Performance analysis of alternative low GWP refrigerant mixtures as a direct substitute of HFC-134a in a Domestic Refrigerator using LSHX

Mohammad Hasheer SK, Kolla Srinivas

Abstract: The main objective of this article is to investigate R290, R600a and three mixtures R1, R2 and R3 composed of R290 and R600a (in the ratio of 40:60, 60:40, and 50:50 by mass, respectively) as direct substitute to HFC-R134a in a domestic refrigerator were analyzed theoretically. At the same time performance improvement of domestic refrigerator was observed with the help of a liquid-suction heat exchanger (LSHX). The performance of the refrigerator was compared in terms of blower discharge temperature, coefficient of performance, refrigeration capacity, and energy consumption of a blower. The results are revealed that R2 had a better results in terms of COP as well as nearly equal cooling capacity as compared to HFC-134a. Compressor outlet temperature of R2 was lower than that of HFC-134a by about 1.33 to 0.70C.At the same time there is an improvement in the performance of a domestic refrigerator using LSHX. It was concluded that R2 can be used as a direct substitute to HFC-134a in refrigerator without doing any modifications.

Index Terms: Domestic Refrigerator, GWP, R600a, R290, HFC-134a.

I. INTRODUCTION

In the last 30 years, chlorofluorocarbons and hydro fluorocarbons are widely used in refrigerators and air conditioners. But ODP and GWP values are very high for these refrigerants, which causes environmental pollution. Due to this higher ODP value, they are prohibited in refrigeration and air conditioning sector accordance to Montreal protocol. So in place 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 based on the Kyoto Protocol. R134a has to be phased out by 2021. Most of the developing countries are drastically reducing their HFC production and consumption. Therefore, there is a greater demand for an adequate replacement for HFC-134a for the possible adaptation of existing systems as well as for new systems. HC (Hydrocarbons) are natural refrigerants. These are having a very low GWP and outstanding properties in terms of efficiency and refrigerating effect. But the main problem with these refrigerants are these are highly flammable refrigerants (A3) according to the ASHRAE. Therefore, special safety considerations must be taken into account during the assembly, the filling of the refrigerant.

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II. IMPACT ON ENVIRONMENT

The alternative refrigerants requires not only protect the ozone layer at the same time it requires a lower GWP value. The low GWP refrigerants R290, R600a and mixtures of R290/R600a were proposed in this document considered as substitutes for HFC-134a. The value of GWP for R600a and R290 is 11.

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

$$GWPmixture = GWPp \times Wp + GWPq \times Wq \qquad (1)$$

Where GWPp is the GWP value of refrigerants p, GWPq is the GWP value of refrigerant q respectively; Wp, Wq are the mass fraction of refrigerant p and q.

A. Effect on Environment:

Refrigerant	R290	R600a	R1	R2	R3	R134a
ODP	0	0	0	0	0	0
GWP	11	11	11	11	11	1430

GWP: Global warming potential ODP: Ozone depletion potential Kim et al. in 1999, conducted an experiment with R600a, which is an alternative to the R12 in a domestic refrigerator. They analyzed theoretically with the help of a software REFPROP, and then performed a series of tests with this refrigerant [1]. Jung et al. [2000] performed an experiment with mixture of R290 / R600a (in the ratio of 60:40 by mass) as a direct substitute to R12 in a refrigerator and they concluded that COP and power efficiency improve by 2.4 and 3.9% respectively [2]. Tashtoush et al. in 2002, conducted an experiment on the domestic refrigerators with hydroflourocarbons/hydrocarbon mixtures as a substitute to R12. From the experimental results they concluded that the mixtures gives an excellent performance as compared to HFC-134a [3]. Lee et al. Conducted an experiment and tested iso-butane in the domestic refrigerator. 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. This study focused only on the performance of a domestic refrigerator with R600a [4].

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Garland in 2005 studied the environmental impact of the R600a hydrocarbon refrigerant installed in the hermetic compressor of the domestic 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 15-year cycle [5]. Wongwises and Chimres (2005) analyzed various blends in various extents of propane, butane, 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 [6]. Dalkilic (2010) 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 HFC134a, HFC152a, HFC32, HC290, HC1270, HC600 and HC600a can be utilized as an option in contrast to the above refrigerants [7]. Mohan raj et al. (2009) directed an investigation on fridge by utilizing an alternate blends of hydrocarbons R290 and R600 (in the proportion of 45.2/54.8%) with various mass charges and results are Compared with HFC-134a,the mixture reduces the power consumption of the blower, exit temperature of the blower and increases the COP by up to 3.6% [8]. Similar experiments were accompanied by He et al. (2014) with R290 and a blend of R290/R600a and Yu et al. (2014) with two different mixtures of R290/R600a and HC-600a [9].M. Rasti1, M.S. Hatamipour et al. (2011) done experiment on investigation of R436a and R600a to replace HFC-134a in fridge and cooler. They presented R600a and R436a that have an ODP esteem zero and lower GWP esteem than HFC-134a in the refrigeration arrangement of a single-evaporator refrigerator-freezer that one actually manufactured for R134a as a test object. They presumed that, contrasted with R134a, the measure of hydrocarbon blend charge is lessened by 52% for R600a and 48% for R436a and compressor work is reduced by 5.3% in 24 hours for R600a and R436a.Finally they decided that from their results and environmental effects of R600a and R436a, they could be regarded as a good substitute for R134a [10]. Gaurav et al. (2012) completed an audit on potential choices for R134a. From the literature, they arrived at resolution that the refrigerants R413A (blend of 9% of R218, 88% of HFC134a, 3% of HC600a), R290/HC600a (68/32% by weight), HC600a/R290 (60/40% by weight) and R290/R123 (3/7 blend), R152a, R125 and R32 are perceived as substitutes for HFC134a. And even more, they added that there is a need to compare alternative refrigerants with the flammability, toxicity and the thermodynamic point of view to discover the best substitute to HFC-134a [11]. Bukola Olalekan Bolaji et al. (2014) made a presentation correlation of low GWP refrigerants like R152a and HC600 hypothetically which are option to HFC134a in a refrigerator. By watching these outcomes they presumed that R152a demonstrates a higher volumetriccooling limit (VCC) and co-efficient of performance when contrasted with HFC-134a. The mean values of COPs accomplished for HC-600a and HC-152a were 6% lower and 12.9% higher than that of HFC-134a. They reasoned that HFC-152a demonstrates a best outcomes as compared with R134a [12]. Zhaofeng Meng et al. (2016) have done thermodynamic examination for HFO-1234ze (E), R152a and HFO-1234ze (E)/R152a mixes as immediate substitute to HFC-134a in a refrigeration framework without making any alterations to the framework [13]. Sanchez et al. (2017) drove an investigations with low GWP refrigerants like HFO-1234yf, 1234ze (E), R290, R152a and HC-600a in refrigeration framework and trial results were contrasted and HFC-134a. From that tests, they arrived at resolution that HFO-1234yf and R152a have a generally excellent substitute to HFC-134a [14].

III. THERMODYNAMIC ANALYSIS OF AN ALTERNATIVE REFRIGERANTS

The main aim of this present study is the thermodynamic analysis of R290, R600a and three mixtures R1, R2 and R3 as a direct substitute to HFC-134a in a refrigeration system by varying the working conditions, i.e. at different condenser temperatures when changing the temperature of the evaporator from -25 to 15°C.The entire analysis has been carried out by using an internal heat exchanger.

Calculations:

Data (from the literature review) used for analysis are given below. The results are plotted as shown in Figures 2.1 to 2.6.

1. Temperatures of the condenser: 30^0C, 40C and 50^0C
2. Temperatures of the evaporator: -25C to 15C
3. Evaporator pressure losses: 0.03MPa
4. Condenser pressure losses: 0.02MPa
5. Isentropic efficiency of a blower: 0.72
6. Volumetric efficiency : 0.8
7. Swept volume: 8.16cm3/rev
8. Blower Speed: 1800rev/min
9. Heat exchanger efficiency (effectiveness): 0.65.

The pressure-enthalpy diagram with heat exchanger as shown in below fig.1. The loss of pressures in the evaporator and condenser are as shown in below figure. At inlet of the blower, the refrigerant is superheated vapour. The properties of a refrigerant at each condition of the cycle are determined with the assistance of REFPROP9.1 programming software, REFPROP is an exceptionally precise programming software for ascertaining the properties of a refrigerants.

Performance characteristics such as pressure ratio, COP, Exit temperature of blower, Refrigeration effect and blower power consumption are the main parameters to accept a direct substitute to domestic refrigerator.

The pressure ratio of the system can be expressed as follows:

$$\text{Pressure ratio} = P_{cond} / P_{evap\_act} \quad (2)$$

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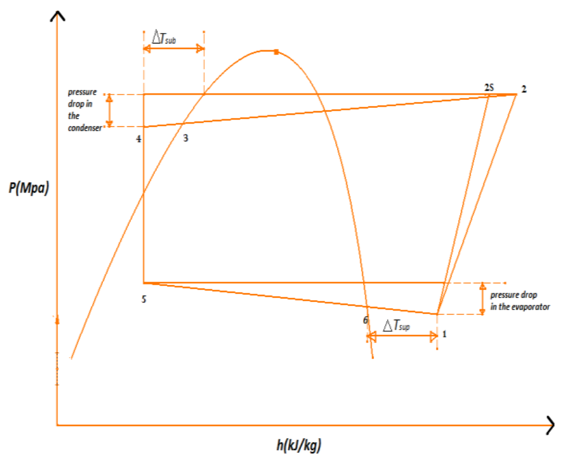

Fig.1.Pressure-enthalpy diagram of a refrigerator with LSHX

Blower work is stated from the Fig. 1 as follows:

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

Where $h_2 = h_1 + (h_{2s} - h_1) / \eta is$ (4)

The Cooling Capacity is obtained from the below formula.

$$Coolingcapacity = QC = h_6 - h_5 \quad (5)$$

The coefficient of performance (COP) of the refrigerator can be expressed as:

COP = Cooling capacity /work done by the blower (6)

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

$$Qvol = (h_6 - h_5) \times \eta vol / v1 \quad (7)$$

Where v1 be the specific volume at compressor inlet.

The refrigerant mass flow rate (Mr) can be obtained from the below formula.

$$Mr = RPM \times Vs \times \rho_1 \times \eta vol/60 \quad (8)$$

Where RPM is the compressor speed, Vs. is swept volume of a compressor, density of the refrigerant at entry to the compressor can be designated as ρ_1.

IV. RESULTS AND DISCUSSION

Variation of mass flow rate of refrigerants:

The mass flow rate of alternative refrigerants versus evaporator temperature is shown in Figure 2.1. Mass flow rate is the refrigerant mass which passes per unit time. It is directly proportional to vapour density. Mass flow rate changes with change in evaporator temperature and do not vary with condenser temperature. For R1 mass flow rate is lower than R134a by 60.5% within evaporator temperature range of -25C to 15C respectively. For R2 mass flow rate is lower than HFC-134a by 53.06% within evaporator temperature range of -25C to 15C respectively. For R3 mass flow rate is lower than HFC-134a by 57.08% within evaporator temperature range of -25C to 15C respectively. For R600A mass flow rate is lower than HFC-134a by 70.18% within evaporator temperature range of -250C to 150C respectively. For 290a mass flow rate is lower than HFC-134a by 24.88% within evaporator temperature range of -25C to 15C respectively. It was observed from above results that refrigerant R290a is better over other refrigerants. Mass flow rate is directly proportional to refrigerant effect produced, so R290a refrigerant will give you more refrigerant effect than other refrigerants.

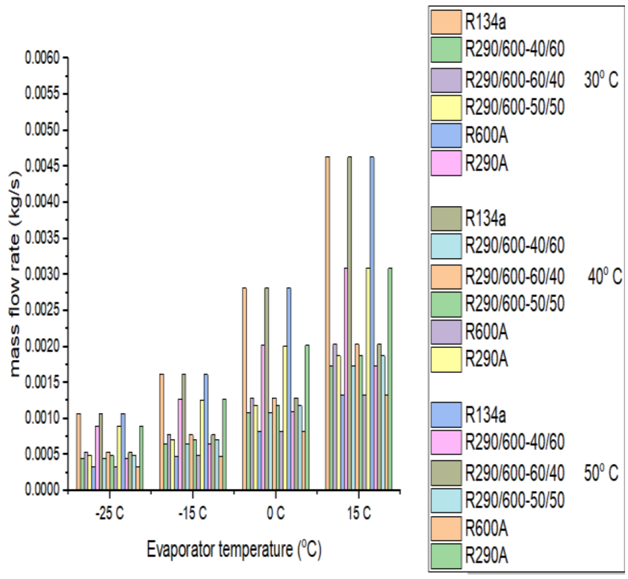

Fig. 2.1 Mass flow rate vs. Evaporator Temperature

Pressure ratio variations:

The pressure ratio of alternative refrigerants versus evaporator temperature is depicted in Figure 2.2. It is a ratio of condenser pressure to evaporator pressure in vapour compression system. At 30C, 40C and 50C of condenser temperature R1 pressure ratio is lower than R134a by 5.8%, 7.07% and 8.15% within evaporator temperature range of -25C to 15C respectively. At 30C, 40C and 50C of condenser temperature R2 pressure ratio is lower than R134a by 8.4%, 10.08% and 11.58% within evaporator temperature range of -25C to 15C respectively. At 30C, 40C and 50C of condenser temperature R3 pressure ratio is lower than R134a by 7.05%, 8.47% and 9.75% within evaporator temperature range of -25C and 15C respectively. At 30C, 40C and 50C of condenser temperature R600a pressure ratio is lower than R134a by 2.59%, 3.14% and 3.67% within evaporator temperature range of -25C and 15C respectively. At 30C, 40C and 50C of condenser temperature R290a pressure ratio is lower than R134a by 17.01%, 20.21% and 23% within evaporator temperature range of -25C and 15C respectively. volumetric efficiency of a refrigerator compressor is effected by pressure ratio and is inversely proportional to compressor volumetric efficiency, so from above results we observed that R1, R2, R3 and R290a has some percentage drop in pressure ratio when compared to R134a. So we can expect very good volumetric efficiency with these refrigerants.

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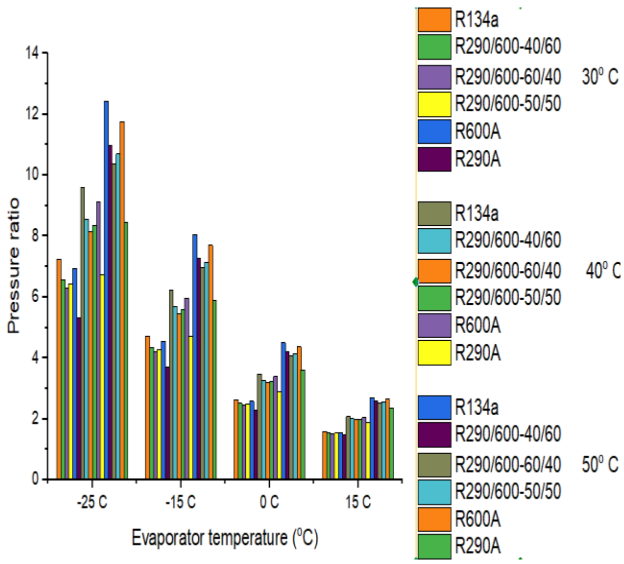

Fig. 2.2 Pressure ratio vs. Evaporator temperature (C)

Deviation of power consumption of a blower and refrigerator cooling capacity:

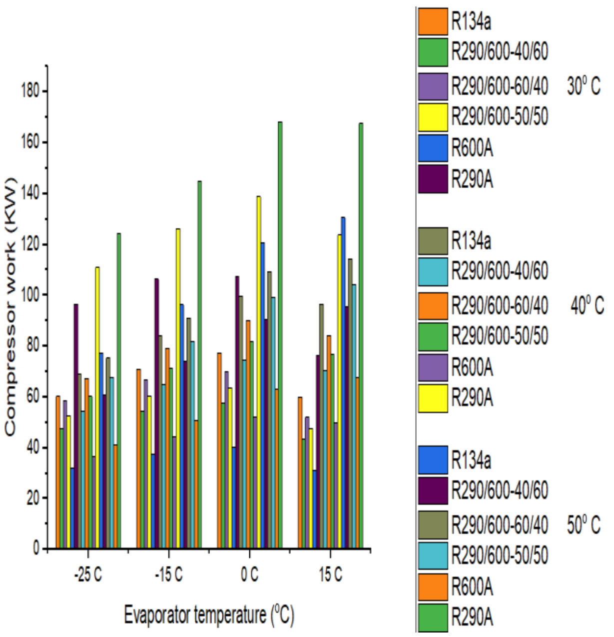

Fig. 2.3 Power consumption of a blower versus Evaporator temperature

The variation of power consumption of a blower and refrigerator cooling capacity versus evaporator temperature as shown in figures 2.3 &2.4.The average blower power consumption refrigerants R1, R2 R3 and R600a was lower than that of R134a by about 24.1%, 7.6%, 16.4%, 47.5%, respectively, and R290a has 44.2% higher blower power consumption nearly at condenser temperatures 30°C, 40°C & 50°C. Power consumption of a compressor of refrigeration system increases with evaporator temperature due to an increase in mass flow rate as well as increases with the condenser temperature because of an increase in enthalpy difference between outlet and inlet of blower. R600a is the lowest power consumption refrigerant in all refrigerants at both condenser temperatures & R290a is the highest power consuming refrigerant. It is obtained that the cooling capacity of refrigerants R1, R2 and R3 & R600a are 26.9%, 12.2%, 20.19% & 46% lower than R134a, but R290a is 42.3% nearly higher than R134a Cooling capacity at the condenser temperatures 30°C, 40°C & 50°C respectively.

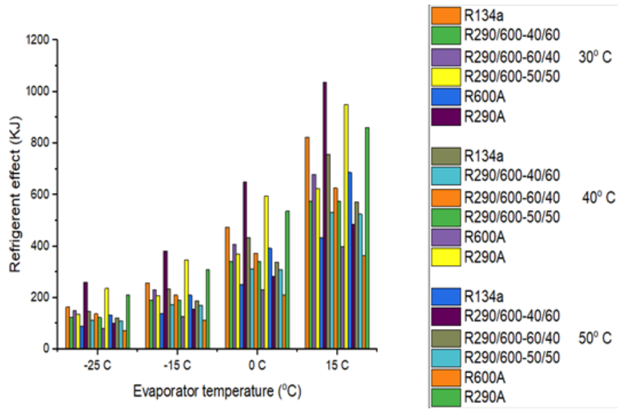

Fig. 2.4 cooling capacity vs. Evaporator temperature

Variation of COP:

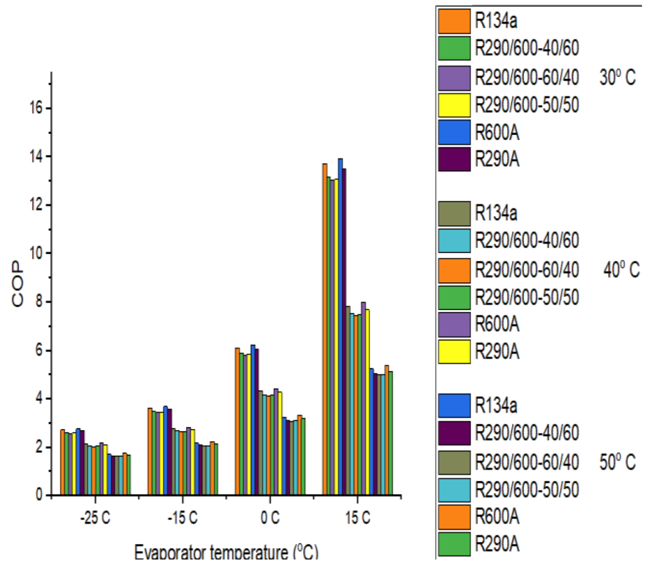

Fig. 2.5 COP vs. Evaporator temperature

Figure 2.5 represents the variation of COP of alternative refrigerants versus evaporator temperature. It was obtained that the average COP of R1, R2, R3 and R290a, were lower than that of HFC-134a by approximately 3.7%, 4.9%, 4.5% & 1.4%. R600a higher than that of R134a by about 2.17% at the condenser temperatures 30°C, 40°C & 50°C respectively.

Variation of blower outlet temperature:

The blower outlet temperature of alternative refrigerants versus evaporator temperature is depicted in the above Figure 2.6. It was obtained that blower outlet temperature of R1, R2, R3 and R600a was lower than that of HFC-134a by approximately 3.72 to 1.36C, 1.33 to 0.7C, 2.4 to 1.01C & 10.14 to 3C, at condenser temperature 30C respectively 4.35 to 2.29C, 1.61 to 1.18C, 2.89 to 1.72C & 11.6 to 5.1C, respectively at condenser temperatures 40C and 4.84 to 3.23C, 1.8 to 1.69C, 3.22 to 2.4C & 13 to 6.9C respectively at condenser temperatures 50C.

R290a have nearly same outlet temperature as

HFC-134a at condenser temperatures 30°C, 40°C & 50°C. The compressor outlet temperature of R290a is higher than that of R134a.The higher outlet temperature affects the motor coil and also affect the properties of a lubricant oil which influence the life of a compressor.

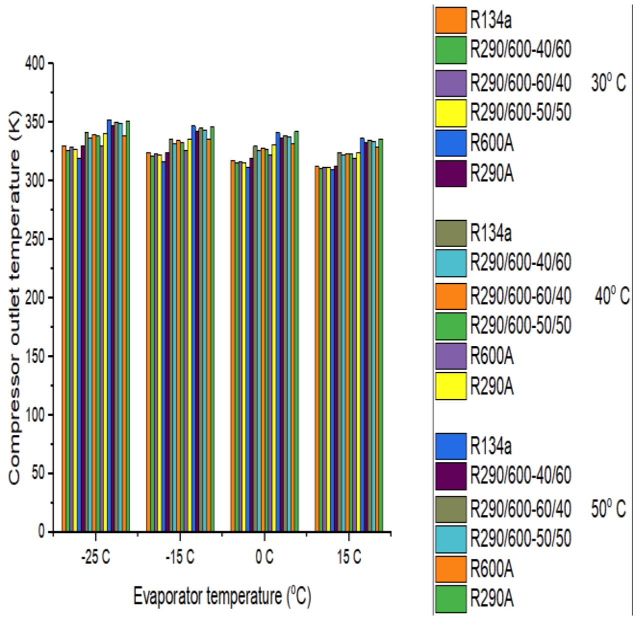

Fig. 2.6 Compressor outlet temperature vs. Evaporator temperature

V. CONCLUSIONS

R290 shows a very encouraging conditions in terms of Refrigerating effect and COP. However, its energy consumption exceeds R134a by approximately 35-51%, which have need of an electric motor bigger than R134a.Therefore, it is not suggested as an alternative to refrigerant R134a. Isobutene (R600a) had a solid drop in compressor power consumption mostly due to its high density value. With LSHX there are no improvements in its performance either. Therefore, a higher displacement compressor is needed to yield the equal cooling effect as that of HFC-134a. R600a is not suitable for direct substitute to R134a.Among R1, R2 and R3, R2 had a better COP as well as nearly equal cooling capacity as compared to HFC-134a. It was concluded that R2 can primely be an energy conservation and environmental protection alternative to HFC-134a in a domestic refrigerator.

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