THERMODYNAMIC ANALYSIS OF LOW GWP REFRIGERANT MIXTURES IN A REFRIGERATOR AS REPLACEMENT TO R-134A

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Abstract: Chlorofluorocarbons and hydro chlorofluorocarbons (HCFCs) are replaced by hydroflourocarbons (HFCs) which is not harmful to the ozone layer. However, few of HFCs have a relatively high global warming potential (GWP) and are subject to further examination due to growing concerns about global climate change. The goal now is to find the next generation of environmentally sustainable work fluids with an insignificant direct environmental impact in terms of ozone depletion and global warming potential. This document introduces the mixture of low-GWP refrigerants like R440A, R430A, R1234ze (E)/152a (50:50 by mass), R290/600a (40/60), R290/600(60/40), R290/600(50/50), ARM 42, ARM 42a and AC5 are used to replace R-134a in a domestic refrigeration system without doing any modifications to the system. The performance of the refrigerator was observed in terms of volumetric cooling capacity, blower discharge temperature, and coefficient of performance, refrigeration effect and energy consumption of a blower.

KEYWORDS: Refrigerator, GWP, R440A, R430A, R-134a.

1 Introduction

In the last 30 years, chlorofluorocarbons and hydroflourocarbons have been widely used in refrigerators and air conditioners. But the ODP and GWP values are very high for these refrigerants, which are causes for environmental pollution. Due to this higher ODP value, chlorofluorocarbons and HCFC are completely prohibited in air conditioning and refrigeration sector accordance to Montreal protocol. Instead of these refrigerants, HFC refrigerants are introduced, but the main problem with these refrigerants is that they have a higher GWP value. Therefore, these should be banned in the coming years on the basis of the Kyoto Protocol. R134a should be eliminated by 2021. Most developing countries are drastically reducing the production and consumption of HFCs. Therefore, there is a greater demand for adequate replacement of HFC-134a for possible adaptation of existing and new systems. Kim et al. in [1], conducted an experiment with R600a, which is a substitute to R12 in a domestic refrigerator. They analysed theoretically with the help of a software REFPROP, and then performed a series of tests with this refrigerant. Jung et al. [2] performed an experiment with mixture of R290 / R600a (60:40 ratio by mass) as a direct substitute to R12 in a refrigerator and they concluded that improvement in coefficient of performance and power efficiency by 2.4 and 3.9% respectively. Tashtoush et al. [3] performed an experiment on refrigerator with Hydrofluorocarbons/hydrocarbon mixtures as a substitute to R12. From the experimental results, the mixtures give an excellent performance as compared to HFC-134a.

Lee et al. [4] conducted an experiment on domestic refrigerator using iso-butane as refrigerant. The input energy of the compressor varies from 225 to 300 W, and the charged refrigerant in a refrigerator is approximately 150 g. It was found that the COP was between

0.8 and 3.5 in a freezing application. Garland [5] studied the environmental impact of the R600a hydrocarbon refrigerant installed in the hermetic compressor of the household refrigerator. The test was carried out using flow tests to establish the wear mechanism and the coefficient of friction and compared the results with R134a. The results showed that the R600a compressor continues to operate without any deterioration as compared to R134a compressor at the end of its life span of 15 years. Wongwises and Chimres [6] analysed various blends in various extents of butane, propane, Isobutane and HFC-134a in an icebox. From that they inferred that the blend R290/R600 (60/40%) was gave great outcome in terms of power utilization. Dalkilic [7] led a hypothetical examination on refrigerator utilizing different elective refrigerants and refrigerant blends as option to R12 and R22. From that hypothetical investigation they reasoned that R134a, R152a, R32, HC290, HC1270, HC600 and HC600a can be utilized as an option in contrast to the above refrigerants. M El-Morsi et.al [8] performed a theoretical analysis of a VCR system using pure natural refrigerants as a substitute to HFC-134a and results revealed that LPG gives a lower COP and Isobutane gives a higher COP than that of HFC-134a by 11% and 5% respectively. M Rasti et.al. [9] using R436a (mixture of 46% iso-butane and 54% propane) and R600a as replacement of R134a in domestic refrigerator showed the results that the energy consumption of R436a and R600a in comparison to R134a at the optimum charges were reduced about 14% and 7%, respectively. Makhnatch et.al. [10] Examined the performance of R450A which is a mixture of R134a/R1234ze (E) (42:58% by mass) as a substitute to HFC-134a in household refrigerators. It has been revealed that the Refrigerating effect and COP of refrigerant mixture were approximately 10% and 3% lower than HFC-134a. At the same time the outlet temperature of compressor is lower than HFC-134a. Z.Meng et al. [11] have done thermodynamic investigation for HFO-1234ze (E), R152a and HFO-1234ze (E)/R152a blends as direct substitute to HFC-134a in a refrigerator system without making any modifications to the system. Sanchez et al. [12] led an experiments with low GWP refrigerants like HFO-1234yf, 1234ze (E), R290, R152a and HC-600a in refrigeration system and experimental results were compared with HFC-134a. From those experiments, they came to conclusion that HFO-1234yf and R152a have a very good substitute to HFC-134a. Hasheer and Srinivas [13] conducted a theoretical investigation on low GWP refrigerants as a direct substitute to R134a in a domestic refrigerator and conclude that R1234yf can be used as a direct substitute to R134a. Kapilan et.al [14] performed a CFD analysis is used to analyse the evaporative cooling system in a refrigerator and air-conditioning system. KABÁT Juraj et.al [15] performed an experiment on heating, ventilation and air conditioning systems and conclude that the onset of stable oscillations of the working fluid heavily increases the heat transfer performance compared to the empty heat exchanger. so heat exchanger also plays an important role in improving the performance of a refrigeration system.

Many researchers have studied alternative to R134a refrigerants. However, mixtures of HC / HFC / HFO with the help of LSHX were not observed in the existing references. The main intention of this article is to improve the performance of the refrigerator by using the low GWP refrigerant mixtures.

2 Environmental impact of Alternative refrigerant mixtures

GWP value of the refrigerant mixtures can be calculated as follows:

$$\text{GWP}_{\text{mixture}} = \text{GWP}_p \times W_p + \text{GWP}_q \times W_q + \text{GWP}_r \times W_r \quad (1)$$

where GWP_p = GWP value of refrigerants p, GWP_q = GWP value of refrigerant q, GWP_r = GWP value of refrigerant r respectively; W_p , W_q and W_r are to be mass fraction of refrigerants p, q and r.

2.1 Thermo-physical and Environmental properties of the Refrigerant

The thermodynamic properties of an alternative refrigerants such as saturated vapour pressure, latent heat, density of liquid and vapour, viscosity (Vapour and liquid) & liquid and vapour thermal conductivity of AC5, ze+152A-50+50, R290/600 (in the ratio of 40/60, 60/40, 50/50), ARM42, ARM42a and R134a for wide range of temperatures (between -30°C and 60°C) are depicted in Figures 2.1 to 2.8. REFPROP 9.1 is used to calculate the properties of a refrigerant mixtures.

Fig. 1 Saturated vapour pressure (MPa) vs. Temperature ($^{\circ}\text{C}$)

Fig. 2 Latent heat (KJ/Kg) vs. Temperature ($^{\circ}\text{C}$)

Fig. 1 depicts the variation of saturated vapour pressure of AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50, ARM42, ARM42a and HFC-134a with temperature. It was obtained that ARM42, ARM42a saturated vapour pressure values higher than that of R134a and for AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50 saturated vapour pressure values lower than that of R134a at a range of temperatures between -30°C and 60°C . Hence, the compressor should run relatively at higher pressure to compensate this change of pressures.

Fig. 3 Liquid density (Kg/m^3) vs. Temperature ($^{\circ}\text{C}$)

Fig. 4 Vapour density (Kg/m^3) vs. Temperature ($^{\circ}\text{C}$)

Latent heat of five selected refrigerants versus temperature is depicted in Fig.2. It was obtained that latent heat of R1234yf ARM42, ARM42a were lower than that of R134a and AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50 were higher than that of R134a at a range of temperatures between -30°C and 60°C . Higher latent heat shows an increase in cooling capacity of the system, which reduces the running time of a compressor.

Fig.3 and Fig. 4 represent the variation of liquid and vapour densities with temperature. At a range of temperatures between -30°C to 60°C , the liquid density of all AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50, ARM42, ARM42a refrigerants were found to be lower than that of HFC-134a, which results in decrease the refrigerant charge requirement. The vapour density of AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50 were lower than that of R134a and ARM42, ARM42a were averagely higher when comparing with R132a. When vapour density increases, gas velocity decreased and shear force between vapour and liquid, which improve the heat transfer and decrease pressure drop in condenser and evaporator.

Fig. 5 Liquid viscosity (uPa.s) vs. Temperature ($^{\circ}\text{C}$)

Fig. 6 Vapour viscosity (uPa.s) vs. Temperature ($^{\circ}\text{C}$)

Fig. 7 Liquid thermal conductivity (mW/m.K) vs. Temperature ($^{\circ}\text{C}$)

Fig. 8 Vapour thermal conductivity (mW/m.K) vs. Temperature ($^{\circ}\text{C}$)

The liquid and vapour viscosity of all selected refrigerants are compared in the above Fig.5 and Fig.6. It was obtained that liquid viscosity of all AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50, ARM42, ARM42a were found to be lower than that of R134a, and AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50 were lower & ARM42, ARM42a were higher vapour viscosity. While viscosity is higher, result in high friction and pressure drop in evaporator and condenser.

The liquid and vapour thermal conductivity of all selected refrigerants are compared in Fig.7 and Fig.8. It was obtained that liquid thermal conductivity of ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50, were higher than that of R134a, and AC5, ARM42, ARM42a were lower than that of R134a. And all AC5, ze+152A-50+50, R290/600-40/60, R290/600-60/40, R290/600-50/50, ARM42, ARM42a refrigerants were higher vapour thermal conductivity than R134a, which result in better evaporator and condenser efficiency.

3. Thermodynamic analysis of an alternative refrigerants

The thermodynamic analysis of AC5, R440A and R430A as a direct substitute to HFC-134a in a refrigeration system by varying the working conditions, i.e. when changing the temperature of the evaporator from -20 to 10°C at different condenser temperatures. The entire analysis has been carried out by using an internal heat exchanger.

Fig. 9 Pressure-enthalpy diagram of a refrigerator with LSHX.

Calculations:

Data (from the literature review) used for analysis are given below.

1. Considering pressure drops in both evaporator, condenser.
2. Isentropic efficiency (η_{is}) and volumetric efficiency (η_{vol}) are 0.75 and 0.8 respectively.
3. Compressor displacement volume (V_{dis}) is 8.16 cm³/rev and a speed is 1800 r/min.
4. Superheating & sub cooling temperatures were 5K at all working conditions.

Temperatures of the condenser: 30 °C, 40 °C and 50 °C.

Temperatures of the evaporator: -25 °C to 15 °C.

Evaporator pressure losses: 0.03MPa.

Condenser pressure losses: 0.02MPa.

Pressure-enthalpy diagram with heat exchanger as shown in above Fig.9. At entry to the compressor refrigerant is in superheated condition and pressure losses are considered while it passes through the evaporator and condenser and are represented in Figure 3.1. REFPROP9.1 software is used to calculate the properties at each state, which is very accurate software for calculating properties.

The pressure ratio can be expressed as:

$$\text{Pressure ratio} = P_{\text{condenser}} / P_{\text{evaporator_act}} \quad (2)$$

The formulae for energy consumption is given by:

$$W_{\text{compr}} = h_2 - h_1 \quad (3)$$

$$\text{where } h_2 = h_1 + (h_{2s} - h_1) / \eta_{is} \quad (4)$$

The formulae for refrigeration effect is given by,

$$\text{Cooling capacity} = h_6 - h_5 \quad (5)$$

COP of the refrigerator can be stated as:

$$\text{COP} = \text{Refrigerating effect} / \text{work done by the compressor} \quad (6)$$

The formulae for VCC (Volumetric Cooling Capacity) is given below:

$$Q_{\text{vol}} = (h_6 - h_5) \times \eta_{\text{vol}} / v_1 \quad (7)$$

where v_1 be the specific volume at entry to the compressor.

Mass flow rate of a refrigerant (m_r) is given by

$$m_r = \text{RPM} \times V_{\text{sv}} \times \rho_1 \times \eta_{\text{vol}} / 60 \quad (8)$$

where compressor speed is expressed as RPM, V_{sv} is swept volume of a compressor, refrigerant density at compressor entry can be designated as ρ_1 .

4. Results and Discussion

4.1 Variation of mass flow rate of alternative refrigerants

Fig. 10 shows the mass flow rate of nine refrigerants versus evaporator temperature is shown in. Mass flow rate is directly proportional to vapor density. Mass flow rate changes with change in evaporator temperature and do not vary with condenser temperature. For AC5 mass flow rate is lower than R134a by 10.59% within evaporator temperature range of -25C to 15C respectively. For R440a mass flow rate is lower than HFC-134a by 41.18% within evaporator temperature range of -25C to 15C respectively. For R430a mass flow rate is lower than R134a by 35.75% to 40% due to its lower liquid density. Hence a lower energy consumption can be expected with this refrigerant. For ze+152A mass flow rate is lower than HFC-134a by 27.39% at an evaporator temperature range of -25C to 15C due to lower vapor density. For R290/600-40/60 mass flow rate is lower than HFC-134a by 60.50% within evaporator temperature range of -25C to 15C respectively. For R290/600-60/40 mass flow rate is lower than R134a by 53.06% within evaporator temperature range of -25C to 15C respectively. For R290/600-50/50 mass flow rate is lower than HFC-134a by 57.08% within evaporator temperature range of -25C to 15C respectively. Hence, all the above alternative refrigerants shows a lower compressor power consumption. For ARM42 mass flow rate is higher than R134a by 18.08% within evaporator temperature range of -25C to 15C respectively. For ARM42a mass flow rate is higher than R134a by 20.51% within evaporator temperature range of -25C to 15C respectively. It was observed from above results that refrigerant ARM42 and ARM42a is showing positive increases in mass flow rate over other refrigerants when compared with R134a. Hence, lower compressor power can be expected with this refrigerants. Mass flow rate is directly proportional to refrigerant effect produced, so ARM42a refrigerant will give you more refrigerant effect than R134a at given conditions with less damage to environment.

Fig. 10 Refrigerant mass flow rate vs. Evaporator Temperature

Note: For the following results (4.2 to 4.6) the below image defines various refrigerants in the graphs at three different compressor temperatures.

4.2 Pressure ratio variation

The pressure ratio of nine refrigerants versus evaporator temperature is shown in Fig.11. It is a ratio of higher pressure to lower pressure in VCR (vapor compression system). Pressure ratio is directly proportional to condenser temperature and inversely proportional to evaporator temperature. At 30C, 40C and 50C of condenser temperatures AC5 pressure ratio is higher than R134a by 1.12%, 1.48% and 1.88% respectively. At 30C, 40C and 50C of condenser temperatures R440A pressure ratio is lower than R134a by about 0.95%, 1.08%, and 1.19%. Pressure ratio of R430A is lower than R134a by about 5.52-8.5%, 6.65-9.8% and 7.65-11% respectively at condenser temperatures 30C, 40C and 50C. At 30C, 40C and 50C of condenser temperatures pressure ratio of R1234ze(E)/152A(50:50 by mass) lower than R134a by 0.97%, 1.13% and 1.27%. The pressure ratio of R290/600a(40/60), R290/600(60/40), R290/600(50/50) were lower than that of R134a by about 5.88-8.15%, 8.4-11.58%, 7-9.87% respectively, at condenser temperatures 30C, 40C and 50C. However, ARM42, ARM42a with pressure ratio more than that of R134a by about 7.02-9.54%, 7.21-9.49%, respectively, at a condenser temperatures of 30, 40 and 50C. Pressure ratio is the key factor that influences volumetric efficiency of a compressor and is inversely proportional to volumetric efficiency, so from above results we observed that R440A, R430A,

R1234ze(E)/152A(50:50 by mass), R290/600a(40/60), R290/600(60/40), R290/600(50/50) has percentage drop in pressure ratio when compared to R134a, from this we can observe that more volumetric efficiency is produced when these are replaced with R134a. The lowest volumetric efficiency that can be obtained with HFC-134a is 0.75. Hence in this work the volumetric efficiency of the compressor can be considered as 0.75.

Fig. 11 Pressure ratio vs. Evaporator temperature ($^{\circ}\text{C}$)

Fig. 12 VCC vs. Evaporator temperature

4.3 Variation of volumetric cooling capacity

Fig. 12 depicts the VCC of alternative refrigerants versus evaporator temperature. It was obtained that the average volumetric cooling capacity of R440A, R430A, R1234ze(E)/152A(50:50 by mass), AC5, R290/600a(40/60), R290/600(60/40) and R290/600(50/50) were lower than that of R134a by about 6.2%, 1.07%, 7.89%, 10.5%, 27.2%, 20.2% and 26.8% respectively, however, ARM42, ARM42a shows a higher vcc by around 5.8%, 4.5%, as compared to R134a at condenser temperature 30°C , 40°C and 50°C . The volumetric capacity of cooling is a main factor for alternative refrigerants, which affect the size of the compressor. The volumetric cooling capacity of the alternative refrigerants should be controlled between -8% and 8% compared to the original refrigerant. R440A, R430A, R1234ze(E)/152a (50:50 by mass), ARM42a, ARM42a can be used as a direct replacement to R134a without any modifications to the compressor, however, AC5, R290/600a (40/60), R290/600(60/40) and R290/600(50/50) are not suitable due to the lower VCC, which influence the compressor performance.

4.4 Variation of compressor power and cooling capacity:

The average compressor power consumption of refrigerants AC5, R440A, R430A, R1234ze(E)/152A(50:50 by mass), R290/600-40/60, R290/600-60/40 and R290/600-50/50 is lower than that of R134a by about 4%, 6.5%, 1.4%, 10.7%, 24%, 7.6% and 16.4% respectively, and ARM42, ARM42a has 6.8%, 10% higher compressor power consumption than R134a taken average at condenser temperatures 30°C , 40°C & 50°C . The energy consumption of the vapour compression system increases with the evaporator temperature due to an increase in the mass flow rate and increases with the condenser temperature due to an increase in the enthalpy difference between the compressor inlet and outlet. AC5 is the lowest power consumption refrigerant in all refrigerants at both condenser temperatures & ARM42a is the highest power consuming refrigerant. It is obtained that the cooling capacity of refrigerants AC5, R440A, R430A, R1234ze(E)/152A(50:50 by mass), R290/600a (40/60), R290/600(60/40) and R290/600(50/50) is lower than that of R134a by about 10.2%, 4%, 0.1%, 9.1%, 27%, 12.3% and 20.2% respectively, and ARM42, ARM42a has 4.7%, 3%

higher as compared with R134a cooling capacity, taken average at the condenser temperature 30°C, 40°C & 50°C respectively.

Fig. 13 Power consumption of a blower versus Evaporator temperature

Fig. 14 cooling capacity vs. Evaporator temperature

4.5 Variation of COP

The COP of refrigerants versus evaporator temperature is shown in Fig.15. It was obtained that the average COP of R440, R430a, R1234ze (E)/152a (50:50 by mass) were averagely higher than that of R134a by about 1.39%, 0.82% and 1.10% respectively at condenser temperature 30C, higher than that of HFC-134a by about 2.58%, 1.35% and 1.61% respectively at condenser temperature 40C and higher than that of R134a by about 4.42%, 2.24% and 2.55% respectively at condenser temperature 50C. It was obtained that the average COP of AC5, R290/600a(40/60), R290/600(60/40) and R290/600(50/50), ARM42, ARM42a were averagely lower than that of R134a by about 5.98%, 3.94%, 4.95%, 4.64%, 1.57%, 5.46% respectively at condenser temperature 30C, lower than that of R134a by about 6.38%, 3.82%, 4.98%, 4.52%, 2.73%, 5.21% respectively at condenser temperature 40C and lower than that of R134a by about 6.85%, 3.56%, 4.89%, 4.34%, 4.21%, 6.19% respectively at condenser temperature 50C. This is mainly due to the relatively higher and lower compressor power consumption, respectively. The COP of most refrigerants compared to R134a increases with increasing condenser temperature, so we can expect better COPs at higher condenser temperatures with R430a, R440a, R1234ze (E) / 152A (mass 50:50), AC5, ARM42 and ARM42a. The COP shows a negative correlation with the evaporator temperature and a positive correlation with the condenser temperature.

4.6 Variation of outlet temperature of compressor:

Fig.16 represents the variation of compressor discharge temperature versus evaporator temperature. It was obtained that the average compressor discharge temperature of AC5, R440a, R430a, R1234ze(E)/152a (50:50 by mass) were averagely higher than that of R134a by about 0.25%, 3.27%, 1.12% and 0.93% respectively at condenser temperature 30C, higher than that of R134a by about 0.325%, 3.78%, 1.61% and 1.09% respectively at condenser temperature 40C and higher than that of R134a by about 0.40%, 4.15%, 1.39% and 1.21% respectively at condenser temperature 50C. The discharge temperature of the AC5, R440a, R430a, R1234ze (E) / 152a (50:50 mass) compressor was higher than that of R134a due to condenser and evaporator temperatures due to its higher specific heat ratio and this affects the motor coil and the lubricant properties, which affect the life of the compressor. It was obtained that the average compressor discharge temperature of R290/600a(40/60), R290/600(60/40), R290/600(50/50), ARM42 and ARM42a were averagely lower than that of R134a by about 0.83%, 0.35%, 0.57%, 1.67%, 1.88% respectively at condenser temperature 30C, lower than that of R134a by about 1.04%, 0.45%, 0.73%, 1.90%, and 2.15% respectively

at condenser temperature 40C and lower than that of R134a by about 1.22%, 0.54%, 0.86%, 2.05% and 2.33% respectively at condenser temperature 50C. It is confirmed that the refrigerants indicated above are the best replacement for R134a due to the relatively close discharge temperature of the compressor.

Fig. 15 COP vs. Evaporator temperature (°C)

Fig. 16 Compressor outlet temperature (K) vs. Evaporator temperature (°C)

CONCLUSION

1. R1234ze (E) / 152A (50:50 mass) was selected as the best direct substitution R134a. Because the refrigerant has a very low GWP value around 72, which is environmentally friendly using the vapour compression system. The volumetric cooling capacity of R1234ze (E) / 152A (mass 50:50) was similar to that of R134a. Therefore, R1234ze (E) / 152A (mass 50:50) can be used as a direct replacement for R134a without modification of the compressor. Energy consumption is also less than R134a. It can be used as a direct substitute without changes in the system.

2. R440A, R430A has a low GWP values as compared to HFC134a. VCC of R430A was found to be closer with R134a. Hence, these refrigerants can be used in refrigerators without any modifications to original system. The COP is also high as compared with R134a. The blower discharge temperature of the refrigerator working with these refrigerants are somewhat higher than that of R134a, which may marginally influence the compressor life.

3. ARM42 and ARM42a have better COP execution and volumetric cooling limit than R134a, which makes it the best substitute to R134a, which make it the best replacement of R134a. ARM42, ARM42a refrigerants which were mixtures have higher COP's and lower compressor power consumption as compared with R134a. This can also be used as direct substitute to domestic refrigerator.

4. R290 / 600a (40/60), R290 / 600 (60/40), R290 / 600 (50/50) show a strong reduction in VCC and also in energy consumption. Among three refrigerants R290/600(60/40) shows a favorable conditions. Therefore, a compressor of greater displacement is needed to produce the same cooling as that of R134a. These are not reasonable for direct drop in the substitution of R134a.

5. AC5 has also slightly reduced energy consumption, volumetric cooling capacity and cooling capacity. This is also not useful for direct replacement of R134a, but can be used as a substitute for R134a by modifying the compressor.

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