Theoretical performance evaluation of R134a and its low GWP Hydrocarbon alternatives in Domestic Refrigerator

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Abstract— **As per the recommendation from Montreal Protocol to out of CFCs and HCFCs and Kyoto Protocol even new developed HFCs refrigerants like R-134a should be gradually phased out on or before 2040, due to their high global warming potentials (1430)[13].The present work is to Explore performance evaluation of most promising drop-in replacements of R134a in domestic refrigerator with Zero ODP and low GWP hydro carbons and its blends. The assessed refrigerants are R290, R600a, R430A, R436A. Basic cycle and performance comparison of all alternative refrigerants have been calculated for standard rating cycle, most commonly used condensing and evaporating temperatures 55^{0}C and -25^{0}C respectively. The result shows that for R290 has the 8% reduce in discharge temperature and COP is increased by 2.09%, compressor power is reduce by 2.06%. R600a was having Compressor power is increased by 9.08% and COP of the system is decreased by 8.32% .For R430A 12.18% and 13.22% reduction in COP & pressure ratio respectively. For R436A COP increased by 24.59%, Also pressure ratio, compressor power, compressor out late temperature and pressure is reduced by 42.68%, 19.75%, 15.9% and 9.45% respectively. Thus R436A having comparable COP and thermodynamic properties that of R134a and can be use as drop in replacement of R134a in domestic refrigerator.**

Key Words— **Domestic refrigerator, Low GWP, Zero ODP, Drop in replacement**

I. Introduction

HCFCs (hydrochlorofluorocarbons) and CFCs (chlorofluocarbons) have been applied extensively as refrigerants in air conditioning and refrigeration systems from 1930s as a result of their outstanding safety properties. However, due to harmful impact on ozone layer, by the year 1987 at Montreal Protocol it was decided to establish requirements that initiated the worldwide phase out of CFCs. By the year 1992, the Montreal Protocol was improved to found a schedule in order to phase out the HCFCs. Moreover in 1997 at Kyoto Protocol it was expressed that concentration of greenhouse gases in the atmosphere should be established in a level which is not intensifying global warming ozone layer. Subsequently it was decided to decrease global warming by reduction of greenhouse gases emissions. [4]

As a consequence of this protocol even new developed HFCs refrigerants like R-134a should be gradually phased out due to their high global warming potentials. Hence in order to meet the global ecological goals, conventional refrigerants should be replaced by more environmental friendly and safe refrigerants in a way the energy efficiency also improved.[3]

1.1 Fluid Selection

In refrigeration and air conditioning systems selection of an appropriate working fluid is one of the most significant steps for a particular application. Low global warming potential has been inserted to the long list of desirable criteria of refrigerant's selection. In fact, environmental characteristics of refrigerants are becoming the dominant criteria provided that their thermodynamic behaviors and safeties are favorable as well.[7]

1.1.1 Environmental impact and safety aspects

Environmental effects are the main problems of common refrigerants so that non environmental friendly impacts of CFCs and later on HCFCs brought about them to be phased out despite of being stable, non-flammable and non-toxic (comparing to Sulfur Dioxide and other refrigerants used before the introduction of CFCs). Ozone depletion potential (ODP) and global warming potential (GWP) are the significant factors demonstrate the direct impact of refrigerants in case of any leakage or releasing to the surroundings. However, using low GWP refrigerants are not the only efficient way to reduce greenhouse gas emissions. In fact it is probable to choose a low GWP refrigerant but still raise total greenhouse gas emissions. When the low GWP refrigerant causes more energy use and fuel consumption actually there are larger indirect emissions. Therefore in developing the low GWP refrigerants always energy efficiency of the system must be studied and its indirect climate impacts should be considered besides its direct emissions.[8] Life cycle climate performance (LCCP) helps to consider overall potential of greenhouse gas emission of the system including materials, transportation, and operation, production, recycling, servicing and end-of-life. Furthermore, toxicity and flammability are the determining factors to select suitable refrigerant for any application. Low toxicity and flammability are the most desirable aspects in safety and health studies.[13]

1.1.2 Zero ODP and Low GWP Refrigerant

Lots of studies are being processed and new blends and refrigerants are being developed to substitute conventional refrigerants. Mainly researches have focused on three groups of refrigerants; natural refrigerants, new blends and developing new refrigerants. Natural refrigerants got out of market with coming CFCs and HCFCs but now can be reconsidered. New blends are mixture of mostly natural refrigerants, dimethyl ether (DME) and HFCs in order to combine all advantages of them and achieve the best thermodynamic result and low GWP. Lastly developing a new refrigerant is another solution to overcome the environmental problem in this study we are mainly focused on HC like R290, R600a and its blends R430a, R436a.[3][10]

Table 1: Comparing properties of different refrigerants.

Refrigerant	**Chemical composition**	**Molecular weight[g/mol]**	**Critical Temp[°C]**	**Critical pressure[MPa]**	**Normal boiling Point[°C]**	**Safety class**	**ODP**	**GWP**
R134a	CH2FCF3	102	101.1	4.059	-26	A1	0	1430
Propane(R290)	CH3-CH2-CH3	44.096	134.67	4.23	-42.09	A3	0	3
Isobutane (R600a)	CH3-CH-CH3 CH3	58.12	134.67	3.65	-11.67	A3	0	3
R-430A	R-152a/R-600a(76/24)	49.08	120.3	3.23	-27.6	A3	0	107
R-436A	R-290/R-600a(56/44)	54.65	130.1	3.39	-34.3	A3	0	<3

1.2. Characteristics of R134a and New proposed refrigerants

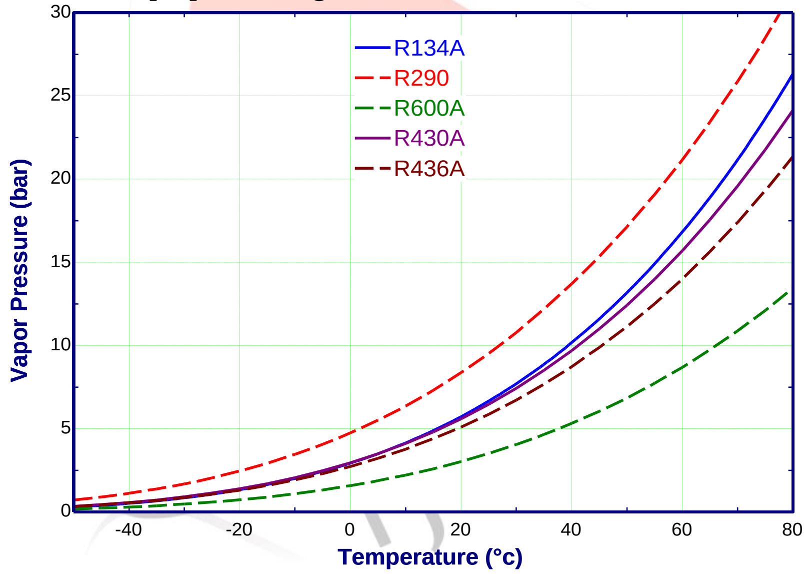

Fig.1 Variation of vapor pressure with Temperature

The properties of the refrigerants (such as vapor pressure, liquid density and liquid viscosity) for wide range of temperatures (between −50 and 60 °C) are compared in Figs. Using Rafprop 9.0 all properties can be evaluate and their comparison as shown in graphs. Fig.1 depicts the variation of vapor pressure of R134a, R290, R600a, R430A, R436A against temperature. It was observed that R430A, R436A has approximately the same vapor pressure as R134A. Hence the compressors can operate relatively at lower pressures.

The liquid densities of R134a and other alternative refrigerants are compared in Fig.2. As the liquid density is low it will significantly reduce the refrigerant charge requirement. Thus we can expect that if we will proceed with R290, R600a, R430a, R436a it requires less charging amount as compare to that of the R134a.

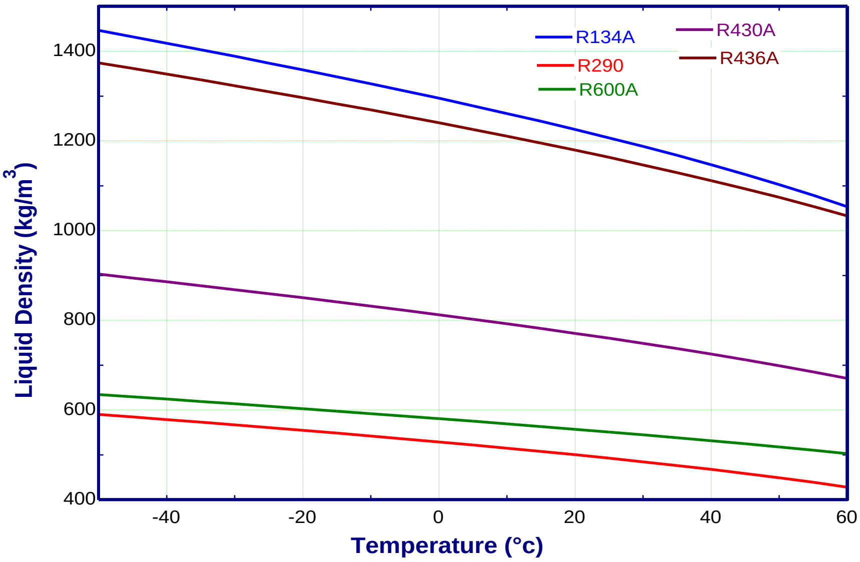

Fig.2 Variation of liquid density with Temperature

The variation of viscosity of R134a and new proposed refrigerants against temperature is illustrated in Fig.3. It was observed that liquid viscosity of R1234ze was found to be almost similar to that of R134a over the wide range of temperature results in low friction (low irreversibility). But at the same time rest of the refrigerant lower viscosity than R134a, Hence less power can be expected with R290, R600a, R436A, R430A and R1234yf. The other properties such as critical temperature, critical pressure, boiling point, molecular weight, ODP and GWP of R134a and R430A are compared in Table 1.

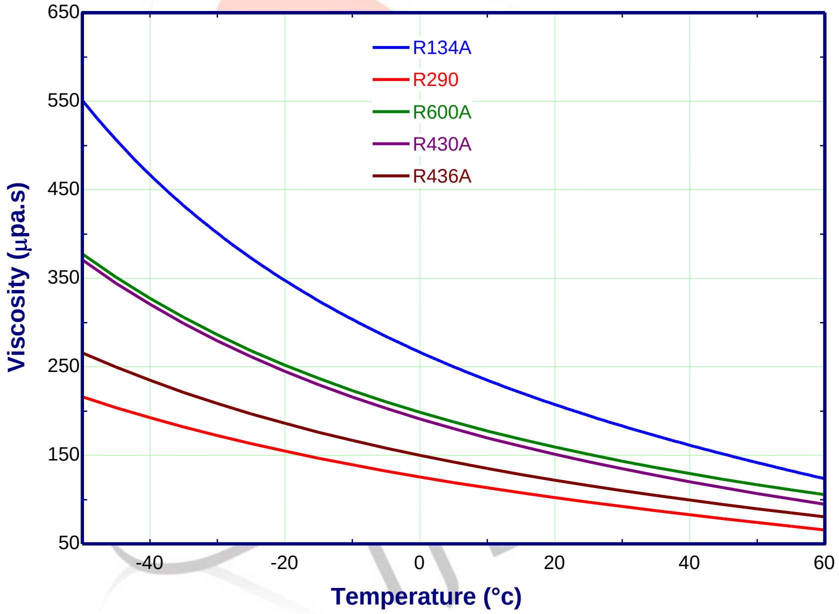

Fig.3. Variation of Viscosity with Temperature

By studying various thermodynamic properties of the refrigerants as shown in table 1.1, According to Montreal and Kyoto protocols, R12 had already phased out and the consumption of R134a must be reduced, and it will be phased out in 2040. R290, R600a its blends like R430A, R436Aare the better option for the drop in replacement of R134a in domestic refrigerator, due to their low global worming potential (GWP) and 0 ozone depletion potential (ODP)compare to R134a(1430)[17].

II. THERMODYNAMIC ANALYSIS

A vapor compression refrigeration system consists of five components such as evaporator, super heating coil, compressor, condenser and expansion valve. These components connected in a closed loop through piping that has heat transfer with the surrounding as shown in Fig.5. At state 9, refrigerant leaves the evaporator at a low pressure, low temperature, saturated vapor and enter the super heating coil where it absorbs the heat from high pressure- temperature refrigerant flows from condenser.

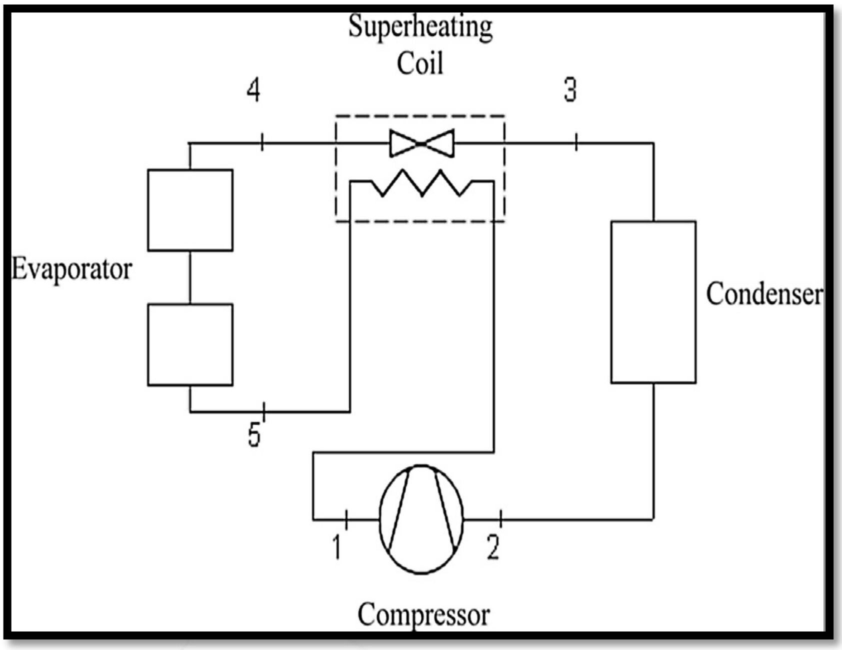

Fig. 4: Schematic representation of Vapor Compression Refrigeration Cycle

The refrigerant from the super heating coil enter into compressor through the suction line in which both temperature and pressure increased at state 1. This process can be shown in fig.6. At state 2, it leaves the compressor as a high pressure, high temperature, superheated vapor and enter the condenser where it reject heat to surrounding medium at constant pressure after undergoing heat transfer in the discharge line. Refrigerant leaves the condenser at state 3, as high pressure, medium temperature, saturated liquid and enters the super heating coil at state 5. The expansion valve allows to flowing the high pressure liquid at constant enthalpy from high pressure to low pressure. At state 7, it leaves the expansion valve as a low temperature, low pressure, and liquid-vapor mixture and enters the evaporator where it absorbs the heat at constant pressure, changed into saturated vapor and cycle is completed.

Thermodynamic analysis based on first law of thermodynamic, the performance of vapor compression refrigeration system can be predicted in terms of coefficient of performance (COP), which is defined as the ratio of net refrigerating effect produced by the refrigerator to the work done by the compressor. It is expressed as

(a) coefficient of performance (COP)

$$COP = \frac{\dot{Q}_{Evep}}{\dot{W}_{Comp}}$$

$$COP = \frac{h_9 - h_8}{h_{2s} - h_1} \qquad \text{..............................(1)}$$

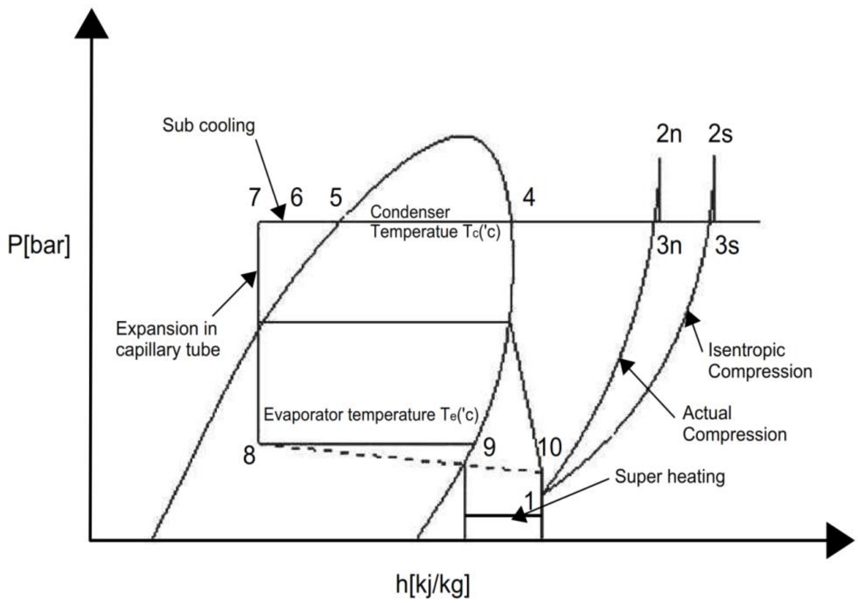

Fig.5: Pressure-Enthalpy Diagram of VCR Cycle

(b) Refrigerating effect ($\dot{Q}_{Evap}$)

$$\dot{Q}_{Evap} = (h_9 - h_8) kj/kg \quad \text{.................................(2)}$$

(c) Mass flow rate($\dot{m}$)

$$\dot{m} = \left[\frac{\dot{Q}_0}{q_0}\right] kg/s \quad \text{...(3)}$$

(d) Compressor work ($\dot{W}$)

$$\dot{W} = \dot{m}\, w$$

$$\dot{W} = \left(\dot{m}(h_{2s} - h_1)\right) kw \quad \text{...................................(4)}$$

(e) Condenser heat rejected($\dot{Q}_k$)

$$\dot{Q}_k = \dot{m}\, q_k$$

$$\dot{Q}_k = \left(\dot{m}(h_{3n} - h_6)\right) kw \quad \text{..................................(5)}$$

(f) Suction vapour volume(v_s)

$$v_s = \left(\frac{60 * \dot{m}}{N} v_{10}\right) cc/rev \quad \text{...............................(6)}$$

(g) Volumetric efficiency of compressor(η_v)

$$\eta_v = \frac{v_s}{v_p} \quad \text{...(7)}$$

(h) Isentropic discharge temperature (T_{2s})

(i) Actual discharge temperature (T_{2n})

$$T_{2n} = T_1 \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma - 1}{\gamma}\right)} k \quad \text{..(8)}$$

III. THEORETICAL SIMULATION ANALYSIS

Analysis on a 165L, 89W refrigerating capacity, 4.33cm^3 piston displacement refrigerator operating on the standard rating cycle. The pressure drops Δp_s and Δp_d at suction and discharge valves were assumed as follows: [16]

For R290	Δp_s=0.2 bar,	Δp_d=0.4 bar
For R134a	Δp_s=0.1 bar,	Δp_d=0.25 bar
For R600a, R430, R436	Δp_s=0.03 bar,	Δp_d=0.05 bar

Studying different refrigerant properties we can say that the refrigerants like R290, R600a, R430a, R436a have the potential to replace R134a in domestic refrigerator. we can carried out an exhaustive theoretical analysis of two pure refrigerants R290, R600a and binary mixture R430a, R436a for finding out the suitability of alternative HC refrigerants. The operating parameters and simulation results are given in table 2and table 3.

Table 2: Property data of R134a and new proposed refrigerants for Te=-25℃ and Tc= 55℃

Refrigerant	Normal Boiling Point	Compressor inlet pressure	Compressor outlet pressure	Pressure Ratio	γ
	(C)	**(bar)**	**(bar)**		
R134a	-26	0.8647	15.17	17.55	1.115
R290	-42.09	1.834	19.32	10.54	1.139

R600a	-11.67	0.3842	7.898	20.56	1.096
R430a	-27.6	0.9349	14.24	15.23	1.134
R436a	-34.3	1.268	12.76	10.06	1.123

Table 3: Calculated performance parameters of new proposed refrigerants for Te=-25℃ and Tc= 55℃

Refrigerant	Mass flow rate	Actual compressor out let temperature	Isentropic compressor out let temperature	Compressor Work	Refrigeration effect	COP
	g/sec	(℃)	(℃)	(kW)	(KJ/kg)	
R12	0.82	57.57	136.4	0.04935	108.5	1.803
R134a	0.6472	60.33	128.8	0.05043	137.5	1.765
R290	0.3427	55.1	122.6	0.04939	259.7	1.802
R600a	0.3831	61.97	116	0.05501	232.3	1.618
R430a	0.4101	58.87	108.7	0.05721	217	1.55
R436a	0.3356	54.63	107.7	0.04047	265.2	2.199

This study also include the performance of assessed refrigerants on varying condition like change in Evaporator temperature. By varying evaporator temperature from -30℃to 0℃ all the basic cycle data of the new refrigerants were calculated to have fast estimation of their cycle performances in different temperature conditions. To study heat transfer and cycle performance of the Hydrocarbons like R290, R600a, and their bland R430A, R436A as an alternative refrigerant in simulation program.

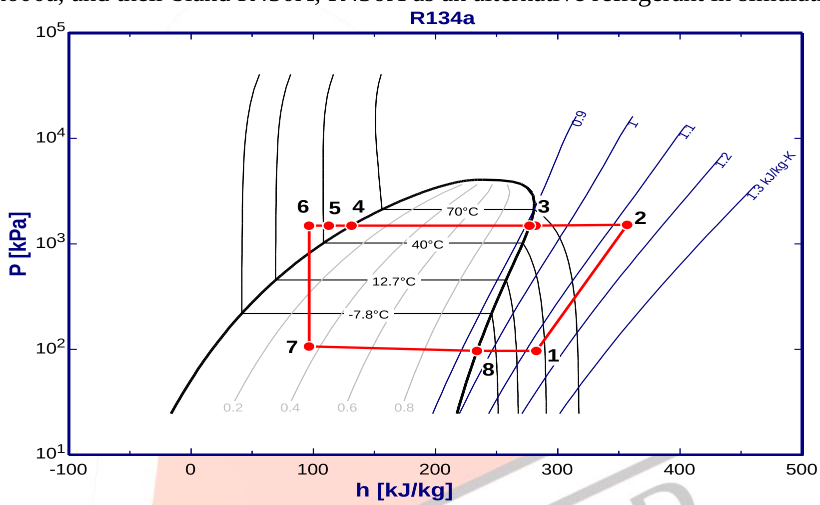

Fig. 6: P~h diagram for R134A refrigerant

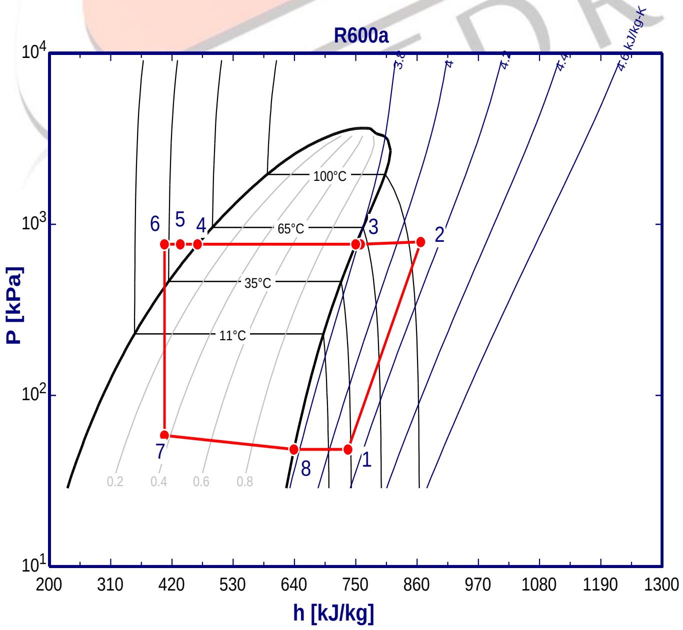

Fig. 7: P~h diagram for R290 refrigerant

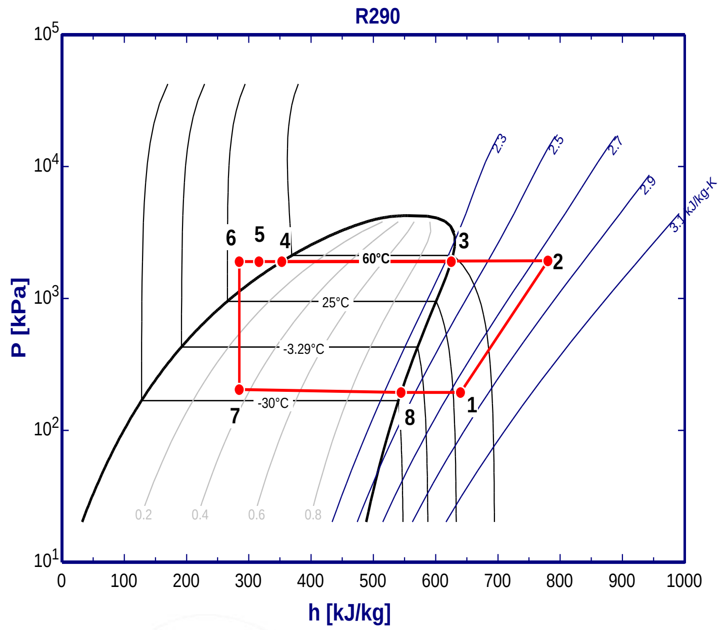

Fig. 8: P~h diagram for R600a refrigerant

3.1.Variation of refrigerant mass flow rate

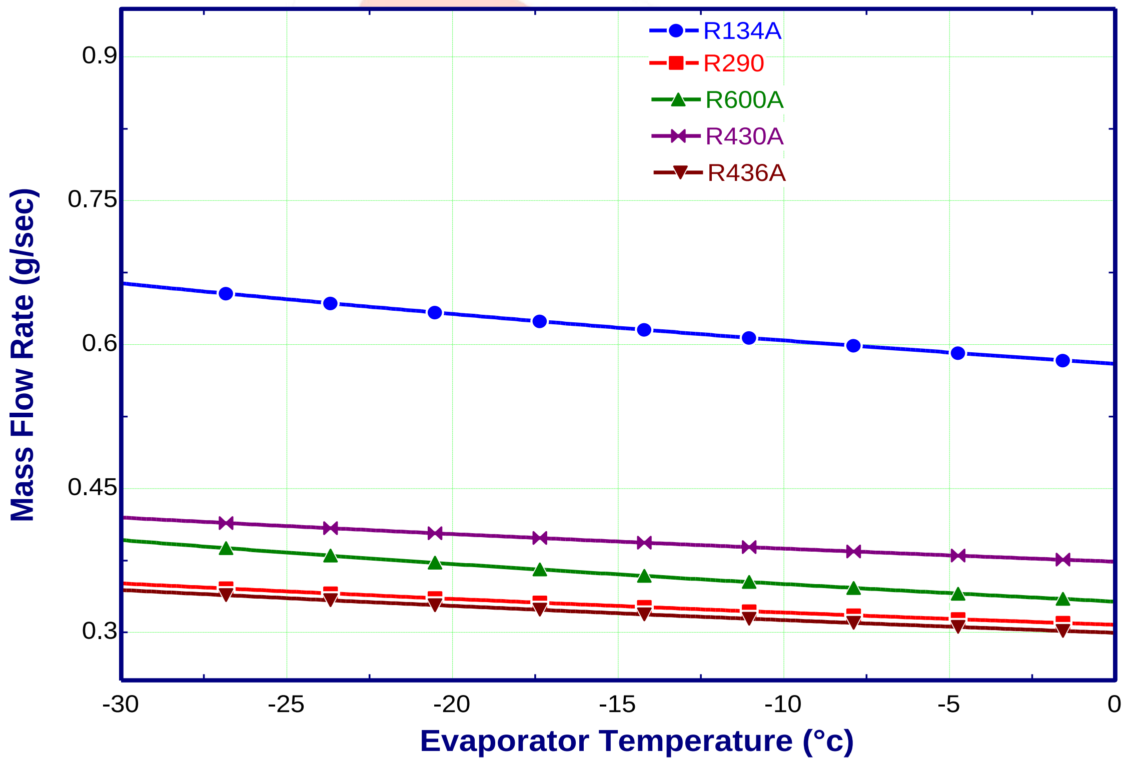

Fig. 9: Variation of Mass flow rate with Evaporator temperature

The mass flow rate of the assessed refrigerants is shown in Fig.9. The mass flow rate of R290, R600a, R436A, R430A was lower than that of R134a due to its lower liquid density Hence lower compressor power can be expected with R290, R600a, R436A, R430A. The mass flow rate variation with reference to condensing temperature was observed to be very small. Hence the mass flow rate of two refrigerants against condensing temperature is neglected.

3.2. Variation of pressure ratio

The pressure ratio of the refrigerant influences the volumetric efficiency of the compressor. The variations of pressure ratio against evaporator temperature are compared in Fig. 10. The pressure ratio of the R290, R430a, R436a are observed to be lower than that of R134a, better volumetric efficiency can be expected. Pressure ratio for the R600a is observed to be greater than R134a.

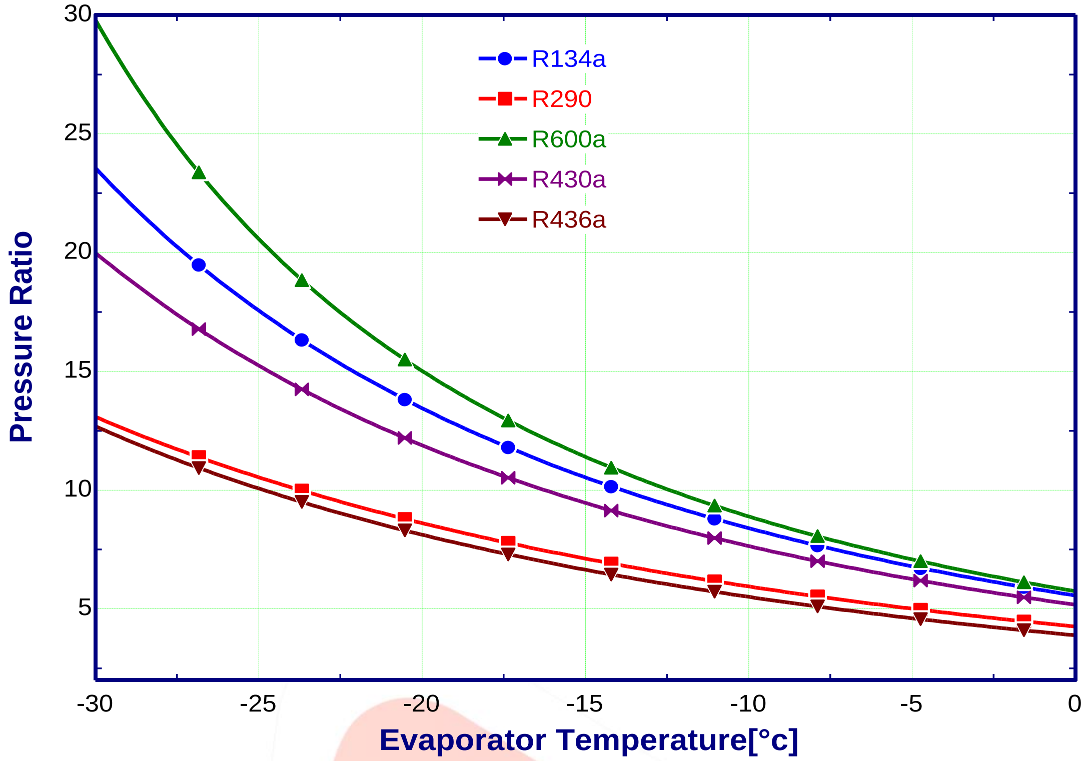

Fig.10: Variation of Pressure ratio with Evaporator temperature

3.3.Variation of Coefficient of performance (COP)

The COPs of the different refrigerants are compared in Fig.11. The COP of R430A, R290 and R600a is near about of the R134a.The COP of R436A is higher than R134A at all evaporator temperature, due to its lower compressor power consumption and higher evaporator capacity with an increase in evaporator temperature from −30°C to 0 °C as shown in following figure.

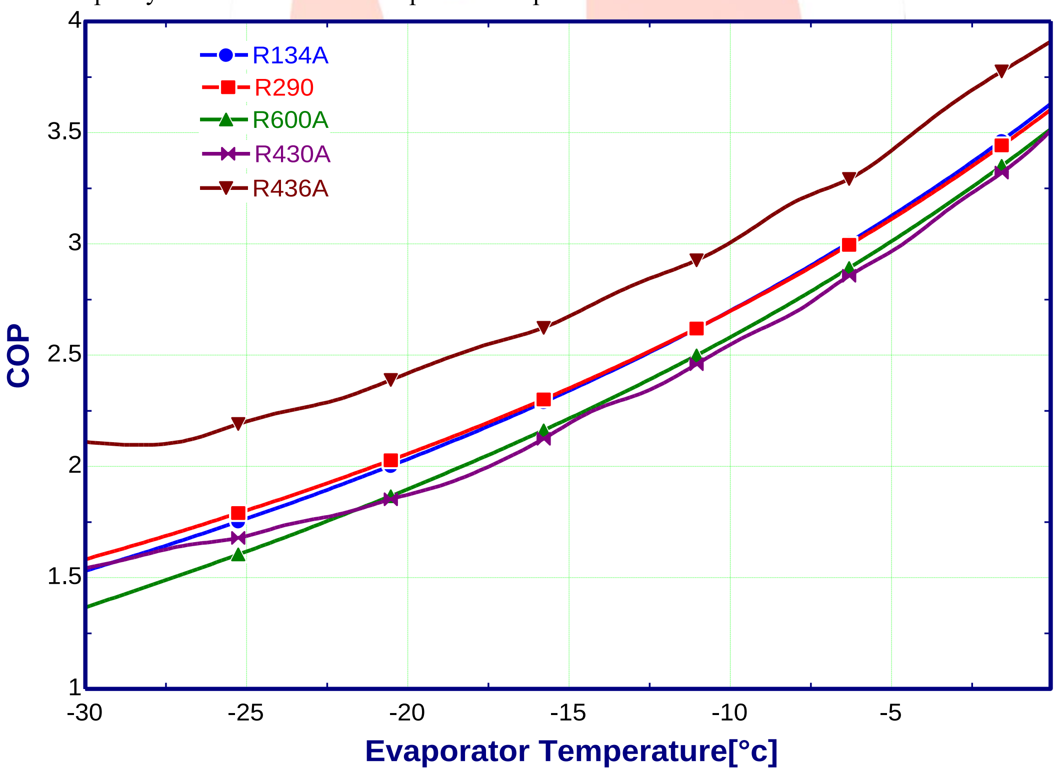

Fig. 11: Variation in Coefficient Of Performance with Evaporator temperature

3.4.Variation of compressor power consumption

Power consumptions of the refrigerants are compared in Fig.12. The power consumption of R290, R430A was found to higher than that of R134a at 55 °C condensing temperatures, and the power consumption of R600a, R436a is lower than R134a respectively for wide range of evaporator temperatures between −30 and 10 °C. The power consumption of the refrigerator increases with evaporator temperature due to an increase in refrigerant mass flow rate.

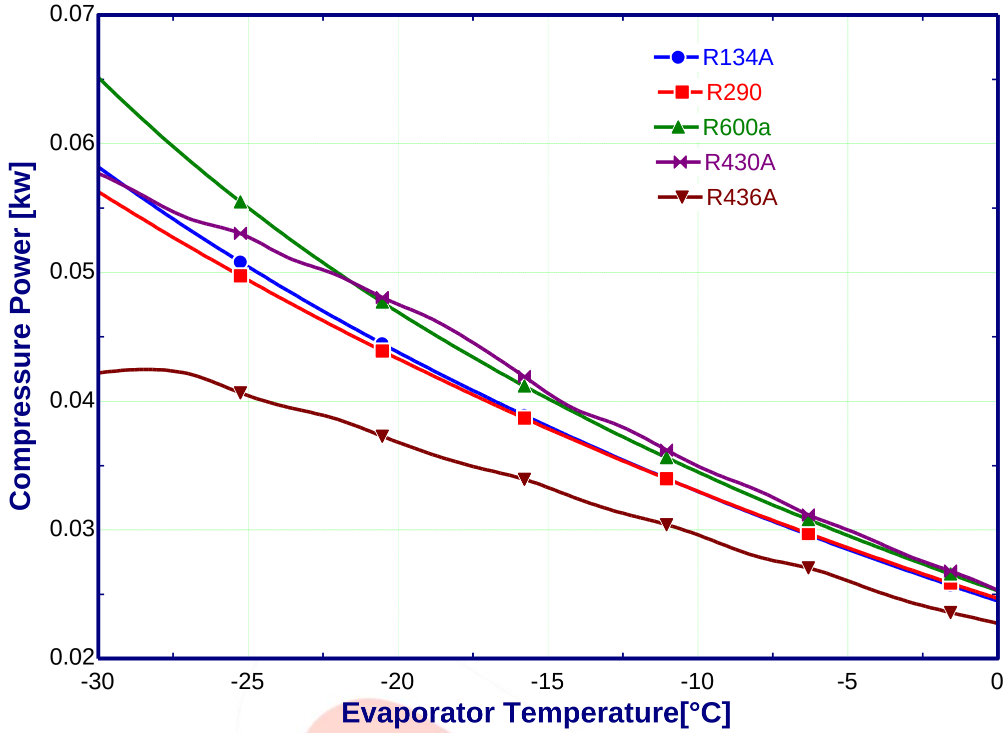

Fig. 12: Variation in Compressor Power with Evaporator temperature

3.5.Compressor discharge temperature

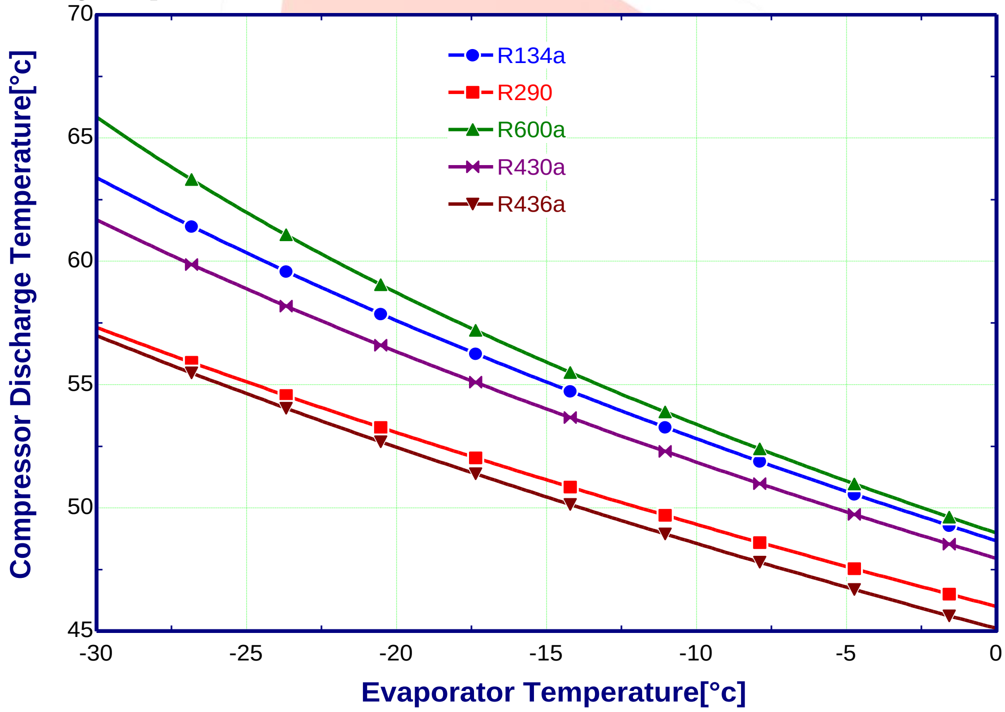

Fig. 13: Variation of Compressor Discharge Temperature with Evaporator temperature

The compressor discharge temperature is the major factor influencing the life of the refrigerant compressors. The higher compressor discharge temperature will affect the properties of lubricants. The comparison of compressor discharge temperature of the different assessed refrigerants is depicted in Fig. 4.8.

The compressor discharge temperature of R430A, R1234yf and R1234ze is found to be higher than that of R134a for a wide range of condenser and evaporator temperatures due to its higher specific heat ratio. The compressor discharge temperature of R436A, R290, R600a and DR11 were found to be lower than that of R134a. Due to the higher compressor discharge temperature, the life of the compressor will be slightly affected. There is increase in compressor discharge temperature with evaporator temperature from−30°C to 0 °C.

IV. Results and discussion

The result of calculation is given in Table 4.3. R290 (propane) is lower boiling and higher pressure refrigerants. Hence, they require smaller displacement compressor. R290 requires more compressor size as compare to R134a. Another point to note is that R134a has the higher discharge temperature due to a very high of γ . However, propane has the 8% reduce in discharge temperature as R134a. COP is increased by 2.09%, compressor power is reduce by 2.06%. it comes in A3 safety group hence it is highly inflammable. Pressure ratio is also decreases by 40% of that R134a.

Table 4.3: performance comparison of assessed refrigerants relative to R134A

Refrigerant	% Relative to R134A				
	COP	Pressure Ratio	Compressor Work (kW)	Compressor out let pressure (bar)	Compressor out let Temperature (^{0}C)
R290	2.09	-40	-2.06	27.35	-8.7
R600a	-8.328	17.15	9.082	-47.94	2.72
R430A	-12.18	-13.22	13.44	-6.13	-2.42
R436A	24.59	-42.68	-19.75	-15.9	-9.45

R600a (isobutane) has lowest value of γ . Hence, it has higher value of compressor discharge temperature of 2.72 % than R134A and also having the highest pressure ratio. However, it has vacuum in the evaporator. Compressor power is increased by 9.08% and COP of the system is decreased by 8.32% if we are using R600a as drop in replacement of R134a it requires longer capillary tube and compressor of greater volume, hence we could not use R600a as direct substitute of R134a without making change in system. One more drawback it comes in A3 group of flammability hence it is highly inflammable.

R430A is a binary mixture of R152a and R600a (76/24) and R436 is a mixture of R290 and R600a (56/44) by mass. R430A has 12.18% and 13.22% reduction in COP & pressure ratio respectively. Compressor power is increased by 13.44%. At the same time compressor out late temperature and pressure is reduced by 2.42% and 6.13% respectively. For R436A result seems to be more positive way it drastically increased in COP by 24.59% with respect to R134a. Also pressure ratio, compressor power, compressor out late temperature and pressure is reduced by 42.68%, 19.75%, 15.9% and 9.45% respectively. However, it is the fact that the mixture undergoes temperature glide during boiling and condensation. If the composition is slightly affected, it may cause instable operation in the refrigerator.

V. Conclusions

In this work, low GWP hydro carbon refrigerants like R290, R600a and its blends like R430A, R436A have been studied as promising drop-in replacements for the common high global warming potential refrigerants R134a, following conclusions made from the standard rating cycle simulation:

- R290 has the 8% reduce in discharge temperature as R134a. COP is increased by 2.09%, compressor power is reduce by 2.06% relative to R134a.
- R600a was having Compressor power is increased by 9.08% and COP of the system is decreased by 8.32% relative to R134a.
- R430A has 12.18% and 13.22% reduction in COP & pressure ratio respectively. Compressor power is increased by 13.44%. relative to R134a.
- For R436A result seems to be more positive way it drastically increased in COP by 24.59% with respect to R134a.
- Thus R290, R436a are the most promising drop in alternative to R134a in domestic refrigerator.

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