Hydrocarbons as Alternative Refrigerants in Domestic Refrigerators

Parashurama S, C. Ahamed Saleel, Govindegowda M. S., S. A. Khan

Abstract: ***The thermodynamic and volumetric properties of hydrocarbons namely Propane, Cyclopropane, Propene, Methyl acetylene, Propadiene and Dimethyether as replacements to substitute R134a have been assessed by means of SRK equation of state. The pressure magnitude, enthalpy, entropy, and specific capacity at vapor and fluid phase have been analyzed over the temperature range from -250C to +55 0C. Ten state point vapor compression cycle is used to carry out thermodynamic investigation of 89W local refrigerator. The theoretical enactment of the hydrocarbons have been comparatively assessed using standard refrigeration parameters such as displacement volume, volumetric efficiency, starting torque, refrigerating effect, discharge temperature, COP and rating of the motor. According to our results, Propane and Propene are appropriate and recommended as alternatives of R134a with lower displacement compressor and Cyclopropane as direct substitute. Also implications with respect to material and lubricant oil compatibility, heat transfer characteristics are discussed.***

Keywords: CFC, HCFC, Discharge temperature, Compressor work input, Discharge temperature, Displacement volume, volumetric efficiency

INTRODUCTION

Now a days, use of refrigeration and air conditioning is indispensable in domestic and industrial purposes. CFCs and HCFCs were the widely used refrigerants during the past few eras. As these refrigerants form a group of ODS (Ozone Depleting Substances), the Montreal protocol demanded its gradual replacement with more environment friendly substitutes. Accordingly, few of them are replaced and the residual are in its course of substitution. HCFCs and CFCs may be wisely substituted by HFCs due to their higher GWP (Global Warming Potential). Hence, these type of natural refrigerants form a group of environment friendly refrigerants.

Serious research studies are in progress to substitute R12. R152a [1, 2] presents comparable thermodynamic properties with agreeable compatibility in lubrication systems, even though there are few challenges in pressure levels. Ammonia [3, 4] is emerged as a suitable refrigerant for low temperature applications, but its toxicity poses few limitations. With regard to environment friendliness, price, availability, miscibility and thermodynamic efficiency, propane seems to be an attractive substitute. Concerning the research of new refrigerants the majority of earlier outcomes [1, 11-16] show that R134a is the best possible substitute of R12. It has zero ODP but it is global warming gas, not miscible with mineral oil, its energy efficiency is slightly lower and poor heat transfer at low temperatures. Jung et al [17] carried out a computational investigation of domestic refrigerator charged with many pure and mixture as possible alternatives of R12 and studied experimentally R290/ R600a (60/40) and obtained 2.45% increase in energy efficiency compared to R12. There is uncertainty in the reliability of derived results as NBP and structural details are the only input parameters. Somchai Wongwises et al [18] have determined the performance of vapour compression system with Propane, HC, HFC mixtures and recommended R290/R600a/R14a (40/30/30) as alternative from energy point of view. B.Tashtoushetal [19] investigated experimentally ternary mixture of butane/propane/R134a (43.91/33.31/22.78) and the obtained performance was higher than that of R12. S. J. Sekhar et al [20] suggested R134a/R600a/R290 as a retrofit mixture for R12 systems and obtained 4.1-7.6 % energy savings compared to R12. L.J.M Kuijipers et al [21] have investigated experimentally HFC 152a, DME, HC270 and HC290/R600a (21/79) and concluded that the performance of R152a, R270 and R290/R600a (21/79) was found to be slightly higher than that of DME. Eric Granryd [22] analysed Hydrocarbons hypothetically and determined that Hydrocarbons are the superior alternatives of R12. Built on Back one relations of state, Saleh et al [23] identified pure liquids as replacements to R12 such as RE170, R152a and RC270.

The problem in case of mixtures is that there is uncertainty of their thermodynamic and thermo physical properties and also in case of leakage it becomes very critical that the performance of the refrigeration system changes. Hydrocarbon refrigerants have zero ODP, negligible GWP and are compatible with universally used inorganic oil. The main disadvantage of these refrigerants is that they are highly inflammable. Hydrocarbons, in relationship to R12 have great hidden warmth of vaporization and little value of concentration make these refrigerants attractive viciousness of their flammability by virtue of low charge for ignition. In the present study theoretic exploration is commenced to establish the required amendments to be assimilated in the scheme for all of the refrigerants R290, R270, R170, R1270, R2250, R2250b and DME making necessary modifications in the same system as is used for R12 to achieve the same capacity viz. 89W evaporator and comparable performance with that of *R134a* thus making the system environmental friendly.

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All Hydrocarbons are compatible with Copper with an exception of Propyne and Propadiene, These hydrocarbons are highly reactive with Copper creating extremely explosive metal acetylides [24]. Hence Propyne and Propadiene require sufficient change in the material of construction of the refrigerator. All hydrocarbons are miscible with conventional mineral lubricant and have outstanding lubrication possessions. Another motivating advantage for these class of refrigerants is positive evaporator pressure with mild corrosion resulting in fewer joint replacements. As we know, negative evaporator pressure admits atmospheric air inside the evaporator causing severe corrosion on mixing with the refrigerants forming strong acids. Studies by Gursaran.D, Mathur and D. S. Jung [25] on heat transfer characteristics of alternate refrigerants indicate that coefficient of heat transfer for Hydrocarbons are meaningfully higher than R12 and R134a both in liquid and gaseous phase. Hence, Hydrocarbons are viable candidates from view point of heat transfer

MODELLING OF THERMODYNAMIC PROPERTIES

The thermodynamic possessions of refrigerants are required to calculate system performance. The basic properties of hydrocarbons were reported by Salvi-Naokhede [4] et al. Table 1 provides the values of property data at design conditions, viz., pressure ratio, NBP of refrigerants, specific volume of suction vapour and latent heat of vaporization at evaporator pressure, and specific heat ratio for R12 and for alternate refrigerants. The thermodynamic properties required for simulation are modeled using S-R-K equality of state. The roots of the algebraic equivalence for explicit capacity in fluid and gasiform stages are resolved using Cardon's technique. Thermodynamic belongings such as fluid enthalpy vapour enthalpy, fluid entropy, vapour entropy are premeditated over a collection of temperatures utilizing heat and entropy parting functions using the procedure given in Appendix. The reference state is chosen in such a way that the saturated values of enthalpy and entropy are 200 kJ/kg and 1kJ/kgK respectively at 0ºC. A C-program was developed using the procedure given in Appendix to acquire thermodynamic variable indicating their properties at some hotness T. The contributions to the program are NBP, acute temperature, acute stress, molecular mass and wagner coefficients. The saturated and superheated properties are exhibited in isolated output files over the kind mentioned by the customer. The vapor pressure data (Wagner coefficients) and Naught stress explicit heat data for the refrigerants are taken from reference[26].The developed Thermodynamic properties are authenticated for R12 and are in decent covenant with ASHRAE[27] values with acceptable inaccuracy. These developed possessions are then used in the assessment of cycle enactment of the method.

THEORETICAL THERMODYNAMIC ANALYSIS

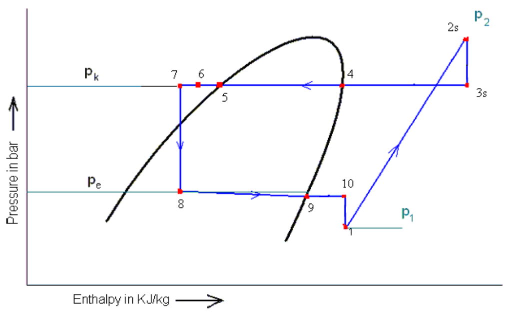

Fig.1-Ten point Vapour compression cycle

The performance investigation and comparison of vapor compression refrigeration scheme with conventional and alternative refrigerants are mainly based on compressor displacement value and COP. Both CFC based refrigerants and suggested substitutes are to be in reasonable agreement with both the aforementioned parameters. A representation of the vapour compression is shown in Figure 1. This cycle is envisioned to fairly accurate the design and operational circumstances of a home fridge. The ten state facts [28] as shown on the p-h illustration in Figure 1 corresponding to the conditions are identified as under:

1. State of refrigerant in the cylinder before compression begins
2. Refrigerant state in the cylinder after compression ends.(2s isentropic compression)
3. Compressor shell outlet/ condenser inlet condition
4. Saturated vapor state in the condenser at 55°
5. Saturated liquid state in the condenser at 55°C
6. Sub cooled liquid state leaving condenser at 43°C
7. Capillary inlet condition at 32°C
8. Capillary outlet/evaporator inlet condition at -25°C
9. Saturated vapor refrigerant state leaving evaporator
10. State at inlet to the shell of hermetic compressor

Pressure descents at inlet and exit taps of compressor are supposed as trails [28]:

1. For R290 and other Hydrocarbons $\Delta P_i = 0.2$ and $\Delta P_o = 0.4$ bar
2. For R12, $\Delta P_i = 0.1$ &$\Delta P_o = 0.25$ bar
3. Pressure descent in evaporator is 0.1 bar & atmospheric temperature is 43°C.

Table 1. Property Data of R134a and alternatives to R134a for T_e =-25°C & T_k = 55°C. [29, 30]

Refrigerant	M(kg/kg mol)	NBP (°C)	v_1 (m^3/kg)	h_{fg}(kJ/Kg)	T_c(°C)	P_c(bar)	ω	q_0 (kJ/Kg)
R12	120.91	-27.95	0.2373	165.13	385	41.4	0.204	123.279
R290	44.094	-42.07	0.2968	409.63	369.8	42.5	0.153	308.068
R1270	42.081	-47.65	0.2482	415.13	364.9	46.0	0.144	316.799

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R270	42.081	-32.85	0.5033	466.47	397.8	54.9	0.130	371.199
DME	46.069	-24.85	0.7929	466.6	400	52.4	0.200	336.197
R2250	40.065	-34.45	0.5155	441.56	393	54.7	0.313	367.752
R2250b	40.065	-23.25	0.9324	565.15	402.4	56.3	0.215	407.669
R134a	102.03	-26.1	0.3720	135.4	101.1	40.6	0.327	104.32

ASSESSMENT OF PERFORMANCE PARAMETERS

Performance considerations with diverse refrigerants to find the similar cooling capability of 89W as with R134a are calculated and listed in Table 2.When compressor designed for R134a refrigerant is used with alternate refrigerants viz., hydrocarbons the volumetric efficiency will be affected. It is essential to have an expression which predicts the volumetric efficiency of the compressor matching with experimental performance. An improved equation adopted in this investigation, has been derived to evaluate the volumetric efficacy of the alternate refrigerants especially the Hydrocarbons whose specific heats are much higher compared to CFCs and HFCs.

$$\eta_v = K\left[1-(C\left(\frac{P_2}{P_1}\right)^{1/n}-1)\right] \qquad (1)$$

The constant K can also be considered to take care of change in the state of the suction vapor from T_{10}, P_{10} to T_1, P_1 resulting from pressure drop at suction valve, & heat gain during cooling of windings and heat exchange with cylinder walls, and also change in the state of the discharge vapor from T_2, P_2 to T_3, P_3 due to pressure drop at delivery valve, heat loss to cylinder walls and the leakage across the piston rings.

$$\text{Pressure ratio,} \quad P = \frac{P_2}{P_1} \qquad (2)$$

$$\text{Refrigerating effect,} \ q_0 = \left(h_9 - h_8\right) \qquad (3)$$

$$\dot{m} = \frac{Q_0}{q_0} \qquad (4)$$

$$V_p = \frac{\dot{m}v_1}{\eta_v 60N} \qquad (5)$$

$$Q_k = \dot{m}\left(h_{3s} - h_6\right) \qquad (6)$$

$$COP = \frac{Q_0}{W_{is}} \qquad (7)$$

$$W_{is} = \dot{m}(h_{2s} - h_1) \qquad (8)$$

$$T_{stg} = \frac{V_p\left(P_2 - P_1\right)}{2} \qquad (9)$$

Table 2. Performance characteristics of R12 and alternatives for T_e =-25°C & T_k = 55°C.

Refrigerant	$m\times10^3$(kg/s)	P_r	T_{2S}(°C)	W_{is} (W)	COP	V_p (cc)	γ	η_v (%)	Q_k (W)	T_{stg}(Nm)
R 12	0.722	10.99	139.1	43.94	2.026	4.6	1.137	0.756	136.23	2.77
R 290	0.289	9.37	120.8	40.62	2.198	2.4	1.124	0.735	133.85	2.06
R 1270	0.281	8.93	133.3	41.1	2.168	1.9	1.146	0.760	133.98	1.92
R 270	0.240	10.22	146.5	40.68	2.189	3.47	1.151	0.719	132.40	2.25
DME	0.240	12.63	150.0	46.43	1.919	6.85	1.139	0.634	137.16	4.02
R 2250	0.242	7.13	98.76	33.06	2.692	3.28	1.106	0.788	128.65	1.46
R 2250b	0.218	13.85	149.3	39.69	2.239	7.15	1.133	0.589	130.12	4.28
R134a	0.597	17.64	125	45.58	1.91	5.3	1.137	0.608	151.9	3.49

RESULTS AND DISCUSSION

The assessed data are recycled in the estimation of the sequence presentation of the system. To indorse the dependability of SRK expression of state volumetric and thermodynamic belongings of R134a have been premeditated and authenticated with tests values from ASHRAE [9].The assessed values are within 1% maximum error for vapour specific volume, for enthalpies within 10% and 8% for entropies over temperature range of -25 ^{0}Cto +55^{0}C. Although there is some uncertainty in the reliability of derived results, yet this analysis broadens the scope for long term alternatives. The uncertainties in liquid specific volume, enthalpies and entropies are due to imperfect estimation of specific heat and liquid specific volume. Experimental studies of these parameters need to be carried out to get better estimates of thermodynamic data. Different parameters of refrigerants are calculated using Equations 1 to 9 and are compared with R12.For tropical countries like India and Africa, the usual design circumstances for refrigerators are T_e =-25°C and T_k = 55°C. Table 2 lists the standards of enactment factors for R134a and alternatives. The deviation of Performance parameters with evaporator temperature are plotted as seen from Figure 2 to 10. Results are discussed as follows.

5.1. Pressure Ratio

As can be seen from Figure 2, the values of Pressure ratio for DME, R2250b appears to be higher, for DME appears to be almost close; this implicates a diminution of changes of the existing compressor for R134a.On the other hand, for R2250, R1270, R290 the values appear to be lower than that of R134a; this implicates the requirement of lower displacement compressor.

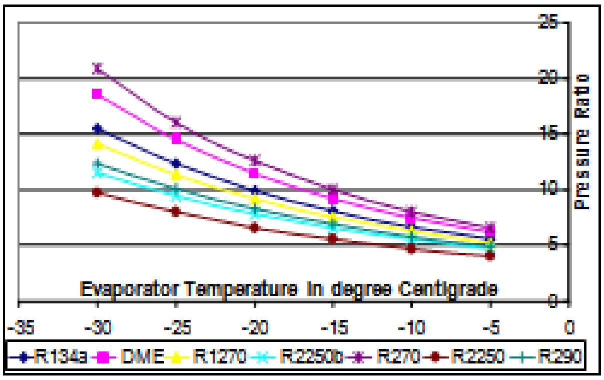

Fig. 2-Variation of Pressure ratio with evaporator temperature.

5.2. Coefficient of Performance

Fig. 3 gives the difference of COP with Evaporator hotness. Its demonstrations that the values of COP for all the refrigerants appear to be slightly higher than that of R134a except for R2250 which is slightly lower. COP values decreases with decrease in evaporator temperature as shown in Figure 3.

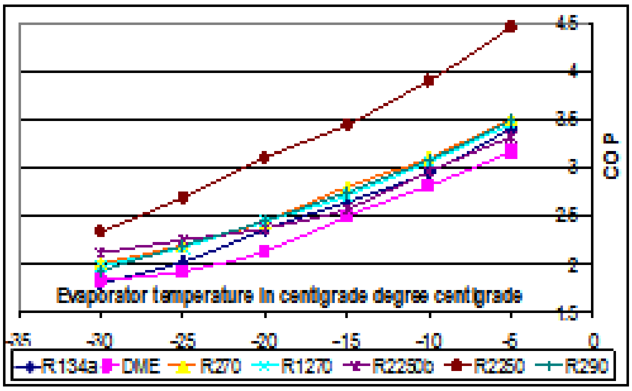

Fig. 3- Variation of COP with evaporator temperature.

5.3. Volumetric efficiency

From Table 2, it can be observed that the values of volumetric efficiencies of the refrigerants are comparable to that of R134a except for R270 and R2250b the obtained values are slightly lower. The volumetric efficiency for R2250 and R270 appears to be closer to that of R134a and for R2250b, DME, R1270, R290 the efficiency appears to be lower and decreases with decrease in evaporator temperature as seen from Figure 4

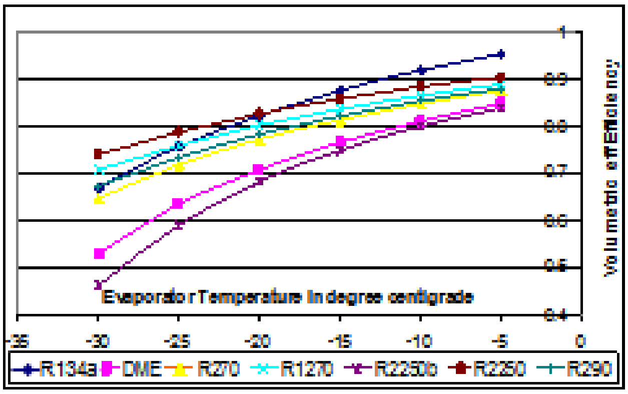

Fig. 4-Variation of volumetric efficiency with evaporator temperature.

5.4. Rating of motor

Table 2 lists the ranking of the electrically powered machine for all the refrigerants for the evaporator capability of 89W. It can be perceived that the lesser steaming refrigerant DME demands greater rated motor. The higher steaming refrigerants R2250, R2250b, R290 and R1270 entail lesser ranking of the electrically powered motor than that of R134a. It can be observed that motor rating of all the refrigerants is almost the same. This links that the energy consumption is somewhat greater in case of DME and lesser for further choices. The energy consumption increases with decrease in evaporator temperature as shown in Figure 5. The analysis of results shows comparable agreement with the discussions presented in Reference 22 and 23.

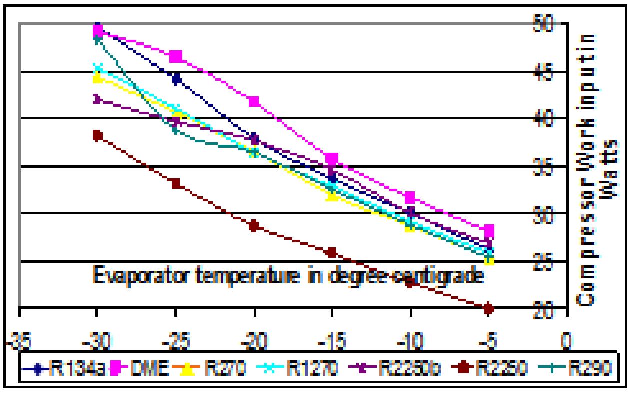

Fig. 5. Variation of compressor work input with evaporator temperature.

CONCLUSION

Proposed hydrocarbons are best substitutes for CFC based refrigerants and have superior performance**.** R270 can be used as direct substitute. Refrigerants R290, R1270 are recommended as alternatives to R134a with lower displacement compressor. DME can be used with higher displacement compressor. To accommodate R290, R1270, and R270, the evaporators are designed smaller with smaller diameter connection pipes due to lesser mass movement rates in comparison with R134a. Similarly, lesser disarticulation compressors with lower wattage motors can be used with R290, R1270, and R270 instead of higher displacement compressors with higher wattage motors with R134a resulting in higher energy savings. More experimentation is essential to attain at optimum motor rating. R2250 and R2250b although thermodynamically attractive cannot be used as alternatives as they are explosive in nature and not compatible with materials of construction.

NOMENCLATURE

C	Clearance factor and Specific heat, kJ/kg°C
COP	Coefficient of Performance
h	Enthalpy,kJ/kg
M	Molecular weight, kg/kgmol
$\dot{m}$	Mass flow rate, kg/s
n	Polytropic index
P	Pressure, bar
Q_0	Refrigerating Effect, KW
T	Temperature, K and Torque, N-m
v	Volume,cc, m^3 and Specific Volume, m^3/kg
W	Power input, W

Abbreviations

N	RPM of the compressor
NBP	Normal Boiling point,°C
CFC	Chlorofluorocarbons
DME	Dimethyl ether
EOS	Equation of state
GWP	Global Warming Potential
HCs	Hydrocarbons
HFCs	Hydrofluorocarbons
HCFCs	Hydrochlorofluorocarbons
ODP	Ozone Depletion Potential
SRK	Soave-Redlick-Kong

Greek symbols

γ	Specific Heat ratio
η	Efficiency

Subscripts

c	Critical
fg	Vaporization
i	inlet
is	Isentropic
k	Condenser
n	Polytropic
o	Evaporator
stg	Starting Torque
0, 1, 2 etc.,	State Points
v	Volumetric Efficiency

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