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Atmospheric pollution

MATHEMATICAL MODELLING AND ANALYSIS OF DOMESTIC REFRIGERATOR WITH ALTERNATIVE ECO-FRIENDLY REFRIGERANTS FOR R134a

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Abstract: This work represents the mathematical modelling of low GWP refrigerant mixtures to replace R134a in domestic refrigeration system. The refrigerants like R290, R600a, R134a and mixtures of R290, R600a and R152a are considered for the performance evaluation in the refrigeration system. The refrigerants such as R134a, R290+R600a (50%+50%), R290+R600a+R134a (47.5%+47.5%+5%), R290+R600a+R134a (45%+45%+10%), R152a, R290+R600a+R152a (47.5%+47.5%+5%), R290+R600a+R152a (45%+45%+10%) are named as R1, R2, R3, R4, R5, R6, and R7. The various performance measures like volumetric efficiency, mass flow rate, volumetric cooling capacity (VCC), condenser heat rejection, refrigeration effect, compressor work, coefficient of performance (COP) are calculated under various condensing and evaporating temperatures. The result shows that the refrigerant R6 provides the better performance in terms of the mass flow rate and compressor work are arrived 55.73% and 14.3% less than of R1 and R5. For the above parameters, the refrigerant R6 could be a better alternate for R134a.

Keywords: alternative refrigerants, environmental friendly refrigerant, domestic refrigerator, vapour compression refrigeration system.

AIMS AND BACKGROUND

Domestic refrigeration system uses refrigerant to transfer heat from low temperature reservoir to high temperature reservoir, which works on the principle of reversed Carnot cycle. Many types of refrigerants are commercially available and used in the refrigerator to create the cooling effect. In India most of the refrigerators use R134a as refrigerant for its excellence in performance. However, R134a is known for the Global Warming Potential (GWP) of 1430. Recently International regulation Kyoto protocol suggests on the reduction of greenhouse gases by using eco-friendly refrigerants. Although it has been suggested that some solutions, such as the construction of domestic refrigeration system operating with R152a and hydrocarbons, remains the need to find a better substitute for HFC134a. Refrigerant R152a and hydrocarbons have zero Ozone Depletion Potential (ODP) and negligible GWP. The main drawback of the refrigerant R152a is its flammability in nature[1]. By reducing its volume fraction in the mixture, it can be negligible.

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Pure hydrocarbons are not suitable for R134a due to its VCC mismatch. R152a is an alternative refrigerant in domestic refrigerators that is energy efficient and environmentally friendly[10]. It is investigated that the hydrocarbon itself is not enough to run the existing refrigeration system. For a better replacement of R134a, HFO refrigerant R1234yf has been introduced to increase the cooling capacity[5]. The possibilities of R290 were explored and a possible replacement is R22. COP is significantly lower with R290 than with R22 (Ref. 4). For applications in domestic refrigerators/freezers using zeotropic mixture R290/R600a, a modified vapour compression refrigeration cycle (MVRC) was used. An ejector and phase separator are connected to a traditional vapour compression cooling cycle (TVRC) in the MVRC cycle to increase the performance of the cycle. The results shows that the MVRC cycle having better performance compared to the TVRC cycle under all operating conditions. COP and volumetric cooling capacity can be improved about 16.71 to 34.97% (Ref. 11). Performance of a cascade refrigeration system using different pairs of refrigerants, namely R152a-R23, R290-R23, R507-R23, R234a-R23, R717-R23 and R404a-R23 were studied. The cooling load is presumed to be 1 kW, the cooled space temperature is -40°C, and the ambient temperature is 300 K, while the degrees of subcooling of the condenser and superheat of the evaporator are 5 and 7°C. With the exception of the narrow polytropic efficiency ranges (50–60%), the coolant pair R717-R23 has the lowest irreversibility and highest COP, while R507-R23 has the highest irreversibility and lowest COP (Ref. 1). An internal auto-cascade refrigeration cycle (IARC) operating with the zeotropic blend of R290/R600a or R290/R600 for domestic refrigerator-freezers was suggested. According to the simulated results, the R290/R600a IARC showed an increase in COP of 7.8 to 13.3%, an improvement in volumetric cooling power of 10.2 to 17.1% and a decrease in pressure ratio of 7.4–12.3% (Ref. 8). It is discussed that the environment impact, energy efficiency, COP, refrigerant mass, and compressor discharge temperatures in the refrigeration system[9]. Performance of refrigeration system were analysed with refrigerant pair of R290 – R600a (HCs); R134a – R152a (HFCs), and R1234yf – R1234ze (HFOs). All the refrigerants have been assessed without changing the experiment facility[6]. Theoretical performance of HFC134a, HFC152a, HFC32, HC290, HC1270, HC600, and HC600a refrigerant mixtures were analysed under different ratios in a conventional vapour compression refrigeration device, and the findings were compared with CFC12, CFC22, and HFC134a to identify potential alternative substitutes[3]. Despite the highly flammable characteristics of the HC refrigerants, the refrigerants can be used in many applications, paying attention to the protection of leakage from the device.

The above literatures showed that the performance analysis on domestic refrigeration system has been done with various refrigerants like R152a, R290, R600a, R1234yf. Hydrocarbon refrigerants are not suitable for the domestic refrigerators, due to its poor performance in COP. However, the possibilities of using the mixture of Hydrofluorocarbon (HFC) and Hydrocarbon (HC) needed further investigation for the better alternative for R134a. Hence, the present work is aimed to evaluate the performance of a domestic refrigerator using mixture of HC refrigerant R290, R600a and HFC refrigerant R134a and R152a under different operating conditions. The simulation has been done to evaluate the performance characteristics such as COP, VCC, Condenser heat rejection, Refrigeration effect, and the Compressor work of the refrigeration system.

Schematic arrangement of a domestic refrigeration system and the corresponding pressure-enthalpy (p-h) diagrams are represented in Figs 1*a* and *b*, respectively. Domestic refrigeration system consists of compressor, condenser, expansion valve and an evaporator. The thermodynamic analysis of the refrigeration cycle is performed by considering the following assumptions: (i) the system is steady state; (ii) vapour is dry saturated at the inlet of the compressor; (iii) no pressure loss along the pipes and in the valves; (iv) speed of the compressor is 1600 rpm. The performance measures considered in this analysis are pressure ratio, volumetric efficiency, compressor discharge temperature, mass flow rate, VCC, refrigeration effect, compressor work, condenser heat rejection, and COP.

The pressure ratio is calculated by:

$$P_r = \frac{P_{con}}{P_{eva}} \tag{1}$$

The temperature (T_2) at the exit of the compressor is obtained by:

$$S_2 = S_g + C_{pg} \ln\left[\frac{(T_{\mathrm{sup}} + 273)}{(T_{\mathrm{sat}} + 273)}\right] \tag{2}$$

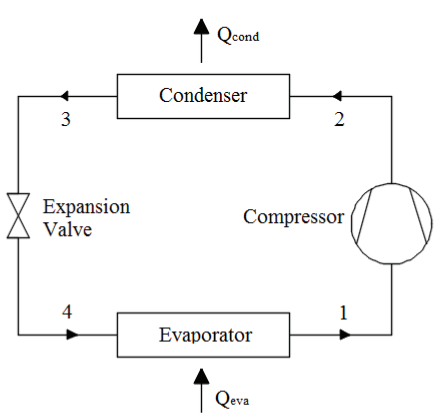

Fig. 1*a*. Domestic refrigeration system

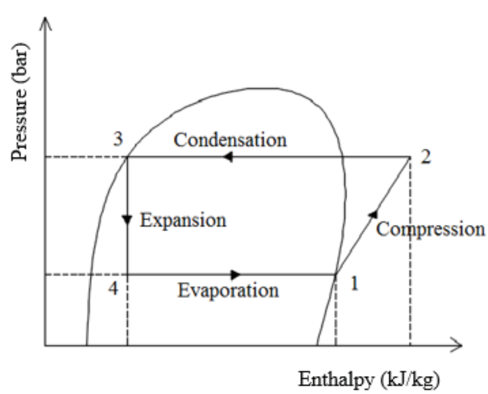

Fig. 1*b*. Pressure – Enthalpy diagram

The enthalpy of refrigerant at inlet of the compressor is given as:

$$h_1 = h_g \tag{3}$$

The enthalpy of refrigerant at the exit of the compressor is given by:

$$h_2 = h_g + C_{pg}(T_{\text{sup}} - T_{\text{sat}}). \tag{4}$$

The enthalpy of refrigerant at the exit of the condenser is represented as:

$$h_3 = h_{f14} - C_{pl}(T_{\text{sat}} - T_{\text{sup}}). \tag{5}$$

The volumetric efficiency is given by:

$$h_{vol} = 1 - C(P_r^{1/n} - 1). \tag{6}$$

VCC can be calculated by:

$$VCC = \frac{(h_1 - h_4)\eta_{vol}}{v_1} \tag{7}$$

The mass flow rate of the refrigerant is estimated by:

$$m_r = \frac{v_{st} N \eta_{vol}}{V_1}. \tag{8}$$

The amount of heat rejected in the condenser is calculated by:

$$Q_{cond} = m_r(h_3 - h_2). \tag{9}$$

The power input to drive the compressor is given by:

$$PI_{com} = m_r(h_2 - h_1). \tag{10}$$

The cooling capacity of the evaporator is represented as:

$$Q_{eva} = m_r(h_1 - h_4). \tag{11}$$

COP is expressed as:

$$\text{COP} = \frac{(h_1 - h_4)}{(h_2 - h_1)}. \tag{12}$$

In order to compare the performance of domestic refrigeration system with different refrigerants, the thermodynamic properties of refrigerants are essential. The various thermodynamic properties of refrigerants which are considered for the analysis are listed in Table 1.

Table 1. Thermodynamic properties of refrigerants

Refrigerant	Chemical name	Critical properties		Boiling point (ºC)	Lower Flammability Limit (LFL)	Environmental properties	
		T_c (ºC)	P_C (kPa)			ODP	GWP
R134a	Tetrafluro-ethane	101.06	4059	–26.3	Non flammable	0	1430
R152a	Difluroethane	113.26	4517	–25	3.9	0	124
R290	Propane	96.7	4248	–42.1	2.1	0	3.3
R600a	Isobutane	134.7	3640	–11.7	1.8	0	3

EXPERIMENTAL

The refrigerants such as R134a, R290+R600a (50%+50%), R290+R600a+R134a (47.5%+47.5%+5%), R290+R600a+R134a (45%+45%+10%), R152a, R290+ R600a+ R152a (47.5%+47.5%+5%), R290+R600a+R152a (45%+45%+10%) are considered and named as R1, R2, R3, R4, R5, R6, and R7, respectively. These refrigerants are analysed under various condensing and evaporating temperatures. The independent and dependent variables which are essential for the simulation study are depicted in Table 2.

Table 2. Range of variables

Parameters	Variables	
	Independent variables	Dependent variables
Condensing temperature	25–50ºC	Pr, COP, Q_{vol}, P
Evaporating temperature	–25 – 0ºC	Q_{cond}
Refrigerants	R134a, R152a, R290+R600a, R290+R600a+R134a, R290+R600a+R152a	Compressor discharge temperature

Saturation pressure of all the proposed refrigerants (REFPROP) are shown in Table 3. Refrigerants R134a and R152a have the same saturation pressure at the same range of operating temperatures. Refrigerant R2 has the lowest saturation temperature, but R4 and R7 have the saturation pressure closer to R1 and R5 over the considered range of operating temperatures.

Table 3. Saturation pressure

Refrigerants	Saturation pressure (bar)			
Temperature (ºC)	–25ºC	0ºC	25ºC	50ºC
R1	1.064	2.928	6.654	13.18
R2	0.9757	2.535	5.508	10.53
R3	0.9976	2.591	5.631	10.77
R4	1.022	2.653	5.764	11.03
R5	1.064	2.928	6.654	13.18
R6	1.003	2.604	5.657	10.82
R7	1.033	2.678	5.814	11.12

RESULTS AND DISCUSSION

EFFECT OF CONDENSING TEMPERATURE

The following results were obtained for a different condensing temperature ranging from 25 to 50ºC with constant evaporating temperature of –10ºC. The refrigerants R1 and R5 shows same results for all operating conditions.

The pressure ratio of the proposed refrigerants is shown in Fig. 2. Refrigerants R1 and R5 have the minimum pressure ratio and R4 has 10% increase in pressure ratio compared to R1 and R5. In addition, refrigerant R4 has 1.55% lower volumetric efficiency with R1 and R5 for the same operating temperature. It has been seen that the increase in pressure ratio will decrease the volumetric efficiency of the compressor which is agree with the result of Mohanraj et al.

The increase in compressor discharge temperature is obtained while increasing the condensing temperature and shown in Fig. 4. The HFC Refrigerants R1 and R5 show the high compressor discharge temperature, which is 9.57% higher

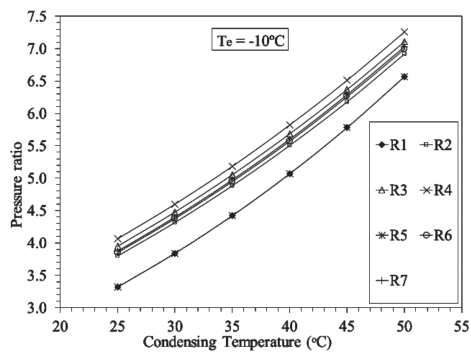

Fig. 2. Variation in pressure ratio with respect to condensing temperature

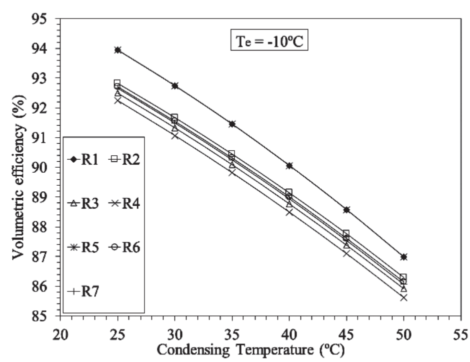

Fig. 3. Variation in volumetric efficiency with respect to condensing temperature

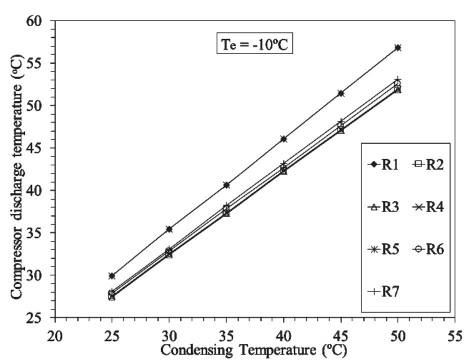

Fig. 4. Variation in compressor discharge temperature with respect to condensing temperature

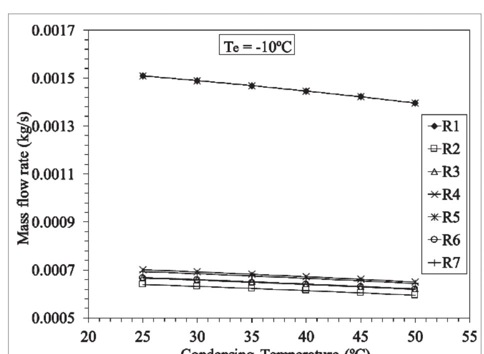

Fig. 5. Variation in mass flow rate with respect to condensing temperature

than that of R3. Refrigerants R2, R3, R4, R6, and R7 show negligible differences for the considered condensing temperature range. Mass flow rate of a refrigerant at different condensing temperature is plotted in Fig. 5. Mixture of HC and HFC refrigerants R3, R4, R6 and R7 has closer value of mass flow rate. The mass flow rate of the HFC refrigerants R1 and R5, is 2.35 times more than R2 for the condensing temperature of 25ºC. The lowest mass flow rate is arrived for the refrigerant R2 which has 57.4% less than of R1 and R5, respectively. It indicates that the increase in condensing temperature shows slight variation in mass flow rate.

Figure 6 shows the volumetric cooling capacity of the proposed refrigerants. The increase in the condensing temperature results in decrease of VCC drastically. Refrigerants R1 and R5 have the highest value of VCC. The value of VCC for R2 decreased by 21.56% compared to R1 and R5 for the condensing temperature of 25ºC. The refrigeration effect of the proposed refrigerants are compared with different condensing temperature. It is seen that refrigerants R1 and R5 show highest refrigeration effect and R2 represents the lowest. Mixture of HFC and

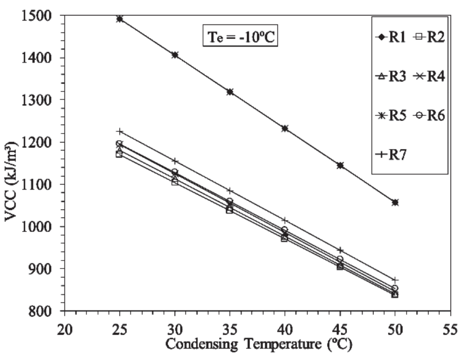

Fig. 6. Variation in volumetric cooling capacity with respect to condensing temperature

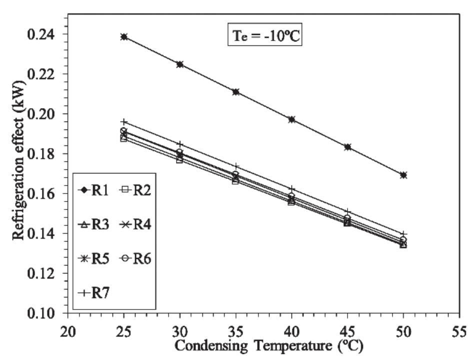

Fig. 7. Variation in refrigeration effect with respect to condensing temperature

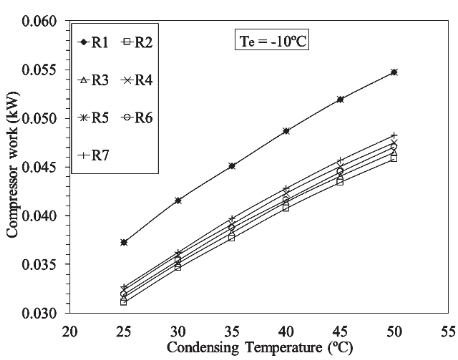

Fig. 8. Variation in compressor work with respect to condensing temperature

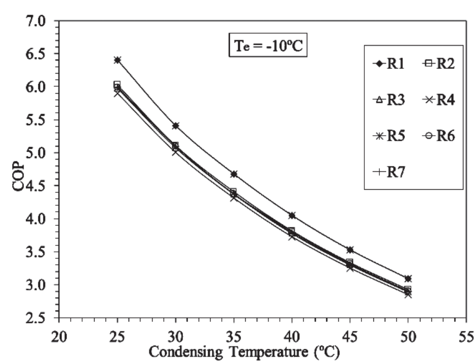

Fig. 9. Variation in condenser heat rejection with respect to condensing temperature

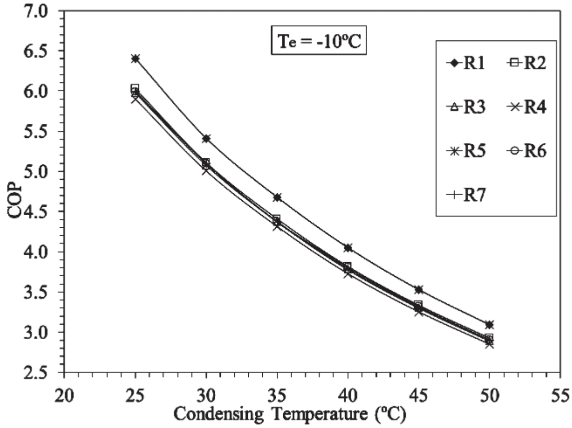

Fig. 10. Variation in COP with respect to condensing temperature

HC Refrigerant R7 shows the closer value, which is 17.46% lower than the HFC refrigerants R1 and R5.

Compressor work requirements of the proposed refrigerants are shown in Fig. 8. Refrigerants R2, R3 and R6 show the minimum compressor work. Refrigerants R1 and R5 consume 19.56% more power compared with R2. Compressor work is increased, while increasing the condensing temperature. Figure 9 shows the change in condenser heat rejection for all the assessed refrigerants with different condensing temperature. Condenser heat rejection is higher for the refrigerants R1 and R5. Refrigerant R2 shows 19.75% decrease in condenser heat rejection compared to R1 and R5.

COP of the proposed refrigerants are shown in Fig. 10. The COP value is high for the HFC refrigerants R1 and R5 while compared R2, R3, R4, R6 and R7. Refrigerants R2, R3 and R6 give the closer value to the HFC refrigerants R1 and R5. The refrigerant mixture R3 and R6 represents 6.08% less than that of R1 and R5.

EFFECT OF EVAPORATOR TEMPERATURE

The following results were obtained for a different evaporating temperature ranging from –25 to 0ºC with constant condensing temperature of 40ºC. The refrigerants R1 and R5 show same results for all operating conditions. Due to very hot climatic condition, the condenser temperature has assumed as 40ºC.

The pressure ratio of the proposed refrigerants is shown in Fig. 11. Refrigerants R1 and R5 have the maximum pressure ratio. The refrigerant mixtures R3 and R6 have 11% decrease in pressure ratio when compared with R1 and R5. In addition, refrigerants R1 and R5 have 1.45% higher volumetric efficiency with R4 for the same operating temperature. Pressure ratio influence the volumetric

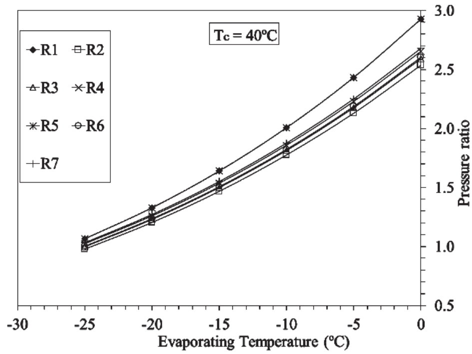

Fig. 11. Variation in pressure ratio with respect to evaporating temperature

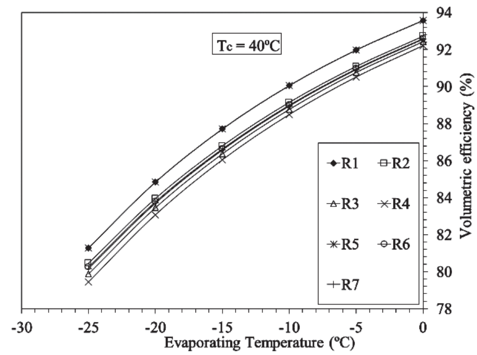

Fig. 12. Variation in volumetric efficiency with respect to evaporating temperature

efficiency of the proposed refrigerants and the effect of volumetric efficiency is shown in Fig. 12.

The decrease in compressor discharge temperature is achieved while increasing the evaporating temperature and indicated in Fig. 13. The HFC refrigerants R1 and R5 show highest compressor discharge temperature, which is 9.93% higher than that of R4. The mass flow rate of refrigerant at different evaporating temperature is shown in Fig. 14. Mixture of HC and HFC refrigerants R3, R4, R5 and R7 holds lower mass flow rate values and closer to each other. The mass flow rate of the HFC refrigerants R1 and R5 is 2.41 times more than R2 for the evaporating temperature of 0°C. The minimum mass flow rate is obtained for refrigerant R2 which decreases 58.59% for R1 and R5.

Figure 15 shows the volumetric cooling capacity of the refrigerants. The increase in the evaporating temperature results in increase of VCC drastically. Refrigerants R1 and R5 have the maximum value of VCC and R2 deceased by

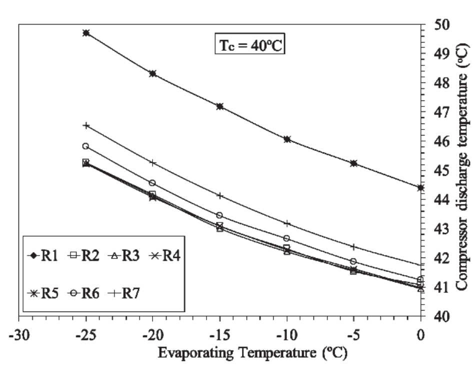

Fig. 13. Variation in compressor discharge temperature with respect to evaporating temperature

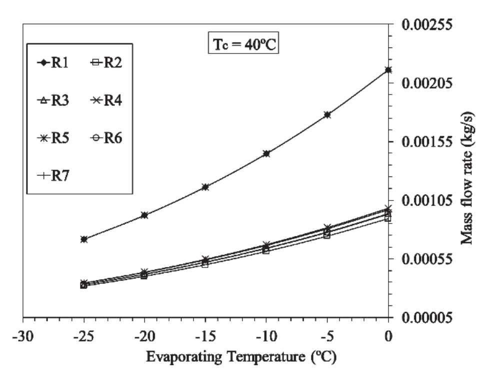

Fig. 14. Variation in mass flow rate with respect to evaporating temperature

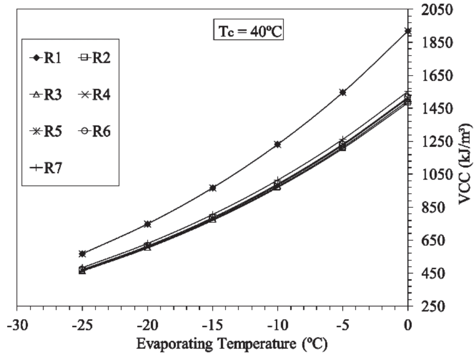

Fig. 15. Variation in volumetric cooling capacity with respect to evaporating temperature

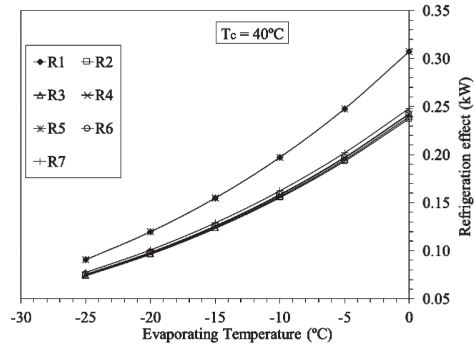

Fig. 16. Variation in refrigeration effect with respect to evaporating temperature

22.67% in VCC compared to R1 and R5. The refrigeration effect of the proposed refrigerants is compared with different evaporating temperature and shown in Fig. 16. It is seen that refrigerants R1 and R5 show maximum refrigeration effect and R2 represents the minimum value. Mixture of refrigerant R7 shows the closer value to R1 and R5, which is 19.17% less than of R1 and R5.

Compressor work of the analysed refrigerants is shown in Fig. 17. Refrigerant R2 shows the minimum compressor work. Refrigerants R1 and R5 consume 22.16% more power to run the compressor compared to R2. Compressor work is increased, when increasing the evaporating temperature. Figure 18 shows the change in condenser heat rejection for all the assessed refrigerants with increase in evaporating temperature. Condenser heat rejection is higher for the refrigerants R1 and R5. Refrigerant R2 represents 21.97% decrease in condenser heat rejection compared to R1 and R5.

COP of the proposed refrigerants are shown in Fig. 19. The COP is high for the HFC refrigerants R1 and R5 when compared with refrigerant mixtures R2,

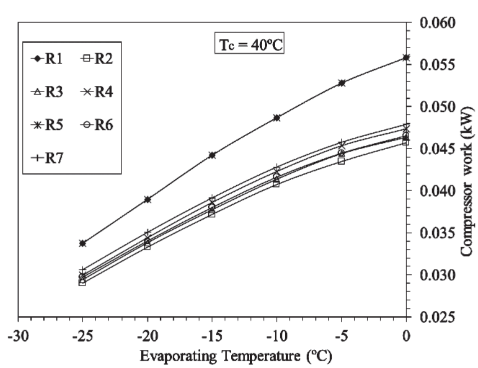

Fig. 17. Variation in compressor work with respect to evaporating temperature

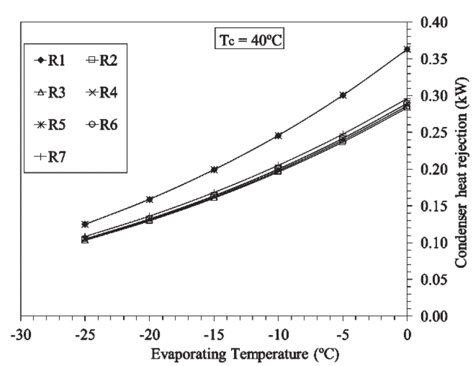

Fig. 18. Variation in condenser heat rejection with respect to evaporating temperature

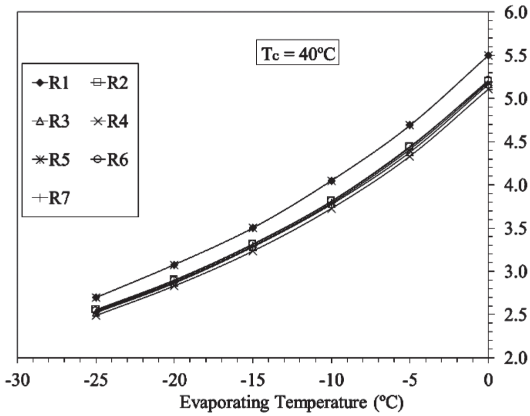

Fig. 19. Variation in COP with respect to evaporating temperature

R3, R4, R6 and R7. Refrigerants R2 and R6 give nearer values related to HFC refrigerants R1 and R5. The refrigerant R6 represents 5.29% lower than R1 and R5.

CONCLUSIONS

Comparative assessment were performed theoretically with different refrigerant mixtures in domestic refrigeration system and the following conclusions are arrived:

- Refrigerant R1 is halogenated compounds which has high GWP which causes harmful effect to the environment.
- Refrigerant R2 offers many desirable characteristics such as low pressure ratio, high volumetric efficiency, high compressor discharge temperature, low compressor work, high COP and low mass flow rate. It gives the closer value to the refrigerant R134a.
- Refrigerant R2 has very low VCC compared to refrigerant R1. Due to mismatch in VCC, pure hydrocarbon refrigerants are not suitable for alternative to refrigerant R1.
- Refrigerants R6 and R7 have achieved closer value of pressure ratio, volumetric efficiency, mass flow rate, compressor work, COP to the refrigerant R2.
- The refrigerant mixture R7 has shown higher value of VCC next to refrigerant R1. It has 4.68% higher VCC than refrigerant R2 for a condensing and evaporating temperature of 25ºC and –10ºC.
- Refrigerant R7 has 4.68% higher refrigeration effect compared to refrigerant R2 under same condensing and evaporating temperature.
- For refrigerant mixture R7 the condenser heat rejection is 4.74% higher than the refrigerant R2 under same condensing and evaporating temperature.

• Refrigerant R6 receives same COP as compared to refrigerant R2 for various evaporating temperatures and the condensing temperature of 40ºC.

The results also prove that the refrigerant mixtures R3 and R6 are found to be the best environmental friendly drop in substitute for the refrigerants R1, R2 and R5 for a domestic refrigeration system.

NOMENCLATURE

C	Clearance ratio
COP	Coefficient of Performance
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
h	Enthalpy (kJ/kg)
LFL	Lower Flammable Limit (%)
m_r	Mass flow rate of refrigerant (kg/s)
n	Polytropic index
N	Speed (rpm)
PI_{com}	Compressor power input (kW)
Pr	Pressure ratio
Q_{eva}	Heat absorbed in evaporator (kW)
Q_{cond}	Heat rejected in condenser (kW)
T	Temperature (ºC)
T_{sup}	Superheated temperature (ºC)
T_{sat}	Saturated temperature (ºC)
VCC	Volumetric Cooling Capacity (kJ/m^3)
v	Specific volume (m^3/kg)
η_{vol}	Volumetric efficiency (%)
ΔT	Temperature difference (ºC)
T_c	Condensing temperature (ºC)
T_e	Evaporating temperature (ºC)
V_{st}	Displacement volume (cm^3)

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