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Theoretical Analysis of Low Global Warming Potential Refrigerant as a Drop in Replacement of R134a in a Domestic Refrigerator

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A B S T R A C T

Nowadays refrigerators and air conditioners are the major energy users in a domestic environment. The improvement of efficiency of a these appliances can be considered as an important step to reduce their energy consumption, Along with the efficiency improvement, the prevention of environmental pollution is also be needed. The CFCs have been almost ruled out since 1995 and a longstanding basis HCFCs must be replaced by 2020 due to their huge impact on the ozone layer. All this events encouraged HFC refrigerants which are harmless to the ozone layer, but HFC refrigerants having a high Global Warming Potential (GWP); which cause environmental pollution if it leaks into the environment. But later Kyoto protocol came into existence which stated the need to replace HFC'S due to their high GWP values. So in this paper, thermodynamic analysis of domestic refrigerator using R134a as a refrigerant was conducted and the results of HFC134a were compared with various low GWP refrigerants like, HFC152a, HC290, HC600a, HFO1234yf and HFO1234ze(E) as a possible alternative to R134a without any modification to the system. Effect of the various operating parameters that is evaporator temperature, condenser temperature, the presence of liquid-suction heat exchanger and pressure drop with performance parameters like COP, refrigeration effect, compressor work and pressure ratio have been reported. Theoretical results revealed that all the alternative refrigerants used in the analysis have a slightly lower performance coefficient (COP) than HFC134a at various condensation temperature of 25 and 45 0C and evaporating temperatures ranging between −200C to 100C. At the same time performance of a conventional refrigeration system improved with the help of liquid-suction heat exchanger.

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INTRODUCTION

In India, the majority of the household refrigerators, HFC134a is used as a refrigerant due to its excellent thermodynamic and thermo physical properties. But the refrigeration sector is under the transition period after the issue of global protocols due to the effect of refrigerant emissions on the environment. According to Kyoto protocol, reduction in the emission of six categories of greenhouse gases and also hydro fluorocarbons (HFC) that are used as refrigerants, R134a is having a high GWP of 1430. Due to this high GWP value most of the developed countries are drastically reducing their HFC production and consumption and it has almost phase out by 2021. So, there is a greater demand for a suitable substitute for R134a for possible retrofitting of existing systems as well as for new systems.

Selection of alternative refrigerants (LOW GWP)

As stated earlier, R134a may be responsible for Global warming even though it does not show any effect on depletion of ozone layer should be phased out by 2021. Therefore, it is beneficial to find out an alternative to R134a which has a low GWP and also does not affect on the ozone layer. Low GWP refrigerants can be classified as hydrocarbons (HC), hydrofluoroolefins (HFO) or pure hydro fluorocarbons (HFC), inorganic refrigerants (R7xx series) and mixtures of the refrigerants mentioned above would be suitable alternative replacement for the CFC type of refrigerants. Discussion of these categories of refrigerants are shown below.

Hydrofluoroolefins are fluorinated propene isomers, and also contain R-1243 isomers, R-1225 isomers and R-1234 isomers. R1243 isomer has been discarded due to its flammability action and R-1225 isomer is not developed because of its toxicity. Among the above refrigerants, R1234yf, R1234ze (E) are the leading refrigerants to replace R-134a in a domestic refrigeration system. R1234yf has a zero ODP because it does not contain chlorine, and also its GWP is very low value (4). Similar to R134a, R1234yf has a low toxicity. In case R1234yf is released into the atmosphere, it is completely transformed into persistent trifluoroacetic acid (TFA). So R1234yf has a no effect on the environment. Mark Spatz and Barbara Minor had said that the related thermo physical properties make R1234yf is a good substitute to

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R134a in various applications of domestic refrigerators and air conditioning systems [1].

Leck [2] assessed the thermo physical properties of R-1234yf and then used them to estimate the theoretical yield of R1234yf in a domestic refrigeration cycle and a comparison was made with HFC134a. HFO1234yf proved to have 2-9.5% less capacity and 2.1-7% less coefficient of performance than HFC134a, depending on the surrounding temperature [2].Yana Motta et al. [3] conducting a experiment with R1234yf, R1234ze (E) and R134a in a vending machine with minor changes according to the refrigerant, in which thermostatic valve replaced by a throttle valve, which is used to keep up the same degree of superheating as that of R134a.R1234yf and R134a showed similar efficiency and R1234ze(E) showed lower efficiency.

Shapiro [4] conducted a series of experiments in a bottle cooler with HFO refrigerants like 1234ze(E), R1234yf and two mixture of them with HFC134a, R450A, R513A. All experiments were conducted in the same bottle cooler and concluded that there is no difference in the compressor energy consumption of a tested refrigerants with respect to R134a, except HFO-1234z(E), which gives a lesser cooling capacity [4].

Karber et al. [5] conducted an experiment with R1234yf, R1234ze(E) and R134a in a two different refrigerators. From that experiment it reveals that R1234yf had a higher energy consumption with respect to R134a and HFO-1234ze(E) gives a lower energy consumption. But HFO-1234ze(E) showed lower cooling capacity compared to R134a and R1234yf [5].

Ansari et al. [6] had conducted an energy and exergy analysis of R1234yf, R1234ze (E) and R134a in a domestic refrigeration system. Finally, they came to the conclusion that HFO-1234yf can be used as a good substitute for HFC-134a at a higher value of the evaporator temperature and R1234ze (E) can be used as a good replacement after certain modification [6].

Mota-Babiloni et al. [7] had performed a research on HFO-1234yf and HFO-1234ze(E) as a drop in replacement of R134a in a domestic refrigerator test rig, by varying the temperatures of evaporator and condenser. A differentiation was carried out between cooling capacity, volumetric efficiency and COP. The results obtained from the experiment are compared with R134a, which is taken as a reference. Volumetric efficiency for R134a drops between 2 and 4%, where as R1234ze drops between 4.5 and 6.5% in the tested range. The average drop in cooling capacity for R1234yf and R1234ze were 9 and 30% when compared to R134a. As the condenser temperature rises, the variation between R1234yf and R134a decreases. Similarly, as the evaporator temperature rises, the cooling capacity for R1234ze decreases, when compared to R134a. While considering COP, R1234yf showed a variation between 3 -12% lower values when compared with R134a. Where as R1234ze shows a values between 2 and 7.5%. From the above results, as the evaporator temperature increases the variation in COP increases for R1234yf and R1234ze, especially when IHX is triggered [7].

Sanchez et al. [8] performed experiments with refrigerants HFO-1234yf,HFO-1234ze(E),R600a,R290 and R152a in a domestic refrigerator and the results were compared with R134a. From those experiments, they concluded that R1234yf and R152a are good fall in replacement of R134a [8]. Meng et al. [9] was reported that the thermodynamic analysis of the HFO / HFC mixtures as a drop in replacement of R134a in a domestic refrigeration system. The mixture R152a / R1234ze (E) (50:50 mass) can be used as a direct substitute to R134a without any modifications to the system [9].

Hydrocarbons are low-GWP refrigerants with excellent properties in terms of coefficient of performance, cooling capacity and volumetric cooling capacity. But ASHRAE classified as hydrocarbons are highly flammable refrigerants. Some safety precautions should be taken in the assembly and charging of the refrigerants. Pure hydrocarbons and blends have been taken into consideration as a direct replacement to R12. Mohan-Raj et al. [10] performed an experiment in a domestic refrigeration system by using a R600/R290 mixture (54.8/45. 2%). This mixture improves the COP and reduces the energy consumption [10]. Similar type of test were conducted by Rasti et al. [11] using R600a and R436A as a drop in refrigerant in vapor compression refrigeration system. Refrigerants R600a and R436a have zero ODP and the value of GWP is less than R134a. They conducted an experiment in a single evaporator domestic freezer that was originally designed for R134a as a test object, without any changes to the refrigerator. They concluded that in comparison with HFC134a - The quantity of hydrocarbon mixture charge is reduced by 52% for R600a and 48% for R436a and compressor power consumption is reduced by 5.4% in 24 hours for R600a and R436a [11].

Dalkilic and Wongwises [12] performed a thermodynamic analysis of various refrigerant mixtures based on HFC134a, HFC152a, HFC32, HC290, HC1270, HC600 and HC600a for various ratios in a domestic refrigeration system, and their results were compared with R12, R22 and R134a as a probable alternative substitutes.

Bolaji et. al, [13] performed an experiment with R152a and R32 to substitute HFC-134a in a domestic refrigerator and concluded that the mean COP of R152a was approximately 5% higher than that of HFC-134a while the COP of R32 was approximately 9.1% less than R134a.

Gaurav et al. [14] made a review on possible alternatives for R134a. From the literature review they concluded that, refrigerants R152a, R125, R32, R413A (mixture of 9% R218, 88% R134a, 3% R600a), R600a/R290 (32/68 by wt %), R600a/R290 (60/40 by wt %) and R290/ R123 (mixture of 3/7) are recognised as substitutes to R134a. And even more, they added that there is a need to compare the alternative refrigerants from environmental, flammability, toxicity, stability and thermodynamic point of view to find the best alternative to HFC-134a [14].

Bolaji et al. [15] had done energy performance comparison of low GWP refrigerants R152a and R600 theoretically as an alternative to R134a in domestic refrigeration system. Their outcomes revealed that the vapour pressure and vapour density of R152a are very similar to that of R134a. R152a shows a higher volumetric cooling capacity (VCC) and COP as compared to R600a and R134a. The average COPs attained for R152a and R600a were 13.5% higher and 5.5% lower than that of R134a, respectively. They concluded that R152a works best as a substitute for R134a [15].

Inorganic refrigerants such as Carbon dioxide (R744) requires a new refrigeration facility and it is not used as a direct drop-in. because it requires a high operating conditions.

After all, the extensive research and studies conducted by the researchers have been found that some possible alternatives for R134a in a household refrigeration system are Hydrocarbon mixtures - Propane (R290), Isobutene (R600a), Low GWP Hydro fluorocarbons - R152a and Hydrofluoroolefins – R1234yf & R1234ze(E).

Thermodynamic analysis

The main objective of this work is to study the energy analysis of R152a, R290, R600A, R1234ze(E) and R1234yf as a direct substitute to R134a in a domestic refrigerator with a different range of operating conditions i.e. at different condenser temperature by changing evaporator temperature from -20 to 10^0C.This theoretical analysis has been done with IHX and considering the pressure drop across the condenser and evaporator. R134a is taken as baseline for comparison.

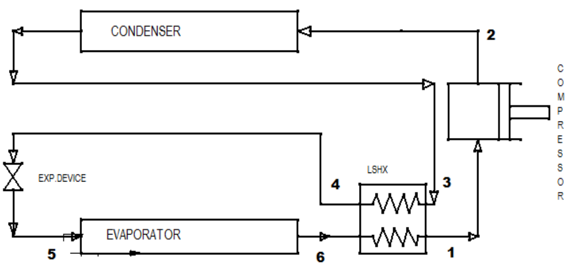

Figure 1. Domestic refrigeration system with LSHX

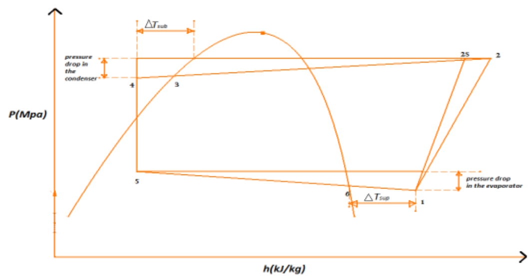

Figure 2. P-h diagram of a domestic refrigeration cycle with LSHX and pressure drop

Calculations

The energy analysis of the system can be carried out by developing a computational model using EES software [16]. The input data (from the literature) used for the analysis are given below. The result plots are shown in Figures 3-10.

1. Condensing temperatures: 25^0C and 45^0C
2. Evaporating temperatures: -20^0C to 10^0C (the variation in condenser temperature is based on ambient conditions)
3. Pressure loss in the evaporator: 0.02MPa
4. Pressure loss in condenser: 0.01MPa
5. Compressor isentropic efficiency: 0.75
6. Volumetric efficiency: 0.8
7.Compressor had a displacement volume: $8.16cm^3/rev$
8. Compressor Speed: 1800rev/min
9. Effectiveness of the heat exchanger: 0.65.

The pressure-enthalpy diagram is depicted in Fig. 3 (b) with the theoretical data considered above. Fig.3 (b) shows the Theoretical diagram with Heat exchanger and Pressure losses. There is a deviation between ideal and actual refrigeration cycles because of the pressure drop of the fluid and heat transfer between the system and surroundings. At inlet of the compressor, the refrigerant is superheated vapour and there is loss of pressure for the liquid when it passes through the condenser, between the condenser and expansion valve and also in the evaporator line. These pressure losses are clearly observed in Fig 3(b).The thermodynamic properties of each state of the cycle are calculated with the help of $REFPROP9.12^0$ software, REFPROP is a highly accurate software for calculating the properties of a refrigerants.

Performance characteristics such as volumetric coolingcapacity, Coefficient of performance (COP), Compressor exit temperature, cooling Capacity (Refrigeration effect), compressor power consumption, and pressure ratio are the main parameters to accept a drop in replacement in domestic refrigeration system.

The pressure ratio of the refrigeration cycle can be expressed as follows:

$$\text{Pressure ratio} = P_{cod} / P_{evap\_act} \quad (1)$$

Compressor work (Isentropic compression) is expressed from the Fig. 2 as follows:

$$Wc = h2 - h1 \quad (2)$$

Where

$$h2 = h1 + (h2s - h1)/\eta is \quad (3)$$

The Cooling Capacity is calculated from the formula given below.

$$\text{Cooling capacity} = Qc = h6 - h5 \quad (4)$$

The coefficient of performance (COP) of the domestic refrigeration cycle can be determined by:

$$COP = \text{Cooling capacity}/\text{compressor work} \quad (5)$$

The Volumetric Cooling Capacity (VCC) is calculated from the formula as given below:

$$Qvol = (h6 - h5) \times \eta vol/v1 \quad (6)$$

Where V_1 be the specific volume of refrigerant at the inlet of the compressor.

The mass flow rate of a refrigerant (m_r) can be calculated from the formula given below.

$$mr = RPM \times Vs \times \rho 1 \times \eta vol/60 \quad (7)$$

Where RPM is the speed of the compressor, $V_{s.}$ is swept volume of a compressor, ρ_1 is the density of t

RESULTS AND DISCUSSION

Variation of mass flow rate in (kg/h)

Figure 3 depicts the variation of the mass flow rate of refrigerant with evaporator temperature for six different refrigerants. The refrigerant mass flow rate is a parameter that is influenced by the volumetric efficiency, the specific volume at the inlet conditions of a compressor and geometrical dimensions of a compressor. The mass flow rate of R290, R152, R1234Ze (E) were found to be lower than that of R134 by about 54%,21% and 24% at evaporator temperature between -20 to 10^{0}C. From the graph it is revealed that the refrigerant mass flow rate driven by the compressor with R1234yf is maximum among all the refrigerants used, while R600a has the least mass flow rate compared with R134a at that operating conditions. The reason being that the vapor density of R1234yf is higher and R600a has the least among the all the refrigerants. The condenser temperature has negligible affect on the mass flow rate for all the refrigerants.

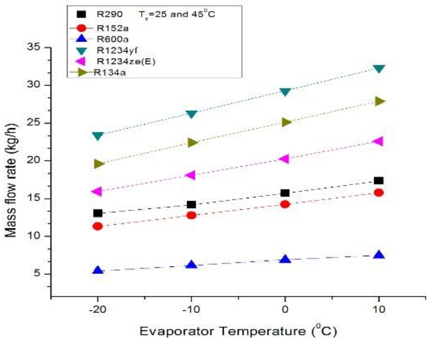

Figure 3. Refrigerant mass flow rate vs. Evaporator temperature

Variation of pressure ratio

Figure 4 represents the variation of the mass flow rate of six refrigerants with evaporator temperature. It was observed that the pressure ratio of R1234Ze (E) and R600a was higher than that of R134a by about 2-9% and 2-14%, respectively. However R290, R1234yf showed lower pressure ratio than that of R134a about 8-30% and 3-14% at condenser temperature 25^{0}C and 45^{0}C, respectively. R152a showed an almost equal pressure ratio with R134a. The volumetric efficiency is mainly influenced by pressure ratio and geometry dimensions of a compressor. Therefore, R290, R1234yf and R152a can have better volumetric efficiency.

Variation of volumetric cooling capacity

Volumetric cooling capacity of the refrigerant versus evaporator temperature for six different refrigerants are highlighted in Figure 5. At a condenser temperature 25^0 and 45^{0}C, R290 showed a higher volumetric cooling capacity than that of R134a, whereas the refrigerants R152a, R1234yf have lower values than that of R134a by around 2-8% and 3-7%, respectively. The refrigerants R600a, R1234ze(E) have lesser than that of R134a by around 50 and 27%. Volumetric cooling capacity has greater influence on the size of compressor. For substitute refrigerants, volumetric cooling capacity can be maintained in limits of -8 to 8% related to R134a. Due to lesser volumetric cooling capacity, the refrigerants R600a, R1234ze(E) are not suggestible as it impacts the compressor performance. Hence these two refrigerants cannot be replaced as an alternative to R134a. Whereas the refrigerants R1234yf, R290, R152a are suggested as a direct substitute of R134a without any alterations to the compressor.

Variation of cooling capacity and compressor power consumption

Figure 6 highlights the variation of compressor energy consumption with evaporator temperature for six different refrigerants. The average energy consumption of R1234yf, R152a, R1234Ze (E) & R600a were lower than R134a by approximately 4, 6, 26 and 50% at a condenser temperature 25 and 45ºC. R290 has a higher energy consumption than R134a by approximately 50% at the condenser temperature of 25 and 45°C, respectively. As the evaporator temperature increases, the compressor power consumption of the domestic refrigeration system increases due to increase in the mass flow rate. As the condenser temperature rises, the energy consumption of the compressor increases due to increase in the enthalpy difference between outlet and inlet of the compressor. As highlighted in Figure 7 showed cooling capacity of alternate refrigerant versus evaporator temperature. At a condenser temperature of 25 and 45°C, it was found that R152, R1234yf, R1234Ze (E) and R600a were lower than those of R134a by around 7, 8, 25 and 50%. Similarly R290 was more than R134a by about 25%.

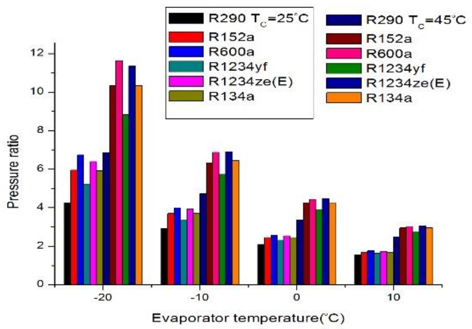

Figure 4. Pressure ratio Vs. Evaporator temperature

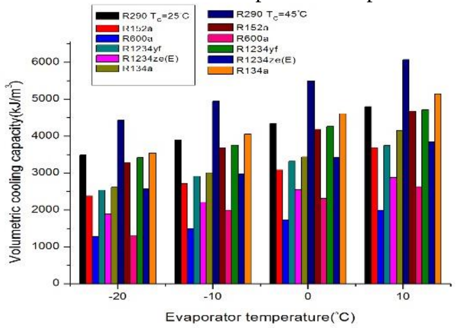

Figure 5. Volumetric cooling capacity vs. Evaporator temperature

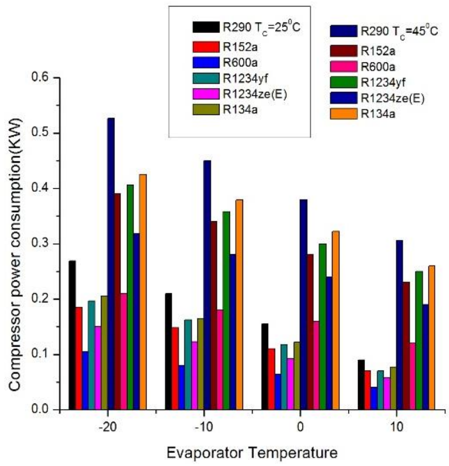

Figure 6. Compressor power consumption vs. Evaporator temperature

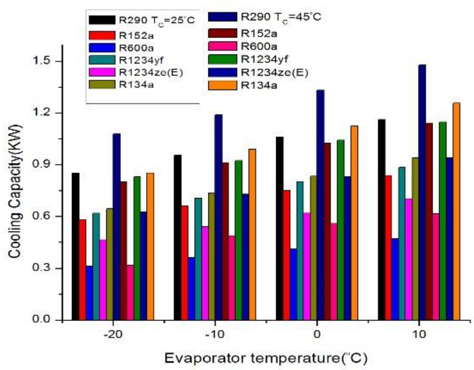

Figure 7. Cooling capacity vs. Evaporator temperature

Variation of COP

Figure 8 highlights the variation of COP of the refrigerant versus evaporator temperature for six different refrigerants. At condenser temperature 25°C, it was found that R152, R1234yf shows almost equal Cop with R134a but R290 was 3% more than that of R134a and R600a, R1234Ze (E) was less than that of R134a by about 6 and 2%. The difference of COP for R152a & R134a, R1234yf & R134a increases with increases in condenser temperature, since one can expect a better COP with R152a, R1234yf, but R290 decreases with the increase of the condenser temperature.

Effect of compressor exit temperature

Figure 9 highlights the effect of compressor exit temperature versus evaporator temperature for six different refrigerants. At a condenser temperature 25^0C, it was found that R290, R1234Ze(E) R600a and R1234yf were lesser than that of R134a by 0.5-3.2^0C, 2.9-5.5^0C, 3.9-14.4^0C and 2.5-6.6^0C and lesser than that of R134a about 1-3.8^0C, 7-7.5^0C, 5.9-15^0C and 3-7.5^0C, respectively at condenser temperature 45^0C but R152a showed a higher discharge temperature 3.8 to 4.9^0C, 7.8 to 17.92^0C at condenser temperature 25^0C and 45^0C, respectively. The higher discharge temperature effects the motor coil and the properties of lubricants flammability is also a problem with R152a as in replacement for R134a in a domestic refrigeration system.

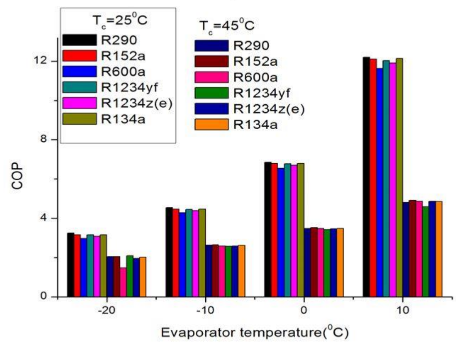

Figure 8. COP vs. Evaporator temperature

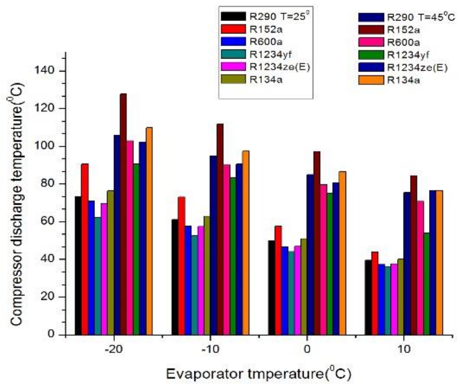

Figure 9. Compressor Exit temperature vs. Evaporator temperature

CONCLUSION

In this paper the thermodynamic analysis of various low GWP refrigerants alternative to R134a in a vapour compressor refrigeration system with liquid-suction internal exchanger was performed and the conclusions are as follows:

1. R290 offers very favourable conditions in terms of volumetric cooling capacity, cooling capacity and COP. However, its power consumption exceeds R134a by approximately 50%, which requires an electric motor larger than R134a. Therefore, it is not recommended as an alternative to the refrigerant R134a.
2. R152a had gave a better results in terms of COP, volumetric cooling capacity and cooling capacity compared to a R134a but the main problem is discharge temperature is more which affects the motor coil and lubricant properties.
3. R600a (isobutene) had a strong reduction in volumetric cooling capacity and compressor power consumption mainly due to its high density value. Therefore, a larger displacement compressor is required to produce the same cooling effect as that of R134a. R600a is not suitable for direct drop in the replacement of R134a.
4. The HFO refrigerant (R1234yf) provides a small reduction in volumetric cooling capacity, cooling capacity, energy consumption and COP, and also R1234yf has a low GWP value. Therefore, it can be considered as a direct drop in replacement of the R134a by taking a corresponding safety requirements.
5. The HFO R1234ze (E) refrigerant shows a noticeable reduction in compressor energy consumption and cooling capacity. The most important is that it requires an electric compressor with a greater displacement to produce the same cooling capacity. As a result, COP of the plant decreases. When considering the above results, it is not suitable to replace the R134a.

By considering all the above results, R152a and R1234yf are two possible alternatives refrigerants that can be directly replaced in the place of R134a considering the cooling capacity and the energy consumption of the refrigerating machine. R1234ze(E), R290 and R600a are not replaceable, because they require different displacements as compared to R134a. At the same time performance of a conventional refrigeration system improved with the help of liquid-suction heat exchanger. Therefore the refrigerants R1234yf and R152 gave a good results with considering the liquid-suction heat exchanger.

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چکیده

امروزه یخچال و فریزر و سیستم های تهویه مطبوع، مصرف کنندگان اصلی انرژی در یک محیط داخلی هستند. بهبود بهره وری از این لوازم می تواند به عنوان یک گام مهم برای کاهش مصرف انرژی خود در نظر گرفته شود. علاوه بر بهبود کارایی، جلوگیری از آلودگی محیط زیست نیز مورد نیاز است. CFC ها از سال ۱۹۹۵ تقریبا رد شده و به دلیل تأثیر زیادی بر لایه اوزون تا سال ۲۰۲۰ باید HCFC ها جایگزین شوند. تمام این رویدادها باعث جذب مبرد HFC شد که برای لایه اوزون بی ضرر هستند، اما مبرد HFC دارای پتانسیل گرم شدن جهانی (GWP) است. که باعث آلودگی محیط زیست می شود. اما بعدا پروتکل کیوتو به وجود آمد که بیانگر نیاز به جایگزینی HFC با توجه به ارزش بالا GWP بود. بنابراین در این مقاله، تجزیه و تحلیل ترمودینامیکی یخچال و فریزر خانگی با استفاده از R134a به عنوان یک مبرد انجام شد و نتایج HFC134a با مبرد های مختلف GWP پایین مانند HFC152a، HC290، HC600a، HFO1234yf و HFO1234ze (E) به عنوان یک جایگزین احتمالی برای R134a بدون هر تغییری در سیستم. اثر پارامترهای مختلف عملیاتی که دمای تبخیر کننده، دمای کنسانتره، وجود مبدل حرارتی مکنده مایع و افت فشار با پارامترهای عملکرد مانند COP، اثر تبرید، کار کمپرسور و نسبت فشار گزارش شده است. نتایج نظری نشان داد که تمام مبرد های جایگزین مورد استفاده در تجزیه و تحلیل دارای ضریب عملکرد پایین (COP) نسبت به HFC134a در دمای تراکم ۲۵ و ۴۵ درجه سانتیگراد و دمای تبخیر در محدوده بین -C۲۰۰ تا C۱۰۰ است. در عین حال عملکرد یک سیستم تبرید معمولی با کمک مبدل حرارتی مایع بهبود یافته است.