Hydrocarbons as Alternate Refrigerants in Domestic Refrigerators-An Overview

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The thermodynamic properties of hydrocarbons namely Propane, Cyclopropane, Propene, Methyl acetylene, Propadiene and Dimethyether as alternatives to replace R12 have been predicted using SRK EOS. The values of vapour pressure,liquid specific volume,vapour specific volume, liquid enthalpy, vapour enthalpy, liquid enropy, vapour entropy have been estimated over the temperature range from -25^{0}C to +55 ^{0}C.Simulation of 89W domestic refrigerator is carried out using ten state point vapour compression cycle.The theoretical performance of the hydrocarbons have been comparatively assessed using standard refrigeration parameters. According to our results, Propane, Propene .are appropriate and recommended as alternatives of R12 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*:** COP, Compressor work input, Discharge temperature,Displacement volume

1. Introduction

Refrigeration technology plays a significant role in safety and health people especially the preservation of food and life saving drugs. Refrigeration technology is also applied to provide comfort through air conditioning systems and for industrial processes. Knowing the CFC hazard and regulations from Montreal and Kyoto protocols one has to consider the *Generation-3* refrigerants -HCs & Natural refrigerants. When applied to the Refrigerator sector CFC-12 is outdated and has been substituted by the intermediate refrigerant HFC-134a (*Generation-2*). However, by 2020 the Generation-2 refrigerants must also be phased out; in this context, prospects of Generation-3 refrigerants need to be analysed and the existing R12 refrigerator inventories need to be retrofit or replaced.

Many works have been done in order to develop alternative refrigerants to R12 in accordance with Montreal and Kyoto protocols.R152a [1,2] presents good thermodynamic properties and a satisfactory compatibility with lubricants. Its pressure level discourages its use as a substitute of R12.Ammonia [3, 4] is one of the refrigerants in the field of refrigeration especially for very low temperatures but it is toxic. Propane is [5] a very interesting substitute regarding its thermodynamic efficiency, its miscibility with mineral oil, its price, availability and its negligible effect on the environment. Concerning the research of new fluids the majority of previous results [1, 6-11] 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 [12] performed a computer simulation 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. The predicted properties are not reliable as only NBP and structural details are used in the development of properties. Somchai Wongwises et al [13] 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.Tashtoush et al [14] 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 [15] 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 [16] 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 [17] analysed Hydrocarbons theoretically and concluded that Hydrocarbons are the better substitutes of R12. B.Saleh et al [18] developed properties of candidare refrigerants as alternatives to R12 using Back one equation of state,did thermodynamic analysis and concluded that RE170, R152a and RC270 are promising refrigerants to replace R12.

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 commonly used mineral oil. The main drawback of these refrigerants is that they are highly flammable. Hydrocarbons, in comparison to R12 have high latent heat of vaporization and low value of density make these refrigerants attractive in spite of their flammability by virtue of low charge. In the present study theoretical analysis is undertaken to ascertain the necessary modifications to be incorporated in the system for each 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 R12 thus making the system environmental friendly.

All Hydrocarbons except Propyne and Propadiene are compatible with Copper. Propyne and Propadiene react with Copper forming metal acetylides which are explosive in nature [19].Hence Propyne and Propadiene require change in the material of construction of the refrigerator. All hydrocarbons are miscible with conventional mineral oil and have excellent lubrication properties. Another advantage of Hydrocarbons is that because of positive evaporator pressure, there is no entry of moist air into the system. Studies by Gursaran.D ,Mathur and D.S.Jung [20] on heat transfer characteristics of alternate refrigerants indicate that heat transfer coefficients for Hydrocarbons are significantly higher than R12 and R134a both in liquid and gaseous phase. Hence, Hydrocarbons are viable candidates from view point of heat transfer

2. Modelling of Thermodynamic Properties

The thermodynamic properties of refrigerants are required to calculate system performance. The basic properties of hydrcarbons were reported by Salvi-Naokhede [4] et al. Table 1 lists the values of property data at design conditions, for R12 and candidate refrigerants. The thermodynamic properties required for simulation are modeled using S-R-K equation of state. The roots of the cubic equation for specific volume in liquid and gaseous phases are solved using Cardon's method. Thermodynamic properties such as liquid enthalpy vapour enthalpy, liquid entropy, vapour entropy have been calculated over a range of temperatures using enthalpy and entropy departure functions using the procedure given in Appendix. The reference state of the refriferants is taken to be having saturated liquid enthalpy and saturated liquid entropy of 200 kJ/kg and 1kJ/kgK at 0^{o}C respectively. A C-program was developed to obtain thermodynamic properties at any temperature T and pressure P. The inputs to the program are NBP, critical temperature, critical pressure, molecular weight and wagner constants. The saturated and superheated properties are displayed in separate output files over the range mentioned by the user. The vapor pressure data (Wagner constants) and Zero pressure specific heat data for the refrigerants are taken from reference [21].The developed Thermodynamic properties are validated for R12 and are in good agreement with ASHRAE [22] values with acceptable error. These developed properties are then used in the evaluation of cycle performance of the system.

3. Theoretical Thermodynamic Analysis

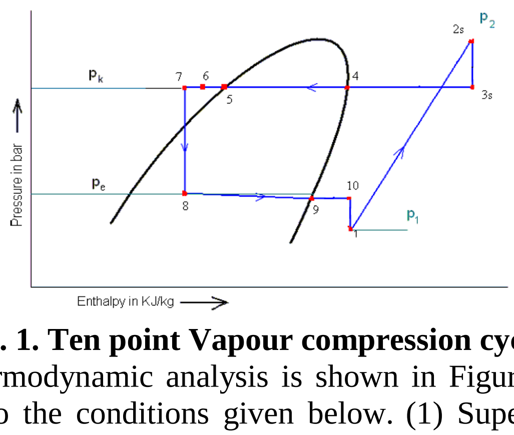

Fig. 1. Ten point Vapour compression cycle

A ten point cycle is used for thermodynamic analysis is shown in Figure 1. The ten state points [23] as shown in Figure 1 corresponds to the conditions given below. (1) Super-heated refrigerant vapour after pressure at suction valve (2) High pressure high temperature refrigerant vapour after isentropic compression (3) High pressure refrigerant leaving compressor (4) Refrigerant in saturated vapor state in the condenser at 55°C (5) Refrigerant in saturated liquid state in the condenser at 55°C (6) Sub cooled liquid refrigerant leaving condenser at 43°C (7) High pressure sub cooled liquid entering capillary tube at 32°C (8) Wet mixture leaving Capillary tube at -25°C (9) Refrigerant in saturated vapor state in evaporator (10) Superheated vapour leaving and entering compressor

Pressure drops at inlet and outlet valves of compressor are assumed as follows: [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 drop in evaporator is 0.1 bar & ambient temperature is 43°C.

Table 1. Property Data of R12 and alternatives to R12 for T_e =-25°C & T_k = 55°C. [24, 25]

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
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

4. Evaluation of Performance Parameters

Performance parameters for candidate refrigerants to obtain the same cooling capacity of 89W as that of R12 are calculated and listed in Table2. When compressor designed for R12 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. A modified expression adopted in this work, has been derived to estimate the volumetric efficiency 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.

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

Refrigerating effect, $q_0 = (h_9 - h_8)$ (3)

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

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

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

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

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

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

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

Refrigerant	m×10^3(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

5. Results and Discussion

The estimated values are used in the evaluation of the cycle performance of the system. To confirm the reliability of SRK equation of state volumetric and thermodynamic properties of R12 have been calculated and validated with experimental data from

ASHRAE [9]. The estimated values are within 1% maximum error for vapour specific volume, for enthalpies within 10% and 8% for entropies over temperature range of -25 ^{0}C to +55^{0}C. 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, the usual design conditions for refrigerators are T_e =-25°C and T_k = 55°C. Table 2 lists the values of performance parameters for R12 and alternatives. The variation of Performance parameters with evaporator temperature are plotted as seen from Figure 2 to 10.Discussion of the results is given in turn as follows.

4.1 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. On the other hand, for R2250, R1270, R290 the values appear to be lower than that of R12; this implicates the requirement of lower displacement compressor.

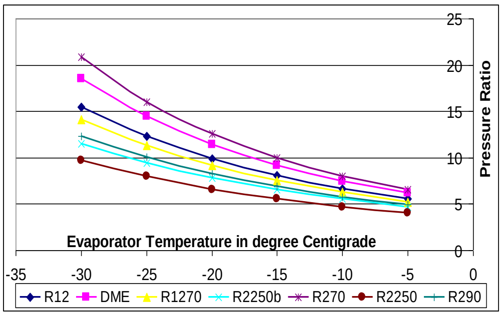

Fig. 2. Variation of Pressure ratio with evaporator temperature.

4.2 Coefficient of Performance

Figure 3 gives the variation of COP with Evaporator temperature. It shows that the values of COP for all the refrigerants appear to be slightly higher than that of R12 except for R2250 which is slightly lower. COP values decreases with decrease in evaporator temperature as shown in Figure 3.

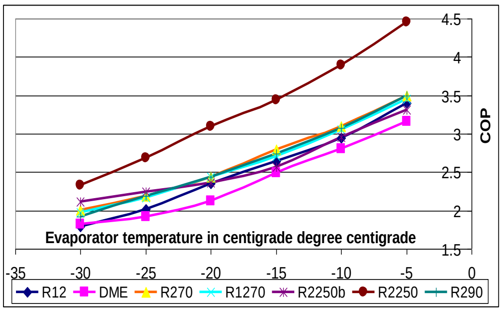

Fig. 3. Variation of COP with evaporator temperature.

4.3 Volumetric efficiency

From Table 2 It can be observed that the values of volumetric efficiencies of the refrigerants are comparable to that of R12 except for R270 and R2250b the obtained values are slightly lower. The volumetric efficiency for R2250 and R270appears to be closer to that of R12 and for R2250b, DME, R1270, R290 the efficiency appears to be lower and decreases with decrease in evaporator temperature as seen from Figure 4.

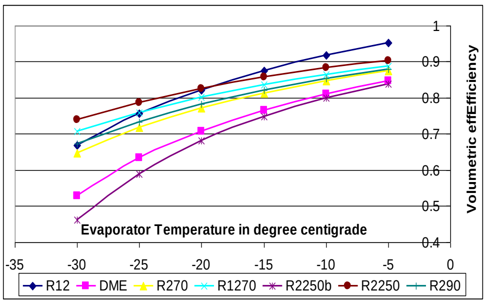

Fig. 4. Variation of volumetric efficiency with evaporator temperature.

4.6 Rating of motor

Table 2 lists the rating of the motor for all the refrigerants for the evaporator capacity of 89W. It can be observed that the lower boiling refrigerant DME demands higher rated motor. The higher boiling refrigerants R2250, R2250b, R290 and R1270 require lower rating of the motor than that of R12. It can be observed that motor rating of all the refrigerants is almost the same. This implicates that the energy consumption is slightly higher in case of DME and lower for other alternatives. The energy consumption increases with decrease in evaporator temperature as shown in Figure 5.

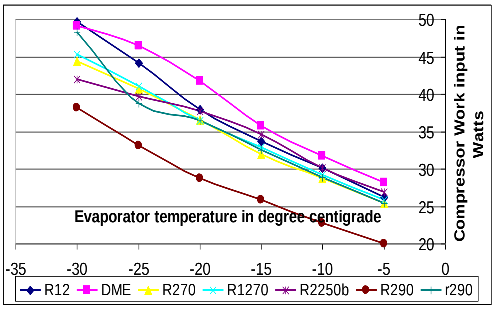

Fig. 5. Variation of compressor work input with evaporator temperature

2. Conclusion

The performance of all proposed Hydrocarbons are higher than that of R12**.**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 compressor displacement. Because of lower mass flow rates the design of evaporator for retrofitting R290, R1270, R270 has to be modified slightly i.e., the evaporator pipes have to be constructed of smaller diameter pipes and also due to lower mass flow rates smaller bore and longer capillary than that used for R12 is to be used for efficient throttling. The existing R12 Compressors fitted with 75 litres Refrigerators have lower displacement compressors can be used for alternate refrigerants from the point of view of power savings.Further experimentation is required to arrive at optimum motor rating. Refrigerants R2250 and R2250b although thermodynamically attractive cannot be used as alternatives as they are explosive in nature and not compatible with materials of construction.

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