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ENERGY ANALYSIS OF HFC-152A, HFO-1234YF AND HFC/HFO MIXTURES AS A DIRECT SUBSTITUTE TO HFC-134A IN A DOMESTIC REFRIGERATOR

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Abstract: The Kyoto protocol emphasized the need of replacement of HFC refrigerant due to their high GWP values that causes pollution in the environment. So in this paper the refrigerants R1234yf, R152a and HFOs/HFCs mixtures of R134a/R152a/R1234yf such as ARM42 (in the ratio of 8.5/14 /77.5 by mass), ARM42a (in the ratio of 7/11/82 by mass) with a view of replacement of the refrigerant HFC-134a in a domestic refrigerator were analyzed theoretically. Volumetric cooling capacity, compressor discharge temperature, coefficient of performance, compressor energy consumption and refrigeration capacity are the main parameters to estimate the performance of the refrigerator. The results are revealed that HFC-152a had gave a superior performance as compared to HFC-134a in terms of COP and equal cooling and volumetric cooling capacities. However, the refrigerant HFC-152a was flammable and runs with high compressor outlet temperature which may restrict its usage. The HFO refrigerant R1234yf showed an almost equal volumetric cooling capacity, compressor energy consumption, refrigerating effect and COP when compared with HFC-134a. Among the refrigerants ARM42 and ARM42a, the refrigerant ARM42a was selected as a good alternative for HFC-134a because the Volumetric cooling capacity and COP of ARM42a were almost equal to HFC-134a. Therefore ARM42a had better choice of direct substitute to HFC-134a in a domestic refrigerator when the corresponding safety requirements are adopted. So on overall comparison of every property of refrigerants we can conclude that R1234yf can be treated as best alternative to HFC-134a in a domestic refrigerator.

KEYWORDS: HFC-134a, ARM 42a, HFO-1234yf, ARM 42, HFC-152a, Domestic refrigerator

1. Introduction

The refrigeration industry is in transition after global protocols issued due to the impact of emanations from the refrigerants in the environment. The Montreal Protocol underscored the need to replace CFCs and HCFCs because they effect the ozone layer drastically. So there is a need to promote HFC refrigerants that are not harmful to the ozone layer. But then the Kyoto Protocol was introduced, with a demand to replace the HFC refrigerants because these refrigerants have a higher GWP values. According to the Kyoto protocol, R134a is the main compound for the emission of greenhouse gases [1]. HFC gases with an estimated GWP value above 150 should be completely eliminated in the new car air conditioning model as of January 1, 2011 and all new air conditioners for automobiles as of January 1, 2017, in accordance with F-gas standards [2]. the European Union inspected the F-gas in 2014 [3], which contained that hydrocarbons (HFC) with a GWP estimation of more than 150 ought to be prohibited in residential coolers and refrigeration machines as of January 1, 2015 together with freezing and commercial freezers as of January 1, 2022. Most of the countries are significantly decreasing the HFC usage and its production. So, there is a greater interest

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towards replacing HFC-134a for the probable retrofit of current systems, as well as for upcoming systems.

Hydrofluoroolefins can be treated as propene isomers and these consist of different types of R-1225, R-1243 and R-1234 isomers. Due to their flammability and toxicity R1243 and R-1225 isomers were not developed. Therefore R1234yf, R1234ze (E) are considered as the main refrigerants from the above mentioned refrigerants, therefore in a household refrigerator this can be treated as better replacement to HFC-134a. Chlorine is not present in the refrigerant (HFO-1234yf), therefore, its ozone depletion potential value is zero (WMO, 2007), and also R1234yf with a low GWP value, approximately 4. Similar to HFC-134a, HFO-1234yf has a low toxicity. While considering the additional environmental effects of HFO-1234yf, if R1234yf is exposed to the environment, it is entirely transmuted into persistent trifluoroacetic acid. So HFO-1234yf does not cause any harm to the environment. Spatz and Minor (2008) had observed the physical properties of HFO-1234yf with HFC134a. Therefore, R1234yf can be treated as good substitute to HFC-134a in refrigeration industry [4]. M. Rasti1, M.S. Hatamipour et al. (2011) conducted an experiment survey of R436a and R600a to swap R134a in a household cooler and fridge. From their previous experiments they reported that R600a and R436a that have a zero ozone depletion potential value and a lower GWP value than HFC-134a in the refrigerator which is having single evaporator and it is fabricated only for the usage of HFC-134a. They predicate that, contrasted with R134a, the proportion of hydrocarbon mixture is decreased by 53% for HC-600a and 47% for R436a and compressor work is diminished by 6% for HC-600a and R436a in a time interval of 24hrs.Finally concluded that from their results and environmental effects of R600a and R436a, they could be considered as a very good alternative to HFC-134a [5]. D.Shapiro (2012) led an investigation on a cooler with a low GWP refrigerants like HFO--1234ze(E), 1234yf mixtures with HFC134a, R513A and R450A. All analyses were carried out in the same cooler and resolved that there is no significant changes in the consumption of compressor power as compared to HFC-134a, aside from HFO-1234z(E), which shows a lesser Refrigerating effect [6]. Karber, Abdelaziz and Vineyard (2012) directed an experiment with R-1234yf, 1234ze (E) and HFC-134a in a different type of two domestic refrigerators. From that they concluded that HFO-1234yf had gave a more compressor power utilization as related with HFC-134a and HFO-1234ze (E) gives a lesser blower work utilization. In any case, HFO-1234ze (E) gives a lower cooling limit contrasted with R134a and R1234yf [7]. Naushad et al. (2013) performed an energy and exergy analysis using Hydrofluoroolefins (HFO) refrigerants like R1234ze(E), R1234yf and HFC134a in a refrigerator. At long last they arrived at the resolution that HFO-1234yf is awesome substitute to HFC-134a when the evaporator temperatures are very high. By making certain alterations to the refrigeration framework, R1234ze (E) can be utilized as a decent substitution for R134a [8]. Zhao Feng, Zhang, Jinyou Qiu and Lei (2016) have done an investigation on HFO/HFC refrigerant mixtures as a stand-in to HFC-134a in a refrigeration system without doing any alternations to the existing system [9].Sanchez et al. (2017) conducted an investigation with HFO, HFC and HC refrigerants in a refrigerator and they concluded that HFO-1234yf and HFC-152a shows a better alternative to HFC134a [10]. Mohan raj et al. (2009) led a test in a refrigerator by utilizing a HC-600/290 blend (54.6/45. 4%).This blend increases the COP and diminishes the compressor work utilization [11]. BO Bolaji et al (2010) done an analysis with HFC-152a and R32 in a refrigerator which is working with r134a as a refrigerant and reasoned that the normal COP of R32 was roughly 9.3% less when contrasted with HFC134a while the COP of R152a was around 6.5% more as related with HFC-134a [12]. Bukola Olalekan et al. (2014) made a comparison between low GWP refrigerants like HFC-152a and HC-600 hypothetically as an option in contrast to HFC-134a in the household fridge. From these outcomes, they inferred that HFC-152a displays a more volumetric cooling capacity (limit) (VCC) and COP

when contrasted with HC-600a and HFC-134a.COPs accomplished for HFC-152a and HC600a were 12.9% higher and 6% lower than that of HFC-134a, individually. They presumed that HFC-152a shows a best outcomes as contrasted and R134a [13]. M. H. SHAIK et al. (2020) performed a first and second law analysis of low GWP refrigerants as a stand-in to refrigerator and from that they conclude that HFO-1234yf is the elite option for swap to R134a in a refrigerator without changes [14]. Kapilan et.al conducted a computational fluid dynamic analysis to study the refrigerator and air-conditioning evaporative cooling system [15]. SK Mohammad Hasheer and Kolla Srinivas (2019) performed theoretical analysis of different refrigerant mixtures as stand-in to R-134 in refrigerator and from that analysis they concluded that R152A/ HFO-1234ze (E) (by mass 50:50) can be utilized as an immediate trade for HFC-134a without rolling out any improvements to the compressor [16].

In contrast to available literature many researchers carried out various experiments and concluded that the alternatives for R134a were found in domestic refrigeration systems: the HFOs/HFCs mixtures of R134a/R152a/R1234yf such as ARM42 (8.5/14/77.5 w/w %) and ARM42a (7/11/82 w/w %). This paper mainly focus on the feasibility of the ARM42, ARM42a mixtures as alternative to HFC-134a. In addition, pure HFO-1234yf and HFC-152a are also cited as alternatives compared to HFC-134a to accomplish this document more convincing.

2 Characteristics of (an) R134a/R152a/R1234yf mixture, R152a, R1234yf and R134a:

2.1 Environmental impact

To preserve the ozone layer depletion and to diminish the GWP value, the stand-in refrigerants requires not only an ozone depletion potential value of zero at the same time it requires a lower GWP value. The low GWP refrigerants R1234yf, R152a, ARM42 and ARM42a were proposed in this document considered as substitutes for HFC-134a. The value of GWP for R152a is 138.

The value of GWP for various refrigerant mixtures can be estimated using the equation as given below:

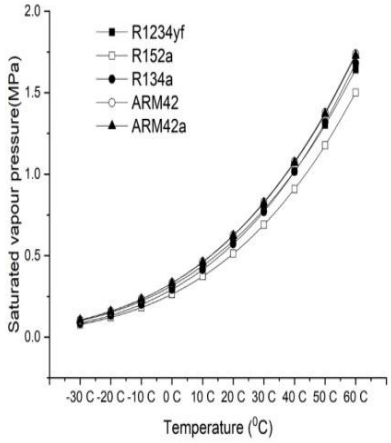
$$GWP_{mixture} = GWP_1 \times W_1 + GWP_2 \times W_2 + GWP_3 \times W_3$$

where GWP_1, GWP_2 and GWP_3 are the value of GWP for respective refrigerants 1, 2 and 3; mass fraction of refrigerants mixture are denoted by W_1, W_2 and W_3

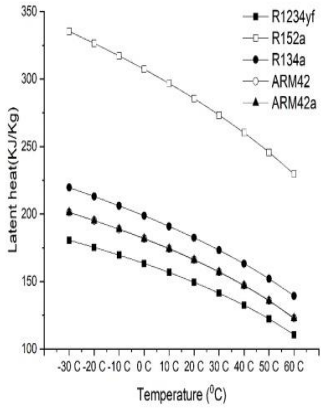
Refrigerant	R152a	R1234yf	ARM42	ARM42a	R134a
ODP	0	0	0	0	0
GWP	**138**	**4**	**110.5**	**117**	**1430**

Figure 1(a) to (h) depicts the various properties like vapour and liquid density, thermal conductivity, viscosity, vapour pressure and latent heat of R1234yf, R152a, ARM42, ARM42a and HFC-134a for various temperatures ranging from -30^0C to 60^0C.The thermodynamic properties of all refrigerants were assessed from software REFPROP 9.1. Figure 2.1 portrays the deviation of saturated vapour pressure of all alternative refrigerants against temperature. The vapour pressure of substitute refrigerants should be identical to that of HFC-134a to attain persistent thermodynamic properties and lower than that of HFC-134a. It was found that the saturated pressure values of R1234yf range from R134a by approximately 1.3% to 2.3% and for R152a it varies from HFC-134a by approximately 8.5% to 10.7%, ARM42, ARM42a are nearly the same saturated vapour pressure values that vary with respect to HFC-134a in around 2% to 3.4% at a temperature range between -30^0C to 60^0C. Therefore, the change in pressures can be accompanied by the operating the

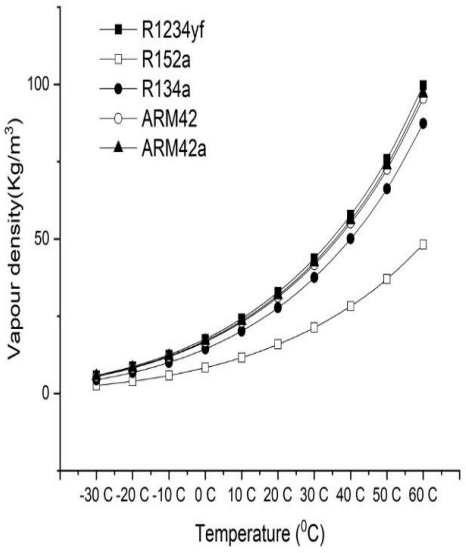
compressor at very high pressure. The latent heat of five refrigerants selected as a function of temperature are shown in Figure 2.2. The latent heat of HFO-1234yf shows a lower value than that of HFC-134a by around 17.7% to 20.6%, and R152a was higher than that of HFC-134a by approximately 52% to 68% at a range of temperatures between -30^{0}C and 60^{0}C.A higher value of latent heat shows an increase in the cooling capacity at the same time it decreases the operating time of the compressor. The vapour and liquid densities of five selected refrigerants are presented in Figure 1(c) and 1(d). The liquid density of HFO-1234yf, HFC-152a, ARM42, ARM42a were found to be lower than that of HFC-134a by about 9% to 10.5%, 26.2% to 24%, 11.6% to 13.4%, and 11% to 13% respectively at a range of temperatures between -30^{0}C and 60^{0}C which gives in saving the charging the refrigerant. The vapour density of HFC-152a was lower than 40% and HFO-1234yf, ARM42a, ARM42 were averagely higher than that of 30% when comparing with R132a. When the velocity of the gas decreases, the vapour density increases and the shear force between the liquid and vapour, which improves the heat transfer and decreases the evaporator and condenser pressure drop. The viscosity of liquids and vapour of the all the selected refrigerants investigated and shown in Figures 1(e) and (f). It was found that the viscosity of the liquid and vapour of R1234yf, ARM42a, and ARM42 was higher than that of HFC-134a, resulting in high friction and evaporator and condenser pressure drop. At different temperature range the vapour and liquid viscosity of HFC-152a was lower than that of HFC-134a.

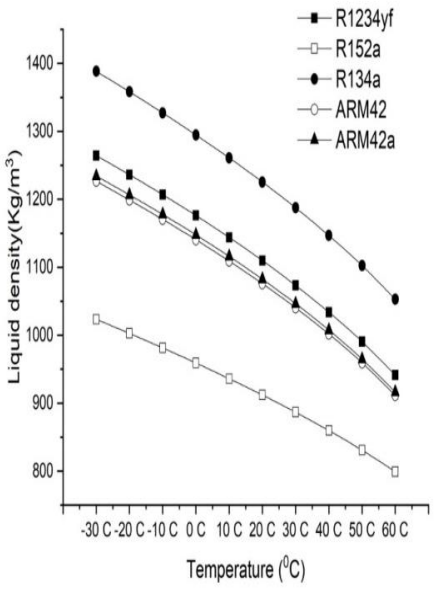


(a)



(b)





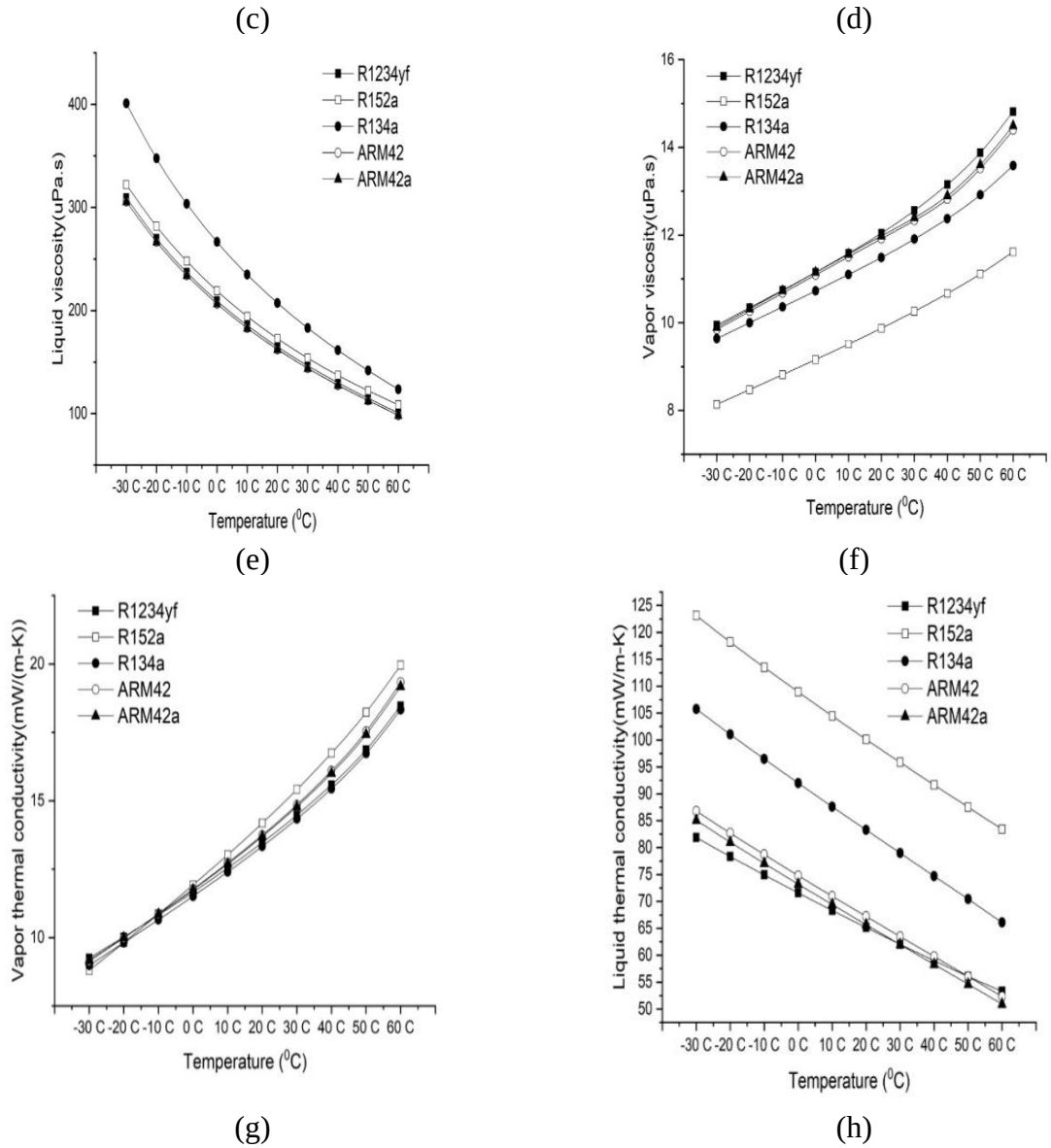


Fig. 1. Thermodynamic properties of all refrigerants variation with temperature: (a) Saturated vapor pressure Vs Temp, (b) Latent heat Vs Temp, (c) Vapor density Vs Temp (d) Liquid density Vs Temp (e) Vapor viscosity Vs Temp (f) Liquid viscosity Vs Temp (g) Vapor thermal conductivity Vs Temp (h) Liquid thermal conductivity Vs Temp.

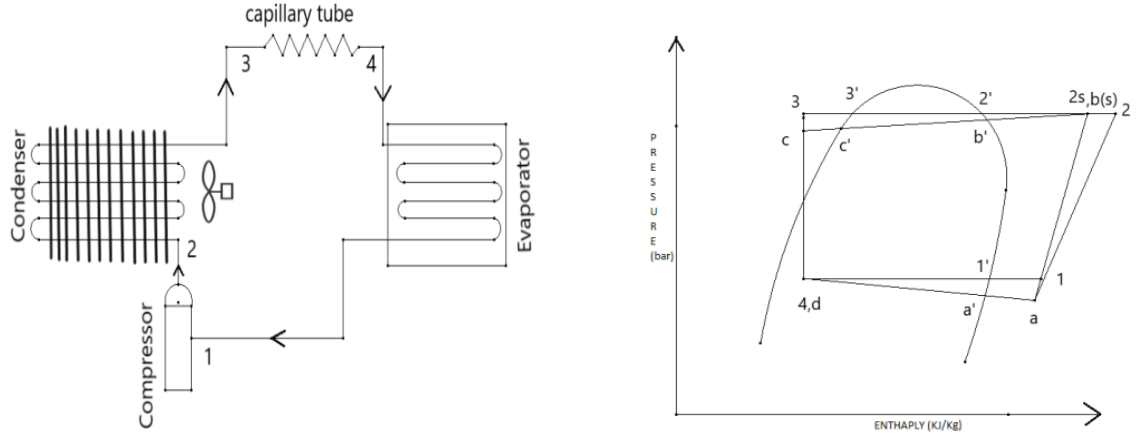
3. Thermodynamic Analysis of an alternative refrigerant

Fig.2 (b) illustrates the theoretical diagram of a domestic refrigerator with pressure losses between condenser and evaporator. The refrigerant is superheated vapour at the compressor entry and while passing through the condenser at the same time in between the condenser, throttle valve and in the evaporator line pressure drop takes place. Pressure losses are also mentioned in Fig 2(b). REFPROP9.1 software is very useful tool for calculating the properties of a refrigerant at each state of the cycle. The theoretical results can be analyzed using the following data as shown below.

For analysis the data is taken from the literature review and is given below. The results are plotted as shown in Figures 3 to 9.

1. Temperature of the condenser: 30^0C and 50^0C
2. Temperature of the evaporator: -25^0C to 15^0C

3. Evaporator pressure losses: 0.02 MPa
4. Condenser pressure losses: 0.01 MPa
5. Compressor (η_{is}) isentropic efficiency: 0.75
6. Volumetric efficiency of a compressor: 0.8
7. Compressor swept volume: 8.16 cm^3/rev
8. The super-heating temperature at evaporator: 5K
9. Sub-cooling temperature at condenser: 5K
10. Compressor Speed: 1800rev/min



(a) (b)

Fig.2. (a) Domestic refrigeration system, (b) P-h diagram of a domestic refrigerator

Volumetric cooling capacity, compressor discharge temperature, coefficient of performance, compressor energy consumption and refrigeration capacity are the main parameters to evaluate the performance of the domestic refrigerator.

The pressure ratio of the system can be calculated as:

$$PR(\text{Pressure ratio}) = Pcon\ /Pevap_act \quad (1)$$

Compressor work is expressed from the Fig. 2(b) as given below:

$$Wcomp\ =\ m_r(h_2 - h_1) \quad (2)$$

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

The Cooling Capacity (Q_c) of the refrigerator can be expressed as:

$$Q_c\ =\ h_1 - h_4 \quad (4)$$

The efficiency nothing but (coefficient of performance) COP of the refrigerator can be expressed as:

$$\text{COP} = \frac{Cooling\ capacity}{work\ done\ by\ the\ compressor} = \frac{Q_c}{Wcomp} \quad (5)$$

The Q_{vol} (Volumetric Cooling Capacity) can be expressed as:

$$Q_{vol} = (h_1 - h_4) \times \eta_{vol} / v_1 \quad (6)$$

Where v_1 be the specific volume (m^3/kg) of a refrigerant at compressor inlet.

The refrigerant m_r(Mass flow rate) can be calculated as.

$$m_r = RPM \times v_s \times \rho_1 \times \eta_{vol}/60 \quad (7)$$

Where speed of the compressor is denoted by RPM, v_s.is compressor swept volume and density of the refrigerant at entry to the compressor is denoted byρ_1.

4. Results and discussion

4.1 Deviation of Mass flow rate of all alternative refrigerants in (kg/h)

Figure 3 illustrates the deviation of different alternative refrigerants mass flow rate with evaporator temperature. The mass of refrigerant which is required per unit time to produce required cooling effect is called mass flow rate. From the plot it is detected that mass flow rate of all the refrigerants increases with increase in evaporator temperature. Condenser temperature doesn't have any impact on the mass flow rate of alternative refrigerants. It was calculated that, the mass flow rate of R1234yf is superior to that of the refrigerant R134a by 14.7% within the evaporator temperature change considered. The mass flow rate generally depends on volumetric efficiency of a compressor which in turn the geometric dimensions of a cylinder in reciprocating machine, refrigerant density at compressor inlet. It was found that the mass flow rate of the refrigerants HFC-152 and HFO-1234Ze(E) were lower than that of HFC-134a by around 20% and 24% respectively at different evaporator temperatures. From the plot it can also be deduced that the mass flow of refrigerant HFO 1234yf is maximum among different refrigerants tested since it have high density when compared with remaining.

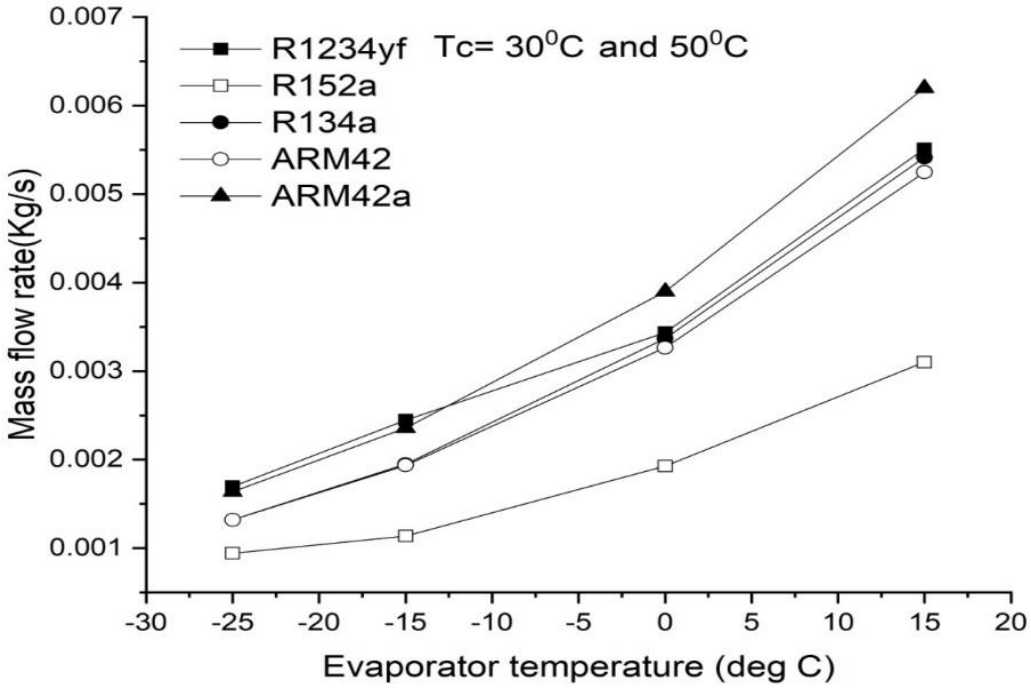


Fig. 3 Mass flow rate of alternative refrigerants vs Evaporator temperature at two condenser temperatures T_c =30℃ and 50℃

4.2 Variation of pressure ratio

Fig. 4 illustrates the pressure ratio variation of five refrigerants with respect to evaporator temperature at a temperatures of 30℃ and 50℃. It is defined as the ratio of higher pressure to lower pressure in vapour compression refrigeration system. It is directly varied with temperature of condenser and inversely varied with temperature of evaporator. At both condenser temperatures considered, the refrigerants R1234yf, R152A. ARM42 and ARM42a have pressure ratio lower than refrigerant HFC-134a by 7.7%, 2.7%, 7.3 % and 6.6% respectively at an evaporator temperature of -25℃. However, at an evaporator temperature of 15 ℃ they have a pressure ratio lower by 2.5%, 0.8%, 9.5% and 9.8 % respectively at both condenser temperatures when compared with R134a. The pressure ratio impacts the volumetric efficiency of a compressor. As the pressure ratio decreases volumetric efficiency increases and have positive effect. So from the results plotted, since all the refrigerants have decrease in pressure ratios at both extreme values of evaporator temperature they can be best suited to replace the conventional refrigerant R134a in a domestic refrigerator, which have high pressure ratio.

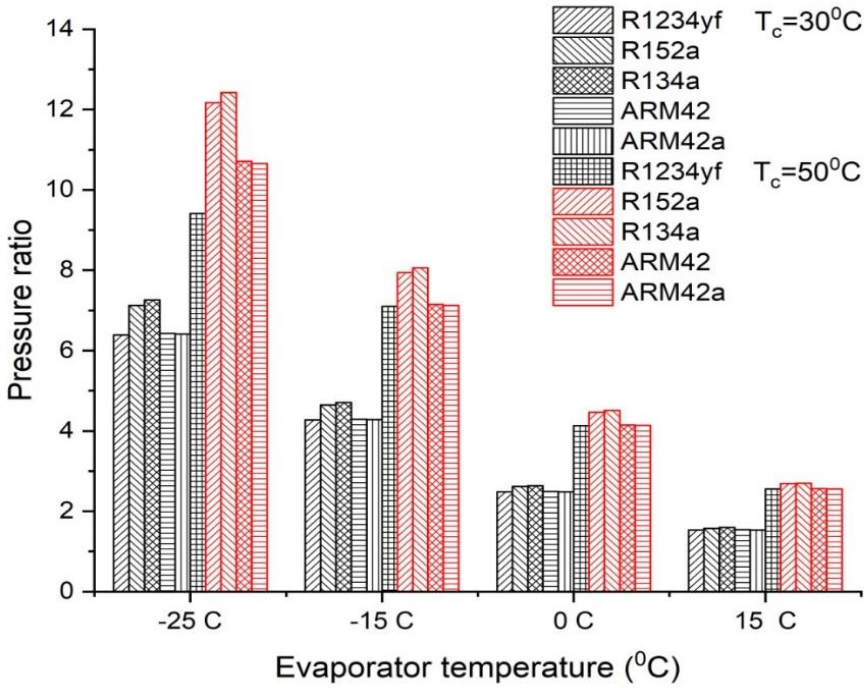


Fig. 4 Pressure ratio Vs. Evaporator temperature at two condenser temperatures T_c =30℃ and 50℃

4.3 Variation of volumetric cooling capacity (VCC)

Fig. 5 Portrays the deviation of VCC with respect to the evaporator temperature for five different refrigerants. It was obtained that the average VCC of refrigerant ARM42a is higher than that of HFC-134a by 8% and while the refrigerants R1234yf and ARM42 have 4% and 2% lower volumetric cooling capacity at both condenser temperatures considered. However, at a condenser temperature of 50^{0}C, the refrigerant HFC-152a have higher VCC by 8% than that of HFC-134a and lower by 2% at a condenser temperature of 30^{0}C. The size of compressor is affected by volumetric efficiency and hence it's an important factor to be considered while selecting alternative refrigerants. Based upon the calculated values of VCC all the refrigerants R152a, ARM42, ARM42a and R1234yf can be suitable as viable alternative refrigerants in the place of R134a.

The deviation of compressor energy consumption with evaporator temperature for alternative refrigerants as shown in Figure 6.The average power consumption of alternative refrigerants like R1234yf, R152a and ARM42 was lower than that of HFC-134a by about 8%, 8.5% and 9% respectively. However, the refrigerant ARM42a has 10% higher compressor power consumption at both condenser temperatures 50°C & 30°C.The energy consumption of VCR system increases due to increase in refrigerant mass flow rate when the temperature of the evaporator is increased. Similarly it also increases with condenser temperature due to the gain in enthalpy of the working fluid when passing through the compressor. At both condenser temperatures the refrigerant R152a have lowest and the refrigerant ARM42a have highest power consumption among all the refrigerants considered.

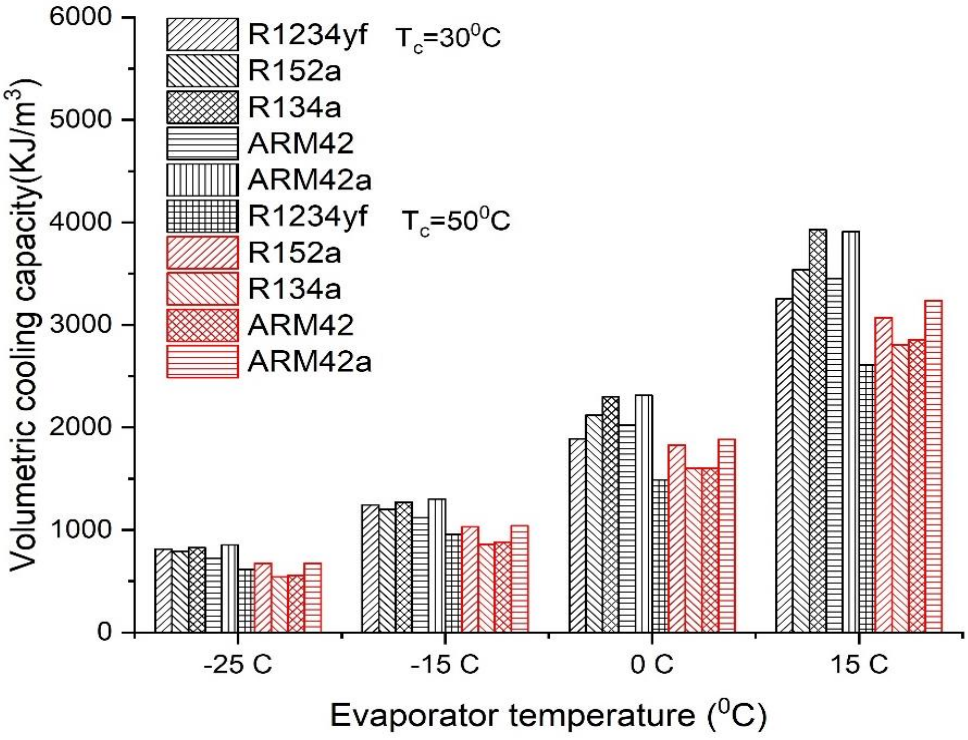


Fig. 5 VCC vs. Evaporator temperature

4.4 Variation of compressor energy consumption and cooling capacity

Fig. 7 highlighted the cooling capacity variation with evaporator temperature for refrigerants at a temperatures of 30 ℃ and 50℃. It was observed that cooling capacity of the refrigerants ARM42 and R1234yf are lower than that of refrigerant R134a by approximately 11.3% and 13.6%. However, the refrigerants ARM42a and R152a have almost nearly the same cooling capacity as that of R134a at both condenser temperatures.

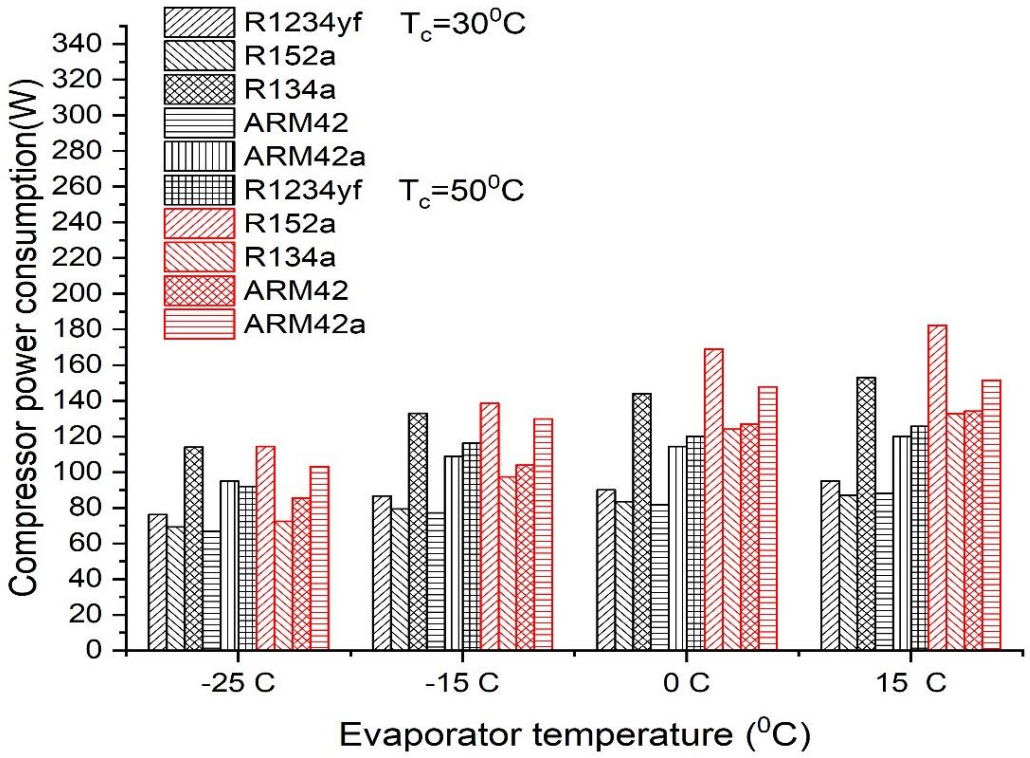


Fig. 6 Compressor energy consumption vs. Evaporator temperature

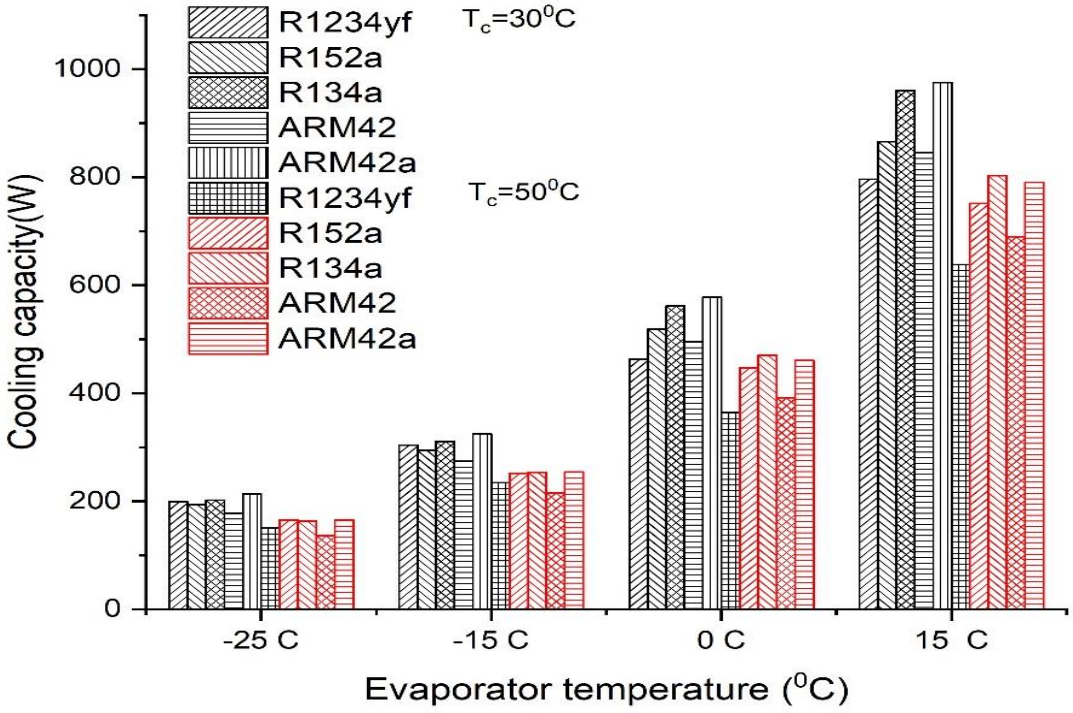


Fig. 7 Cooling capacity vs. Evaporator temperature

4.5 Variation of COP

Fig. 8 delineates the deviation of COP with evaporator temperature for five refrigerants. It was calculated that at a condenser temperature of 50°C the average COP of the refrigerants R123yf, ARM42 and ARM42a were lower by 19.8%, 20.9% and 20% respectively when

compared with R134a. However at condenser temperature 30°C, they have COP higher by 23.76%, 24.9% and 20% respectively with respect to R134a. This is due to the more power consumption at high condenser temperature and low power consumption at low condenser temperature. The COP of refrigerant R152a was higher by 20% at condenser temperature of 30°C and lower by 17% at a condenser temperature of 50°C. Therefore it is inferred that the refrigerants R1234yf, ARM42, ARM42a and R152a can yield high COP at elevated condenser temperatures. Evaporator temperature increase has positive effect and condenser temperature increase have negative effect on the COP.

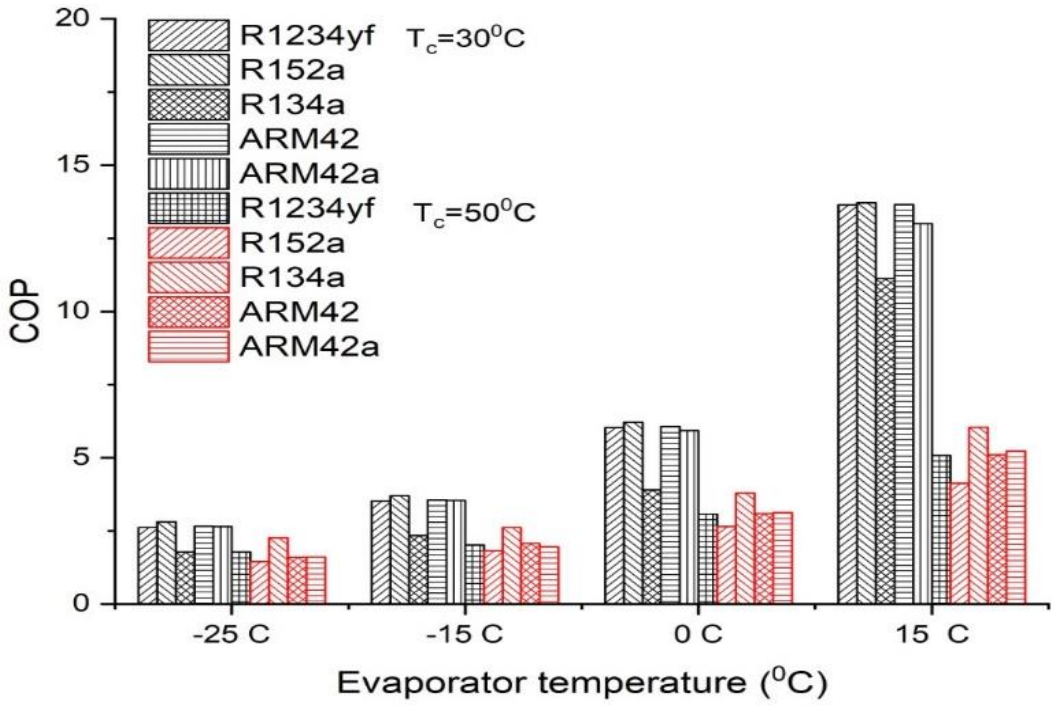


Fig. 8 COP vs. Evaporator temperature

4.6 Effect of compressor exit temperature

Fig. 9 illustrates the effect of the compressor outlet temperature with respect to the evaporator temperature for alternative refrigerants at various condenser temperatures. At a condenser temperature 30^{0}C, it was found that the refrigerants HFO-1234yf, ARM42 and ARM42a have lower than that of HFC-134a by 3-9^{0}C and 3^{0}C-10^{0}C, about 8^{0}C-13^{0}C and 2^{0}C-10^{0}C by 1.5-3^{0}C and 2^{0}C-4^{0}C respectively at condenser temperature of 30^{0}C and 50^{0}C. But R152a shows a higher outlet temperature 3-11^{0}C, 9-19^{0}C at condenser temperature 30^{0}C and 50^{0}C respectively. Higher compressor outlet temperature effects the properties of lubricants and the compressor motor coil used in the compressor.

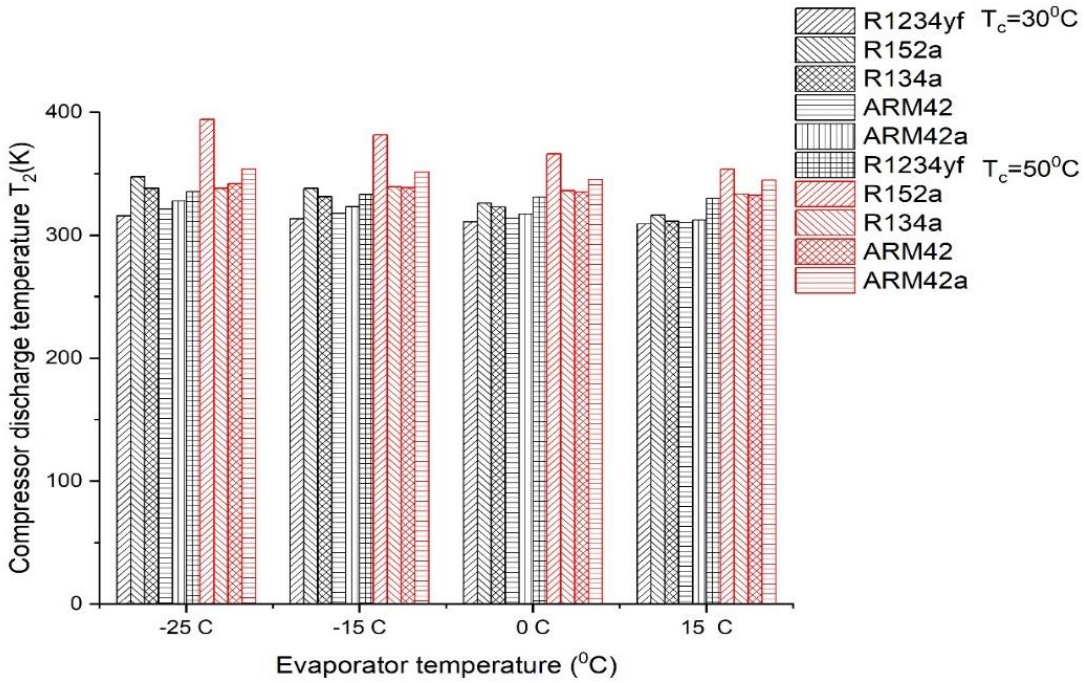


Fig. 9 Exit temperature of the compressor vs. Evaporator temperature

CONCLUSION

In this research paper different HFOs/HFCs mixtures of R134a/R152a/R1234yf such as ARM42, ARM42a along with R1234yf and R152a refrigerants have tried to replace conventional refrigerant R134a in a domestic refrigerators. Various performance parameters have analyzed and the following conclusions are arrived based on theoretical study.

1. R152a offers better COP and volumetric cooling capacity as compared to HFC-134a, which makes it the best substitute to HFC-134a; however, R152a running with a very high compressor discharge temperature which causes a high level of uncertainty in the domestic refrigerator. Therefore, R152a is not recommended as a direct substitute to HFC-134a.

2. The HFO refrigerant R1234yf shows almost equal in volumetric cooling capacity, refrigerating effect, energy consumption and COP when compared to R134a. Therefore, it can be treated as a very good alternative to HFC-134a.

3. ARM42, ARM42a are refrigerant mixtures having a lower energy consumption compared with HFC-134a at condenser temperature 30^{0}C.But this situation is completely reversed at 50^{0}C, ARM42a has nearly 10% more power consumption at condenser temperature of 50^{0}C.

ARM42 has less cooling capacity among these three refrigerants, with ARM42a almost similar to that of R134a.Also these two refrigerants operate at lower pressure ratios compared with R134a.ARM42a had grater volumetric cooling capacity compared to ARM42 and R134a where both of these exhibited similar volumetric cooling capacities. ARM42, ARM42a had lower compressor discharge temperature at condenser temperature of 30^{0}C while at 50^{0}C ARM42a had more compressor discharge temperature than ARM42 and R134a.So on overall comparison of every property of refrigerants we can conclude that ARM42a had better choice of direct substitute to HFC-134a in a domestic refrigerator when the corresponding safety requirements are adopted.

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