirements. The industries also experimenting with hydrocarbons (HCs) as refrigerants, particularly with the development of the hydrocarbon compressor. Hydrocarbon blends, especially R600a, are widely used in North America in domestic refrigerators. Although there is a concern about flammability, the small amount of charge required is the main point in its favor.

The Indian refrigeration and air conditioning area have a long history of a century ago. India at present produces refrigeration and air conditioning units abundantly with hydrocarbon-based refrigerants R134a, R22, and R717. Since 2002, the usage of CFC refrigerants in new systems has been discontinued. The selection of a refrigerant for a specific application mainly depends on the availability and cost. Halogenated refrigerants like R717, R134a, and R12 are available at a cheaper cost. Right now, the combination of HCs and HFCs, for example, R410a, R407, and R404a are not manufactured in India and thus should be imported which increases the cost. In India, the growth of refrigeration and air condition sectors will be hampered due to the non-availability of these refrigerants. This will probably influence the development of the refrigeration systems in India and the absolute transformation to green alternatives shortly. It has been noticed as of late that R134a refrigerants contribute to increasing global warming since they contain fluorine in the structure of the atom. In this manner, R134a has been viewed as an ozone-depleting substance because of its remarkable impact on environmental change. The release of such greenhouse gases has unpredictable consequences on the thermal balance of the earth, such as an increase in ambient temperature. The HFC refrigerants have a high GWP when compared with CO_2. The release of HFC gas to the atmosphere contributes 1000 to 3000 times more global warming than the release of one kg of CO_2. Most vapor compression refrigeration (VCR) systems continue to use halogenated refrigerants in developing countries like India. They have environmental issues like ODP and GWP that cause health risks for both humans and animals. Based on these observations it is felt that there is an urgent need to find alternative refrigerants which have a low ODP and GWP in view of replacement of halogenated refrigerants.

Many researchers have tried to identify suitable refrigerants from different groups in the perspective of replacement to R134a in a domestic refrigerator.Nielsen et al. [1] showed that R1234yf has good environment properties, zero ODP and its atmospheric lifetime is 11 days, in the span of 100 years' time reference of low GWP refrigerants. Navarro-Esbri et al. [2] led an investigation on HFO refrigerant R1234yf in a refrigerator that is running with R-134a. From those results, it was concluded that the COP is approximately 20% lower and refrigerating effect is about 9% higher when compared to R-134a. But these differences were drastically reduced by using an liquid suction heat exchanger (LSHX). Zillio et al. [3] performed an experimental investigation with HFO-1234yf in a small-sized mobile air conditioning system and from the investigation, it was resolved that COP and cooling capacity of R1234yf displays a marginal change in its value as related with R134a. Mohan raj et al. [4] performed theoretical research on the chance of utilizing hydrocarbon refrigerants like R152a, R600, R290, R1270, and R600a as a stand-by refrigerant to R-134a in home refrigerators. In that analysis, COP, compressor pressure ratio, outlet temperature, and power consumption of a compressor were considered as performance parameters. From the results, it comes to know that by using pure HC refrigerants there is a mismatch in saturation properties which may require compressor change, hence those were not suitable to replace R134a. The refrigerant R152 exhibits the same saturation properties as that of R134a, and hence the same compressor can be used with that refrigerant. Aprea et al. [5] led an experimental investigation with refrigerants R134a, R1234yf, and a refrigerant blend of R1234yf/ R134a (90/10 percentage by weight) in a household refrigerator. From those results, the refrigerant mixture has the closest behaviour to that of R134a in terms of temperatures and pressures. Furthermore, the cycle working with the optimal charge of the mixture shows an energy saving of 16% and 14% with respect to R134a and R1234yf, respectively. By comparative study, Golzari et al [6] concluded that in an air conditioning system the refrigerant R1234yf showed a more exergetic efficiency contrasted with R134a.

Rasti et al. [7] did an investigation using refrigerants R600aand R436a (which consists of 46% of iso-butane & 50% of propane) in a home refrigerator in place of R134a. From that experiment, they concluded that the power consumption of various refrigerant compressors at the various charges was declined by about 15%, 8% respectively. Meng et al. [8] led an examination on automobile air conditioning (AAC) system with the refrigerants like R134a and the blend of R134a/R1234yf in a proportion of 11:89, by mass. The new refrigerant mix has been reported to have approximately 5-15% lower COP in heating and 5-10% lower COP in cooling mode. Hasheem, S.M et. al. [9] performed a theoretical analysis of different refrigerant mixtures as a stand-in to R134 in the refrigerator, and from that analysis, they concluded that R152A/ R1234ze (E) (50:50 by mass) can be utilized as an immediate trade for R134a without rolling out any improvements to the compressor. Shaik, M.H et al [10] led a theoretical study on different refrigerants as a replacement to R134a in a refrigerator. From that investigation, they concluded that the R1234yf can be used as standby to R134a without any changes to the existing refrigerator. Bilen et al. [11] investigated theoretical analysis on automobile air conditioning systems using R152a, R22, and R12 to find out alternatives to R134a. From the results, they reported the performance does not change significantly by using R152a as compared with R134a. Righetti et al. [12] did an investigation and compared the outcomes of R1234yf and R600a with R134a at different mass flow rates and different evaporation temperatures. He found that all the refrigerants are acceptable for a direct substitute in place of R134a. Lee et al. [13] recommended that the combination of R1234yf/R134a can be used in different applications with some adjustments, where R134a is used as a refrigerant. Their outcome recommended that the R1234yf / R134a mixture has a similar compressor outlet pressure, COP, and cooling capacity as compared with R134a.

Meng et al. [14] conducted a thermodynamic investigation of a refrigerator with different refrigerant mixtures like R1234ze (E) and a mixture of R1234ze (E) & R152a in different proportions and R152a without any modification in the system. From that analysis, they concluded that R152a and R152a and R1234ze(E) in the proportion of 50:50 gave better results in a refrigeration system. M.M. Joybari et al. [15] performed a second law analysis to find the optimal load of R600a used as a stand-by to R134a, the optimum load required for HC-600a was 0.050kgand 65% lower than R134a. Hasheer, S.M. et. al. [16] led an investigation theoretically with the refrigerants R1234yf, R152a, and HFCs / HFOs group refrigerant mixtures such as ARM42 (a mixture of R134a/R152a/R1234yf in the ratio of 8.5/14 /77.5 by mass), ARM42a (a mixture of R134a/R152a/R1234yf in the ratio of 7/11/82 by mass) with a view of replacement of the refrigerant R134a in a domestic refrigerator. From that investigation, they conclude that among the refrigerants ARM42 and ARM42a, the refrigerant ARM42a was selected as a good alternative for R134a because of the volumetric cooling capacity (VCC) and COP of ARM42a were almost equal to R134a. Therefore, ARM42a had a better choice of the direct substitute to R134a in a domestic refrigerator. Shaik, M.H et al. [17] conducted a theoretical investigation on eco-friendly refrigerant mixtures AC5, R430A, and R440A as a replacement to R134a in a domestic refrigerator. It was found that the average COP of R440A and R430A was higher by approximately 2.5% and 1.47% than R-134a. However, the COP of AC5 was 6.1% lower than that of R134a. The VCC of R430A is almost equal to R134a. The results also showed that the refrigerants AC5, R440A, and R430A consume less power than R134a. The compressor outlet temperature with R440A, AC5 provides higher values than R-134a, which affects the compressor life. The best overall performance was achieved with the refrigerant R430A in the household refrigerator and suggested as an alternative to R 134a. El-Morsi.M et al. [18] led an investigation theoretically using pure natural refrigerants as a substitute for R134a in a refrigerator. The outcomes showed that the isobutane gives a higher COP of 5% and liquefied petrol gas (LPG) refrigerant provides a lower COP by 11% than R134a. Bhatkar V.W [19] experimented with R134a and 152a in an aluminium micro-channel condenser domestic refrigeration system. It is demonstrated that the refrigerant charge of R152a has been decreased by 40%, contrasted with R134a.

Grauso et al.[20] found that local heat transfer coefficient for refrigerants R1234ze (E) and R134a were very similar during flow boiling, especially at medium and high saturation temperatures. However, for the refrigerant R1234ze (E) heat transfer coefficient falls more at low vapour qualities. Adiabatic pressure drop of R1234ze (E) is slightly higher than that obtained for R134a. Makhnatch et al. [21] examined the performance of R450A, which is a mixture of R134a / R1234ze (E) (42/58% by mass) as a substitute for R134a in domestic refrigerators. The cooling effect and COP of the refrigerant mixture were found to be approximately 10% and 3% lower than R134a. At the same time, the compressor outlet temperature is lower than that of R134a. Gaurav et al. [22] carried out energetic and exergetic computational analyzes of R1234yf, R1234ze and R134a and their blends with different proportions in the domestic refrigerator. From that research, they concluded that 38% of R1234ze, 40% of R134a and 22% of R1234yf refrigerant mixture is a better substitute to R134a.

From the above literature review, it is coming to know that even though most research was done to find alternative refrigerants much of the works were confined to identify alternatives from groups only and a combination of mixtures of refrigerants from different groups has not been tried extensively. Hence it is strongly felt there is an urgent need to analyze the properties of mixtures of refrigerants from different groups to find alternatives to R134a to fill the research gap in this area.

Selection of Alternative Refrigerants in Place of R134a in a Domestic Refrigerator

In earlier days, the HFC refrigerant R134a was used as a standby refrigerant in a domestic refrigerator to replace R12. It has been noticed as of late that R134a refrigerants contribute to increasing global warming since they contain fluorine in the structure of the atom. In this manner, R134a has been viewed as an ozone-depleting substance because of its remarkable impact on environmental change. Usually, the refrigerant blends can be classified as:

- Azeotropes: A blend comprising of at least two refrigerants with comparable boiling points that act as a single fluid. The parts of azeotropic blends don't separate under ordinary working conditions and can be charged as vapor or liquid.
- Zeotropes: It is a mixture of liquid components having a different boiling point. Since it is the opposite of an Azeotropic mixture can be called a non-azeotropic mixture.

Some of the alternatives analyzed in this work are

- R513A: It consists of a mixture of 56% of R1234yf and 44% of R134a, it is an azeotropic blend with no temperature glide.
- R513B: It consists of 58.5% R1234yf and 41.5% R134a. This is an azeotropic mixture. This has been developed for chiller applications typically covered by R134a.
- R515A: It is a mixture of 88% R1234ze(E) and 12% R227ea which is non-flammable with the ASHRAE safety classification A1. Its GWP value is 387.

Using REFPROP software different properties of selected refrigerants are obtained and listed in Table 1 for comparison.

From the previous table, it was concluded that the selected refrigerants have low GWP values when compared to R134a.

Thermodynamic Analysis of Refrigerants Mixtures

Theoretical modeling is one of the most widely accepted practices to study the performance of VCR systems. This research deals with the performance evaluation of a domestic refrigerator operating on a VCR system with the conventional refrigerant R134a and with different above-mentioned alternative refrigerants. The entire analysis is carried out by providing different condenser and evaporator temperatures. The schematic diagram showing the domestic refrigerator along with liquid suction heat exchanger (LSHX) is shown in Figure 1.

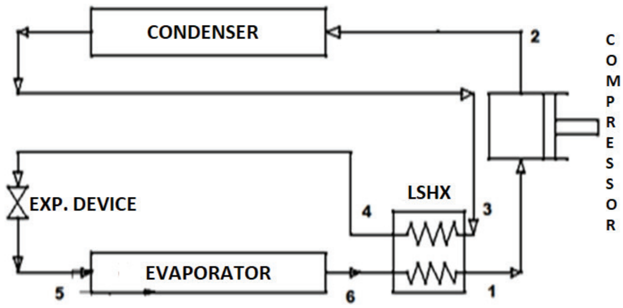

Figure 1. Refrigerator with LSHX.

Data used for this investigation is given below. The results are plotted as shown in the Figures3 to 14.

1. Condensing temperatures: 313K and 323K
2. Evaporating temperatures: 223K to 273K
3. Evaporator pressure loss: 0.03MPa
4. Condenser Pressure loss: 0.02MPa
5. Isentropic efficiency of a reciprocating compressor: 0.70
6. Compressor volumetric efficiency: 0.75
7. Compressor Speed: 30 rev/sec
8. Compressor swept volume: 8.16cm3/rev
9. Effectiveness of the heat exchanger: 0.6
10. Ambient state temperature (To): 298K

In this Analysis, it was taken that the refrigerant enters the compressor in the superheated vapor condition. Then it is compressed to a higher pressure and from there it passes through the condenser. The pressure losses take place in the condenser, and the refrigerant leaves in a liquid state without undergoing any sub-cooling. Now the refrigerant

Table 1. Salient features (Properties) of selected Refrigerants

Properties	R134a	R513A	R513B	R515A
Safety group	A1	A1	A1	A1
Toxicity	NO	NO	NO	NO
Critical temperature, ^{0}C	101.01	97.7	95.5	108.6
Critical Pressure (kPa)	4060	3700	3660	3555
Boiling point, (BP) ^{0}C)	- 26.1	-28.3	-29.2	-18.75
Liquid density at 35^{0}C (kg/m^3)	1206.7	1121	1131	1185
Lubricating oil	POE	POE	POE	POE
ODP	0	0	0	0
GWP	1430	570	596	387

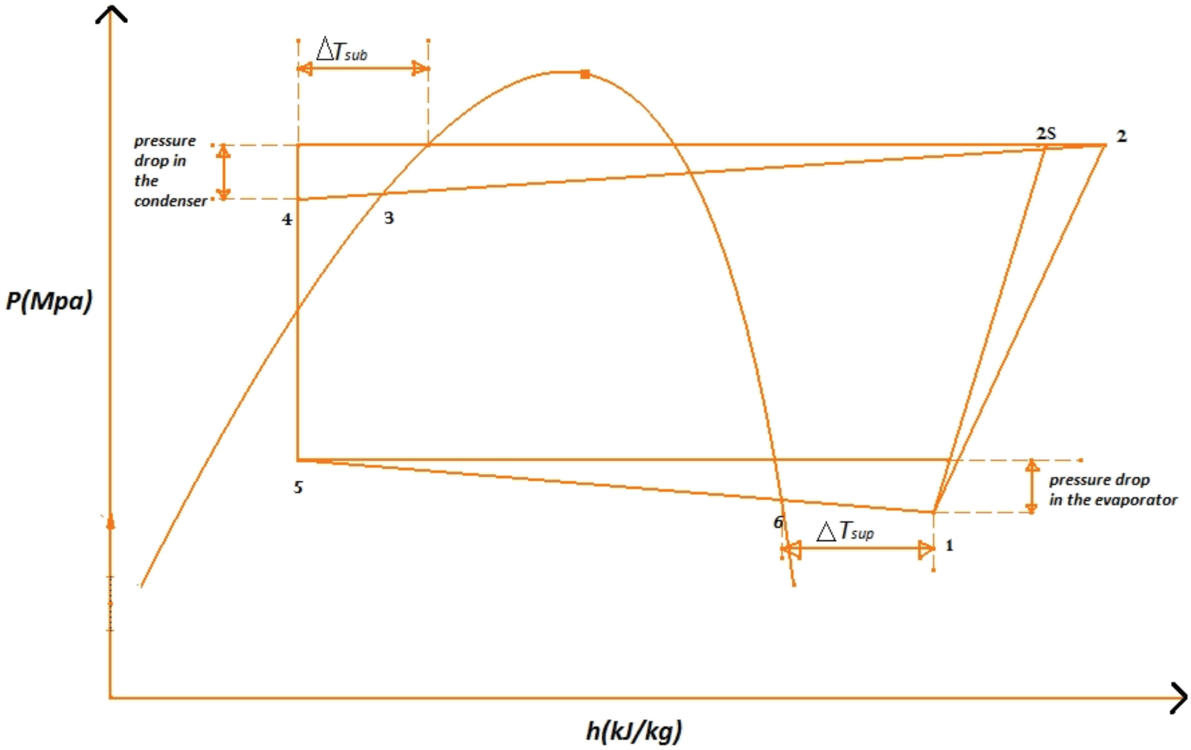

Figure 2. Pressure-enthalpy diagram of a refrigerator with LSHX.

passes to the expansion valve where it undergoes a throttling process with a reduction in pressure. Now the refrigerant passes to the evaporator where again it suffers pressure loss. The P-h chart showing the various processes taking place in the components of a domestic refrigerator along with pressure losses occurring at condenser and evaporator is shown in Figure 2.

To find out the thermodynamic properties at different states REFPROP software is used. To accept these refrigerants as a standby to R134a in a refrigerator, the performance characteristics such as Compressor power consumption, COP, Pressure ratio, VCC, and Compressor discharge temperature are evaluated.

Energy Analysis

The pressure ratio of a refrigerator can be expressed as:

$$r_p = P_{cond} / P_{evap\_act} \quad (1)$$

The compressor power consumption is given by:

$$\dot{W}_{comp} = \dot{m}_r \, (h_2 - h_1) \, kW \quad (2)$$

$$\text{Where } h_2 = h_1 + (h_{2s} - h_1) / \eta_{isen} \quad (3)$$

The cooling capacity is given by:

$$\dot{Q}_c = \dot{m}_r Q_r = \dot{m}_r (h_6 - h_5) \; kW \quad (4)$$

The COP of the refrigerator can be stated as:

$$\dot{Q}_c = \dot{m}_r Q_r = \dot{m}_r (h_6 - h_5) \; kW \quad (5)$$

The Volumetric Cooling Capacity is given by:

$$Q_{vol} = (h_6 - h_5) \times \eta_{vol} / v_1 \;\; kJ/m^3 \quad (6)$$

Where v1 be the specific volume at entry to the compressor. The mass flow rate of a refrigerant) is given by:

$$\dot{m}_r = V_s \times \rho_1 \times RPM \times \eta_{vol}/60 \;\; kg/s \quad (7)$$

Where RPM = speed of the compressor, Vs = Displacement of the compressor

ρ_1 = density of the refrigerant at the compressor inlet.

Exergy Analysis

Exergy investigation can assist with distinguishing and evaluating the source of irreversibilities of every component of the system. separately This methodology depends on the second law of thermodynamics. The exergy balance is given by:

$$\dot{E}_i + \dot{E}_j = \dot{E}_e + \dot{W}_j + \dot{ED}_j \quad (8)$$

$$\dot{E}_i = \sum_{IN} \dot{m}_\varepsilon \tag{9}$$

$$\dot{E}_e = \sum_{OUT} \dot{m}_\varepsilon \tag{10}$$

$$\dot{E}_J^Q = \sum(\dot{Q}_j\,(\tfrac{T-T_0}{T})) \tag{11}$$

$$e = (h - T_0 S) - (h_0 - T_0 S_0) \tag{12}$$

Where

$\dot{E}_i$ = exergy rate at the inlet of control volume (kW)

$\dot{E}_e$ = exergy rate at the exit of control volume (kW)

$\dot{E}_j^Q$ = thermal exergy flow rate in the jth component (kW)

$\dot{W}_j$ = Rate of work transfer of *j*th component of the system (kW)

$\dot{ED}_i$ = Rate of Exergy destruction in jth component (kW)

$\dot{Q}j$ = Rate of heat transfer in jth component

T_0 = ambient state temperature (K)

Exergy destruction rate can be represented by $E\dot{D}$ which can be calculated by

$$E\dot{D} = \sum(me_x)_{in} - \sum(me_x)_{out} + \sum \dot{Q}\left(1 - \tfrac{T_0}{T}\right)_{in} - \sum \dot{Q}\left(1 - \tfrac{T_0}{T}\right)_{out} \pm \Sigma \mathrm{W} \tag{13}$$

Exergy destruction in Evaporator is given by

$$E\dot{D}_e = \dot{m}_r(h_4 - T_0S_4) + \dot{Q}_e(1 - T_0/T_r)) - \dot{m}\mathrm{r}(h_6 - T_0S_6) \tag{14}$$

Exergy destruction in Compressor is given by

$$E\dot{D}_{Comp} = \dot{m}_r T_o(S_2 - S_1) \tag{15}$$

Exergy destruction in Condenser is given by

$$E\dot{D}_{Cond} = \dot{m}_r(h_2 - T_0S_2) - \dot{m}_r(h_3 - T_0S_3) \tag{16}$$

Exergy destruction in the Throttle valve is given by

$$E\dot{D}_t = \dot{m}_r(h_5 - T_0S_5) - \dot{m}_r(h_6 - T_0S_6) \tag{17}$$

Exergy destruction in internal vapour heat exchanger is given by

$$E\dot{D}_{Lshx} = \dot{m}_r((h_3 - h_5 + h_6 - h_1) - T_o(S_3 - S_5 + S_6 - S_1)) \tag{18}$$

$E\dot{D}_T$ is the total exergy destruction in the system is given by

$$E\dot{D}_T = E\dot{D}_e + E\dot{D}_t + \dot{E}D_{Lshx} + \dot{E}D_{Cond} + \dot{E}D_{\mathrm{Comp}} \tag{19}$$

Exergetic Efficiency (ηex)

For a home refrigeration system, the main objective is, heat to be removed from the objects which are to be cooled and placed in the evaporator by the refrigerant at a temperature T_r and minimum exergy is essential to accomplish this task.

$$\eta_{ex} = \frac{COP\ of\ VCR}{COP\ of\ Reversible\ Refrigerator} = \frac{COP}{COP_{rr}} \tag{20}$$

$$\mathrm{EDR} = \frac{\dot{ED}_T}{\dot{ED}_{\min}} \tag{21}$$

Exergy efficiency is given by

$$\eta_{ex} = \frac{Q_e(1-(\frac{T_0}{T_r}))}{W_{comp}} \tag{22}$$

Exergy Destruction Ratio (EDR)

The total exergy destruction rate in the VCR system to the minimum exergy rate is defined as Exergy destruction ratio (EDR) and is given by

$$EDR = \frac{\dot{ED}_T}{\dot{E}_e} = \frac{COP\ of\ VCR}{COP\ of\ Reversible\ Refrigerator} - 1 \tag{23}$$

EDR can also be represented in terms of Exergetic efficiency i.e.

$$Exergy\ destruction\ ratio = \left(\frac{1}{\eta_{ex}}\right) - 1 \tag{24}$$

Efficiency Defect ($\boldsymbol{\delta j}$)

Efficiency defect is defined as shows how much input energy is wasted due to irreversibility present in the various components. It is defined as the ratio between the rates of destruction of the exergies in the Jth component to the actual exergy consumed (i.e. actual work of the compressor) and is given by

$$\delta_j = \frac{E\dot{D}_j}{\dot{W}_{comp}} \tag{25}$$

RESULTS AND DISCUSSION

The performance of the refrigerator is going to be influenced by evaporator and condenser temperature. The performance parameters, Exergetic efficiency, EDR, and Efficiency defect of different components are evaluated at two condenser temperatures of 40^0 C and 50^{0}C and the results are plotted.

Variation in Compressor Power Consumption, Cooling Capacity with Respect to Evaporator Temperature

The Compressor power consumption and cooling capacity variation with evaporator temperature for different refrigerants discussed in this analysis are shown in Figures 3 and 4 respectively at a condenser temperature of 40^0 C and 50^0C. As the evaporator temperature increases, the amount of heat to be extracted increases, and hence the cooling capacity also increases. The trend depicted by refrigerant R515A is nearer to the refrigerant R134a. The power consumption of the refrigeration system increases due to an increase in the refrigerant mass flow rate when the evaporator temperature increases. At the chosen condenser temperature the compressor power consumption of the refrigerants R513A, R513B, and R515A was lower than the refrigerant R134a.

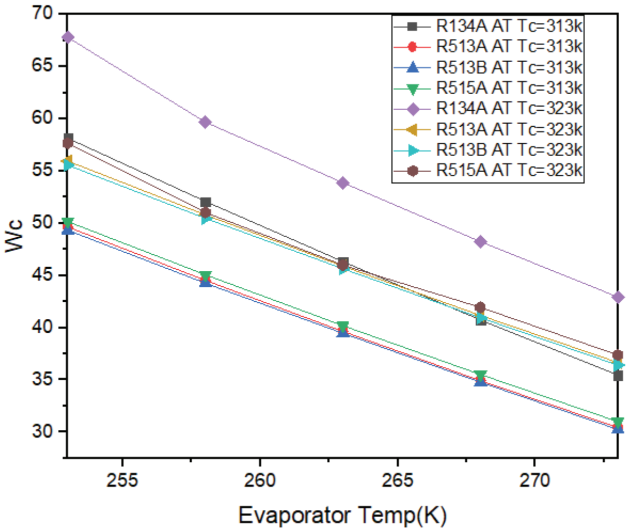

Figure 3. Compressor power consumption vs Evaporator temperature.

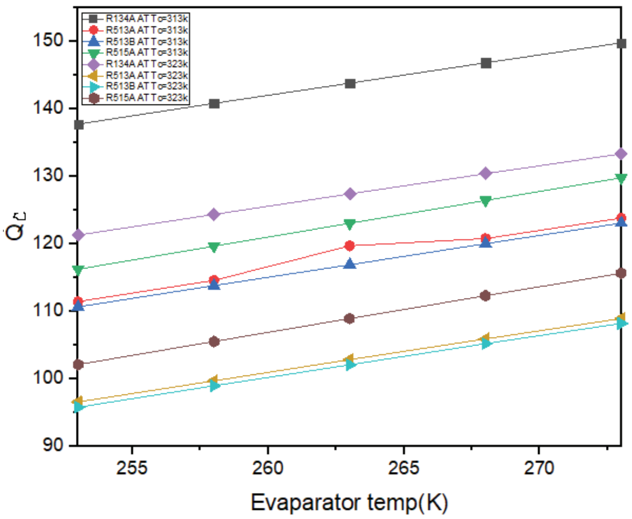

Figure 4. Cooling capacity Vs Evaporator temperature.

COP Variation with Evaporator Temperature

Figure 5 displays the deviation of COP with Evaporator temperature for different refrigerants discussed in this analysis. R134a shows most noteworthy COP among all the refrigerants, followed intently by R513A and R513B which gives practically the same COP. The refrigerant R515A shows lesser COP than R-134a. As the condenser temperature rises, pressure proportion builds causing compressor work to increase and at the same time refrigerating effect decreases, consequently COP decreases. The refrigerants R513A, R515A shows a more COP value as compared with R134a approximately by11.5%-8.5% and 5%-12% respectively at a condenser temperature of 40^0C and 50^0C.

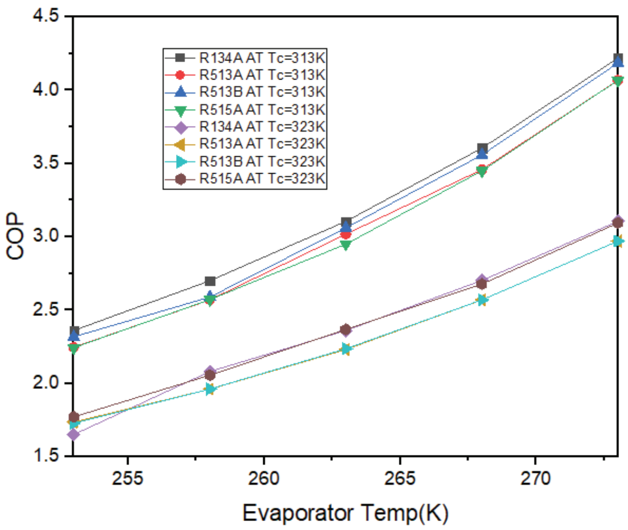

Figure 5. COP vs Evaporator temperature.

Deviation of Exergetic Efficiency with Evaporator Temperature

The Exergetic efficiency variation with Evaporator temperature is presented in Figure 6 at a condenser temperature of 40^0C and 50^0C. As the evaporator temperature increases exergetic efficiency gradually decreases and this change is attributed to two parameters (ref equation 22). The first parameter is exergy flow in the evaporator i.e. $\dot{Q}$ (1 – TQ/ Tr), as the evaporator temperature rises, the cooling effect Q rises. However, the term (1 – TQ/ Tr), diminishes since Tr reaches To. The Second parameter is compressor power, which decreases as the evaporator temperature increases. The effect of $\dot{Q}$c and $\dot{W}$c is to rise the exergetic efficiency as opposed to the decreasing effect of (1 – TQ/ Tr). The result of these two parameters is to rise in the exergetic efficiency up to the maximum point and the evaporator temperature corresponds to this efficiency is the optimum evaporator temperature. Beyond which it reduces the exergetic efficiency. Exergetic effectiveness of R134a is 1.4% and 0.5% more than R513A at 40^{0}C and 50^{0}C, having least contrast at more evaporator temperature and 5.6%, 1.8% higher than R515A at lower evaporator temperature.

Deviation of EDR with Evaporator Temperature

The variation of EDR with Evaporator temperature is presented in Figure 7 at different condenser temperatures of 400 C and 500C and it can be shown by equation 23. As the evaporator temperature rises, the refrigerant R513A shows a more value of EDR as compared with R134a, and this change falls in the range of 10.7-9% and 8.3-13.3% at the above-mentioned condenser temperatures. The below shows that the exergy destruction ratio gradually increases as evaporator temperature increases.

Figures 8-12 portrays the change in Efficiency defect in the condenser, evaporator, throttle valve, compressor and internal vapour heat exchanger (ivhe) with the evaporator temperature for different refrigerants analysed in this work. The most efficient component of a system is internal vapor heat exchanger which shows least minimum efficiency defect. The decrease in efficiency defect in the refrigerator components can be placed in the order of condenser, compressor, throttle valve, and evaporator respectively. It is observed that efficiency defect in compressor and throttle valve shows a higher value than that of R513A and the difference is reduced as the evaporator temperature rises.

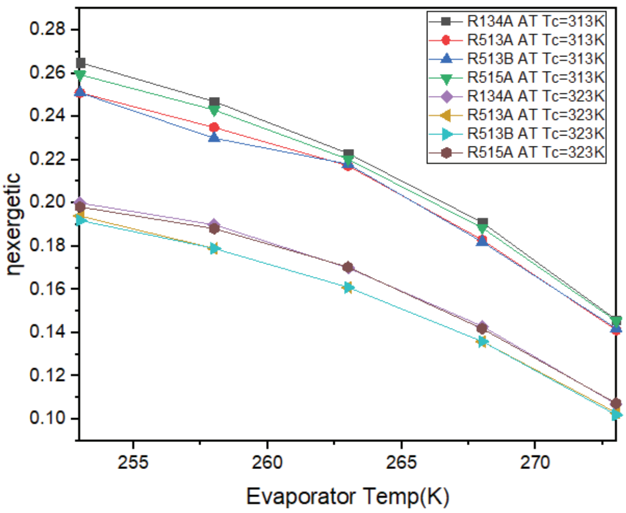

Figure 6. Exergetic efficiency vs Evaporator temperature.

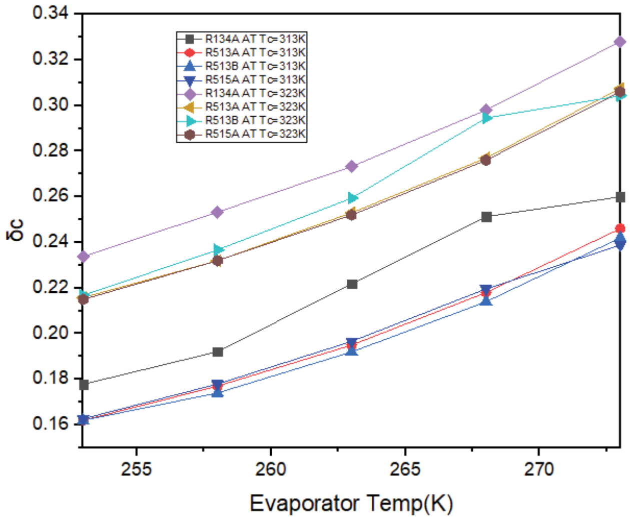

Figure 8. Efficiency defect of condenser vs Evaporator temperature.

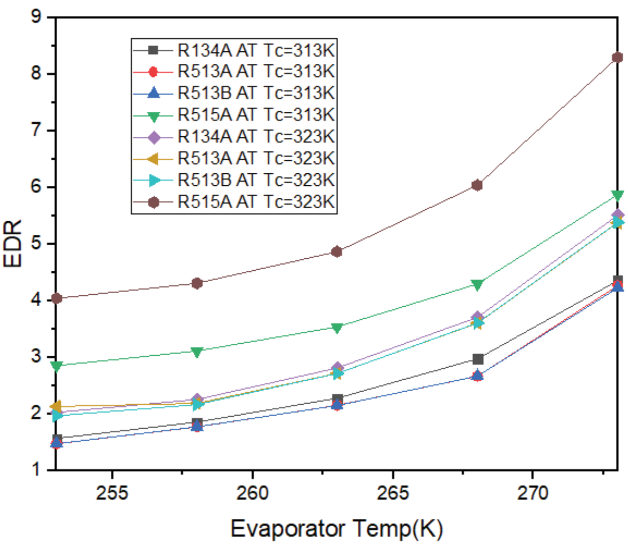

Figure 7. EDR vs Evaporator temperature.

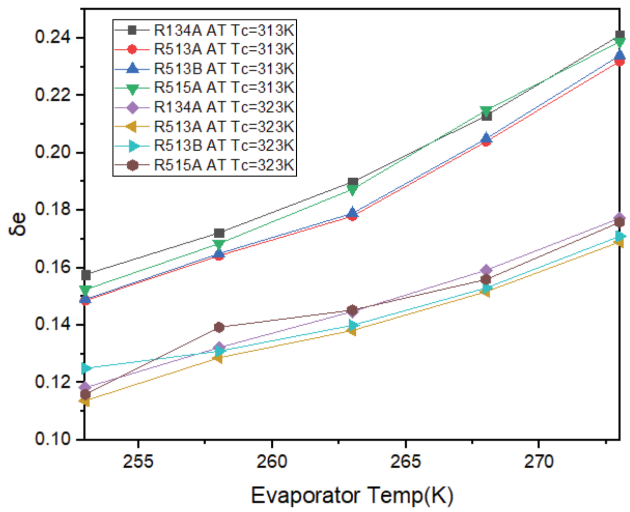

Figure 9. Efficiency defect of evaporator vs Evaporator temperature.

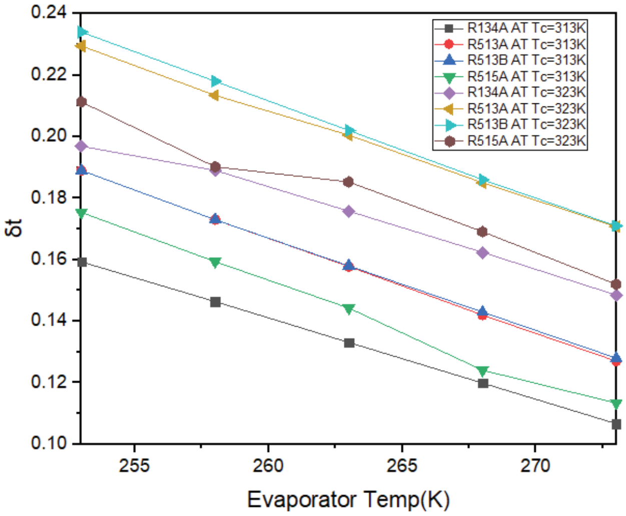

Figure 10. Efficiency defect in throttle valve vs Evaporator temperature.

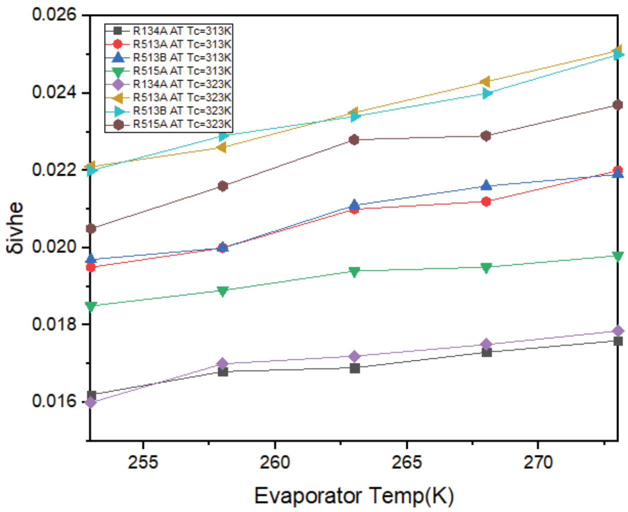

Figure 11. Efficiency defect of Internal vapour heat exchanger with Evaporator temperature.

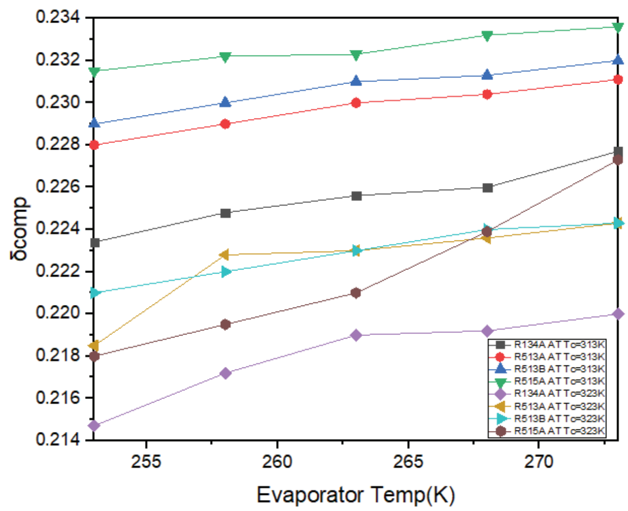

Figure 12. Efficiency defect of Compressor Vs Evaporator temperature.

Change in Energetic Efficiency with Ambient State Temperature

Figures 13 & 14 portrays Exergetic efficiency and EDR with Ambient temperature respectively for different refrigerants analyzed in this work. The value of exegetic efficiency rises with the rise in ambient temperature. From the plot, it was displayed that the EDR value diminishes and Exergetic efficiency rises with increase in ambient temperature. This change is because of the term $(1-T_o/T_r)$, from the equations (22) and (24). It can be evident that there is no change in power consumption of compressor and cooling effect. It is observed that the EDR has a positive effect with rise in ambient temperature, because it rises with rise in ambient conditions.

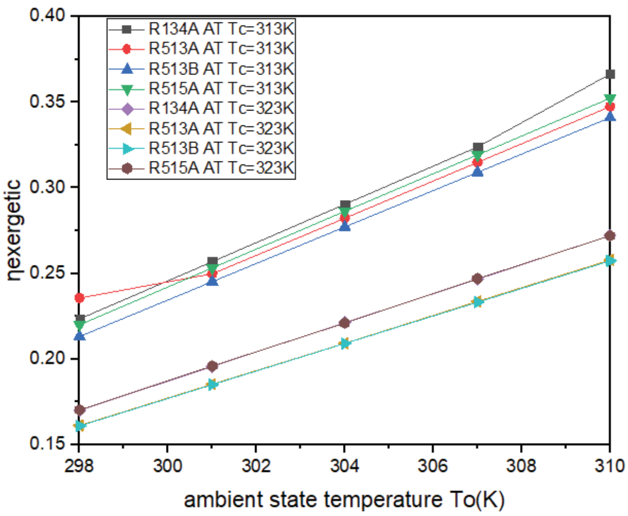

Figure 13. Exergetic efficiency vs Ambient state temperature.

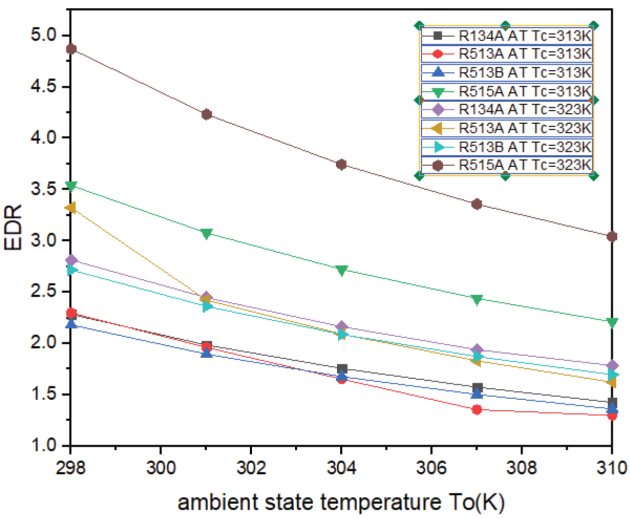

Figure 14. EDR vs Ambient state temperature (at T_E = 273K).

CONCLUSIONS

The results obtained from the theoretical investigation of the performance of domestic refrigerator operating on VCR system with different alternative refrigerants along with conventional refrigerant R-134a are summarized as follows;

- COP obtained with the refrigerants R513A and R513B is almost the same and has a small drop of 5.6% when compared with R134a at low evaporator temperatures and the difference decreases with an increase in evaporator temperature. As the condenser temperature increases the COP decreases for all the refrigerants considered.
- The Exergetic efficiency of R515A is almost the same as R134A throughout the operating range of evaporator temperature. However, there is a slight reduction in exergetic efficiency in the case of R513A and R513B. As the condenser temperature increases the exergetic efficiency of all the refrigerants decreases with an increase in evaporator temperature. The refrigerants R513A and R513B have almost the same trend and the refrigerants R134a and R515A have the same trend at increased condenser temperature.
- Most exergy destruction is observed in the condenser followed by the compressor, throttle valve, evaporator, and liquid-vapor heat exchanger.
- The total efficiency defect is more for R513A, R513B followed by R515A and R-134a with a small difference among them.
- The increase in ambient state temperature has a positive effect on Exergetic efficiency and EDR i.e., Exergetic efficiency increases and EDR decreases with increase in ambient state temperature for all refrigerants discussed.

Hence it can be concluded that, most of the performance parameters for the refrigerants R513A, R513B are slightly lower than R134a they can be good alternative to R134a because of their low value of GWP which is essential from environmental safety point of view. However, R515A can also be thought of another alternative with slight modifications in compressor design because its properties are almost similar to that of R134a.

NOMENCLATURE

COP	Coefficient of performance
GWP	Global warming potential
LSHX	Liquid –suction heat ex-changer
ivhe	Internal vapour heat exchanger
Qvol	Volumetric cooling capacity (kW/m^3)
Qc	Cooling capacity (Refrigeration effect, kW)
h	Specific enthalpy (kJ/kg)
m	Mass flow rate (kg/s)
v	Specific volume (m^3/kg)
Vs	Displacement of the Compressor (m^3/rev)
W	Power required for Compressor (kW)
η	Efficiency (%)
ρ	Refrigerant density (kg/m^3)

Subscripts

1, 2, 3,4,5,6	state points
Comp	compressor
isen	isentropic
R	refrigerant
vol	volumetric

Acronym

CFC	chlorofluorocarbon
HCFC	Hydro chlorofluorocarbon
HFO	hydrofluoroolefins
HC	hydrocarbons
HFC	hydrofluoro carbons
RPM	Revolution per minute

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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