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Ashok Babu Puttaranga Setty Talanki
National Institute of Technology Karnataka, India, tpashok@rediffmail.com

Sharmas Vali Shaik
National Institute Of Technology Karnataka, India, sharmasvali.nitk@gmail.com

Thermodynamic Analysis of Vapour Compression Refrigeration System with Sustainable Refrigerant Blends as Alternatives to Replace R22

Shaik SHARMAS VALI[1], Talanki Puttaranga Setty ASHOK BABU [2]*

[1] NITK Surathkal, Department of Mechanical Engineering,
Mangalore, Karnataka, India
(+91 8904358048, sharmasvali.nitk@gmail.com)

[2*] NITK Surathkal, Department of Mechanical Engineering,
Mangalore, Karnataka, India
(+91 9986548546, tpashok@rediffmail.com, tpab57@gmail.com)

* Corresponding Author

ABSTRACT

The phase out schedule of a hydrochlorofluorocarbon refrigerant R22 demands the development of an ecofriendly refrigerants. Since R22 has adverse ecological effects like high ODP and high GWP. Hence this paper emphasis on the thermodynamic analysis of various ozone friendly refrigerant blends as an alternatives to R22 used in a vapour compression refrigeration system (VCRS). In this work eight refrigerant blends consists of R290, R134a, R152a, R125 and R32 at various compositions are developed. All the developed refrigerants possess zero ODP and low GWP compared to R22. The main goal of the study is to calculate the performance characteristics of actual VCR cycle using R22 and its various developed alternatives. The performance characteristic of eight studied refrigerants are computed at evaporating and condensing temperature of 7.2ºC and 54.4ºC respectively by using a MATLAB code. The results showed that COP of a refrigerant mixture RM40 (3.541) is higher among the eight studied refrigerants and it is 0.2 % higher than the COP of R22 (3.534). GWP of RM40 (10) is lowest among the GWP of R22 (1760) and eight studied refrigerants. The compressor discharge temperature of RM40 is lowest among the eight studied refrigerants and it is reduced by 6.6ºC when compared to R22. Power spent per ton of refrigeration of RM40 (0.992 kW/TR) is lower among the eight studied blends and it is marginally lower than that of R22 (0.994 kW/TR). Volumetric cooling of capacity of RM40 (2837 kJ/m^3) is higher among the eight investigated mixtures and it is quite similar to R22 (3086 kJ/m^3). Overall the thermodynamic performance of a novel binary blend RM40 (R290/R152a 95/5 composition mass %) is very close to R22 and hence it is a sustainable alternative refrigerant to replace R22.

1. INTRODUCTION

From past several years refrigerant R22 was extensively used in the heat pump and air conditioner sectors due to its favorable characteristics (Mohanraj et al., 2009). However R22 has high global warming potential (GWP) and it contains ozone depleting substance named chlorine. Hence an international protocol like Montreal protocol has been taken the decision to ban the R22 by the year 2030 (UNEP, 1987, Powell, 2002). In this regard many nations were spending the ample focus and effort to develop their own replacements to refrigerant R22. From past several years, various performance studies has been carried out to find viable replacement to R22. Godwin specified that the performance of ternary mixture R32/R125/R134a (30/10/60 by wt %) was relatively similar compared to R22 (Godwin, 1994). Spatz and Motta conducted the theoretical studies with R290 and R22 used in commercial refrigeration applications (Spatz and Motta, 2003). Results exhibited that COP of R290 was higher compared to R22 in the range 2-4%. Performance investigation of R22 and R32/R134a (0.3/0.7 mass fraction) was done with a conventional refrigeration cycle (CRC) and new refrigeration cycle (NRC) which recollects the Lorentz cycle (Jianyong Chen and Jianlin Yu 2008). Results showed that performance of the above blend with CRC was nearer to R22 whereas COP of R32/R134a (0.3/0.7 mass fraction) with NRC was higher than the R22 in the range of 8-9%.

Experimental studies were carried out in a split air conditioner with R22 and R1270 (Jianbo Chen et al., 2011). Results exhibited that performance of R1270 was better than the R22 and cooling capacity was quite nearly about 96% that of the base line refrigerant R22. Refrigerant R32 was recommended as a viable candidate to replace R410A used in air conditioners (Adrián Mota-Babilonia et al., 2017). Segment-to-Segment modeling of microchannel heat exchangers (condenser and evaporator) were developed in order to predict the performance of an air conditioning system using various alternative refrigerants (Bo Shen et al., 2016). The benefit of microchannel heat exchangers was it reduces the charge of refrigerant required to the system. Investigation results revealed that R32 showed the better performance compared to R410A whereas R22 and R290 had similar performance, however R290 required a larger displace volume of compressor. Experimental performance testing of an inverter based heat pump was done with R32, R290 and R410A (Supharuek Konghuayrob and Kornvalee Khositkullaporn, 2016). From the performance comparison of above refrigerants, it was observed that the R32 was the potential Refrigerant for heat pump application when discharge superheat control concept has been implemented. Theoretical studied reported that the similar compressor would be used for R1270 as that of R22 (Sharmas Vali Shaik and Talanki Puttaranga Setty Ashok Babu, 2018). From past many yeras R410A and R407C were used as alternatives to R22 (Calm, and Domanski, 2004). Altough R407C and R410A were ozone friendly, but their usage was limited due to high global warming potential (GWP). Hence this study focuses on developing the new alternative refrigerants having zero ODP and low GWP.

2. DEVELOPMENT OF NEW BLENDS

In this work eight refrigerant blends consists of R32, R125, R134a, R152a, and R290 at different compositions are developed. The designation and basic properties of above refrigerant blends are given in table1 and table2 respectively.

Table 1: Designation of Refrigerants

Designation of Refrigerants	Compostion (mass %)
R22	Pure refrigerant
RM10 (R32/R134a)	26/74
RM20 (R32/R134a)	30/70
RM30 (R32/R134a)	35/65
RM40 (R290/R152a)	95/5
RM50 (R32/R134a/R152a)	20/40/40
RM60 (R32/R134a/R152a)	15/35/50
R410A (R32/R125)	50/50
R407C (R32/R125/R134a)	23/25/52

Table 2: Properties of Refrigerants

Refrigerant	MW (kg/kmol)	BP (°C)	T_{bub} (°C)	T_{dew} (°C)	T^*_{glide} (°C)	T_c (K)	P_c (Mpa)	ODP	GWP (100 years)
R22	86.5	-40.81	0	0	0	369.3	4.990	0.055	1760
RM10	81.631	-	-40.49	-33.46	7.03	365.83	4.776	0	1138
RM20	79.194	-	-41.68	-34.51	7.17	364.73	4.858	0	1113
RM30	76.346	-	-43.0	-35.8	7.2	363.41	4.954	0	1082
RM40	44.841	-	-42.53	-42.40	0.13	368.93	4.253	0	10
RM50	72.356	-	-36.27	-29.07	7.2	374.55	4.803	0	711
RM60	72.028	-	-33.70	-27.61	6.09	377.24	4.716	0	627
R410A	72.585	-	-51.44	-51.36	0.08	344.49	4.901	0	1924
R407C	86.204	-	-43.63	-36.63	7.0	359.29	4.639	0	1624

*$T_{glide} = T_{dew} - T_{bub}$ at 101.325 kPa

From the table 2 it is noticed that all the eight developed refrigerant blends are ozone friendly and having low GWP compared to R22. Refrigerants like RM40, RM50 and RM60 possess zero ODP and low GWP compared to R22. Specifically RM40 can be considered as environmental friendly refrigerant. Since RM40 has zero ODP and very low

GWP compared to R22. From table 2 it is also evident that the refrigerant blends (RM10 to RM30, RM50 to RM60 and R407C) are zeotropic in nature due to their high temperature glide. Whereas refrigerants RM40 and R410A are near azeotropic in nature due to their low temperature glide.

Thermodynamic properties are useful to evaluate the performance characteristics of various R22 developed refrigerants. Hence in this study, Martin-Hou equation of state is used to compute the thermodynamic properties of all the investigated blends (Martin Joseph J and Yu-Chun Hou., 1955).

$$p = \frac{RT}{v-b} + \frac{A_2 + B_2 T + C_2 e^{\frac{-5.475T}{T_c}}}{(v-b)^2} + \frac{A_3 + B_3 T + C_3 e^{\frac{-5.475T}{T_c}}}{(v-b)^3} + \frac{A_4}{(v-b)^4} + \frac{b_5 T}{(v-b)^5} \quad (1)$$

The mixing rules and binary interaction parameter used in the development of the properties of refrigerant mixtures are taken from the literature and they are given below (Bruce E Poling et al., 2001, Chueh and Prausnitz, 1967).

$$P_{cm} = \frac{Z_{cm} R T_{cm}}{V_{cm}} = \frac{\left(\sum_{i=1}^{n} y_i Z_{ci}\right) R \left(\sum_{i=1}^{n} y_i T_{ci}\right)}{\left(\sum_{i=1}^{n} y_i V_{ci}\right)} \quad (2)$$

$$T_{cm} = y_i^2 T_i + y_j^2 T_j + 2 y_i y_j Tc_{ij} \quad (3)$$

$$T_{cij} = (1 - k_{ij})(T_{ci} T_{cj})^{1/2} \quad (4)$$

Binary interaction parameter k_{ij} is given by

$$k_{ij} = 1 - \frac{8\left(V_{ci} V_{cj}\right)^{1/2}}{(V_{ci}^{1/3} + V_{cj}^{1/3})^3} \quad (5)$$

The developed properties matches well with the experimental properties of ASHRAE refrigriants data hand book (ASHRAE, 2009). The percentage variation of estimated properties of R410A, R407C and R22 from ASHRAE is within 1.75 to 2.5% for the given operating conditions. Hence the procedure followed to develop the properties of R410A, R407C and R22 is reliable. Therefore same methodology is followed to develop the properties of new refrigerant blends as well.

3. METHODOLOGY AND COMPUTATIONS

Normally thermodynamic analysis is carried out to find a suitable alternative to base line refrigerant R22. Refrigerant R22 is widely used in air conditioners. Basically air conditioners works on the principle of vapour compression refrigeration system (VCRS). The basic representation of VCRS is shown in figure1 (Arora, 2009). The VCRS consists of four process like isentropic compression, constant pressure condensation, isenthalpic expansion and constant pressure evaporation. However in actual practice pressure losses occurs at various system components. Hence this study focuses on the actual VCR cycle for the performance analysis. Pressure-Enthalpy diagram of the actual cycle is shown in figure 2 (Arora, 2009). The capacity of air conditioner is taken as 1.5TR. The description and losses occurred at various state points of the actual cycle are taken from the literature and they are listed in table 3 (Arora, 2009) and 4 respectively (Sharmas Vali Shaik and Talanki Puttaranga Setty Ashok Babu, 2018).

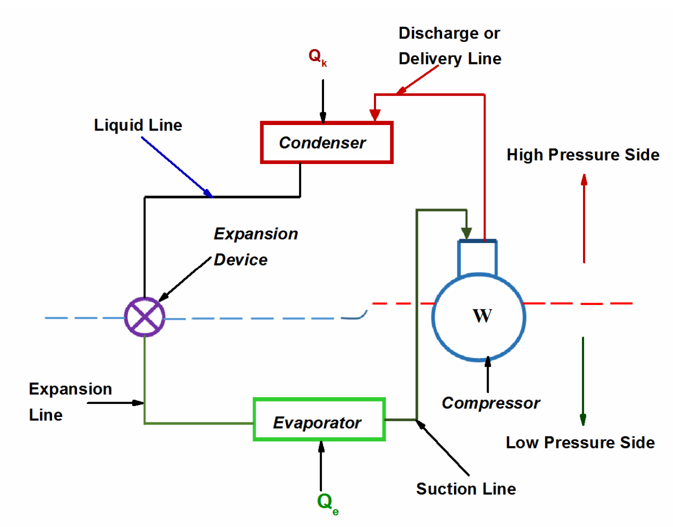


Figure 1: Representation of VCR system

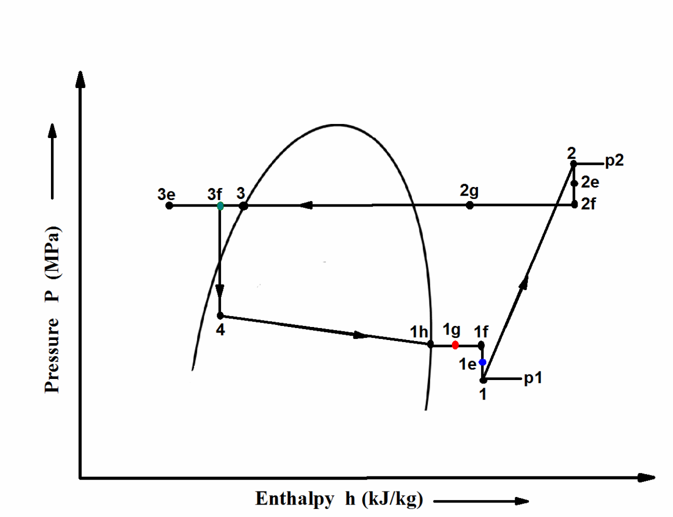


Figure 2 : Pressure-Enthalpy diagram of actual VCR cycle

Table 3: Description of the actual VCR cycle

Various state points of the cycle	Description
4-1h	Evaporator pressure loss
1h-1g	Superheating of refrigerant in the evaporator
1g-1f	Refrigerant superheating and heat gain in the suction line
1f-1e	Suction line pressure loss
1e-1	Suction valve pressure drop
1-2	Polytropic compression work
2-2e	discharge valve pressure drop
2e-2f	Pressure loss in the discharge line
2f-2g	Desuperheating of refrigerant and heat loss through discharge line
2f-3	Condenser pressure loss
3-3e	Refrigerant subcooling in the condenser
3e-3f	Heat gain through the liquid line

Table 4: Various losses considered in the actual cycle

Description	Values
Suction valve pressure drop	0.2 bar
Discharge valve pressure drop	0.4 bar
Suction line pressure drop	0.1 bar
Discharge line pressure drop	0.1 bar
Evaporator pressure drop	0.1 bar
Heat gain at compressor inlet due to temperature rise	10ºC
Heat loss at compressor exit due to temperature drop	10ºC
Degree of superheating	10ºC
Degree of subcooling	5ºC

Performance characteristics of R22 and its considered alternatives are evaluated at ARI conditions and these conditions are shown in Table 5.

Table 5: ARI conditions for air conditioners

Operating conditions	Temperature (ºC)
Evaporator temperature	7.2
Condenser temperature	54.4

The calculations involved during the performance computation of air conditioner is given below.

Mass flow rate of refrigerant is calculated as

$$m = \frac{Q_c}{RE} \tag{6}$$

Refrigeration effect is calculated as

$$RE = (h_{1g} - h_4) \tag{7}$$

Isentropic work of compression is calculated by

$$W_c = (h_2 - h_1) \tag{8}$$

Coefficient of performance is computed as

$$COP = (RE/W_c) \tag{9}$$

Power per ton of refrigeration is calculated as

$$PPTR = \left(\frac{3.5167}{COP}\right) \tag{10}$$

Volumetric cooling capacity is computed by

$$VCC = (\rho_{1g} \times RE) \tag{11}$$

Heat rejected through the condenser is computed by

$$CHR = (\mathrm{h}_{2\mathrm{f}} - h_{3e}) \tag{12}$$

Discharge temperature of compressor can be found with the help of refrigerants superheated properties tables and by interpolating for the given superheating value equivalent to difference in entropy which is known. Results of performance parameters of R22 alternatives are tabulated in Table 6.

Table 6: Thermodynamic performance results of R22 alternatives

Refrigerant	**m (kg/min)**	**RE (kJ/kg)**	**Wc (kJ/kg)**	**COP**	**CHR (kJ/kg)**	**T_d (°C)**	**PPTR (kW/TR)**	**VCC (kJ/m³)**
R22	2.298	137.672	38.949	3.534	179.706	95.85	0.994	3086
RM10	2.047	154.580	53.526	2.887	218.362	97.71	1.217	2546
RM20	2.001	158.163	56.375	2.805	224.819	102.73	1.253	2653
RM30	1.941	163.024	58.275	2.797	231.659	104.97	1.257	2791
RM40	1.169	270.698	76.434	3.541	365.206	89.21	0.992	2837
RM50	1.553	203.768	63.457	3.211	278.460	101.35	1.095	2477
RM60	1.490	212.315	62.113	3.418	285.965	97.15	1.028	2371
R410A	2.114	149.654	46.198	3.239	207.003	95.63	1.085	4542
R407C	2.283	138.613	49.444	2.803	198.157	95.83	1.254	2745

4. VALIDATION OF RESULTS

The computer MATLAB program is developed in this work to calculate the performance characteristics of various considered R22 alternatives. The significance of this program is, it incorporates the saturated and superheated properties of given refrigerants and also any given operating conditions of the system. The present MATLAB program results are compared with previous researchers' results available in literature (Dalkilic and Wongwises, 2010). Dalkilic et.al computed the performance characteristics of simple VCR cycle using refrigerant R22 at T_e= -10°C and T_k=50°C with no subcooling and superheating . For the validation, same refrigerant and operating conditions were used in the program as that of Dalkilic et.al. The R22 results obtained from the program were compared with the Dalkilic et.al results for R22 ((Dalkilic and Wongwises, 2010). The deviation of program results with Dalkilic et.al is below 1% and hence the developed computer MATLAB program is reliable. The percentage variation of results for the R22 is given in Table 7.

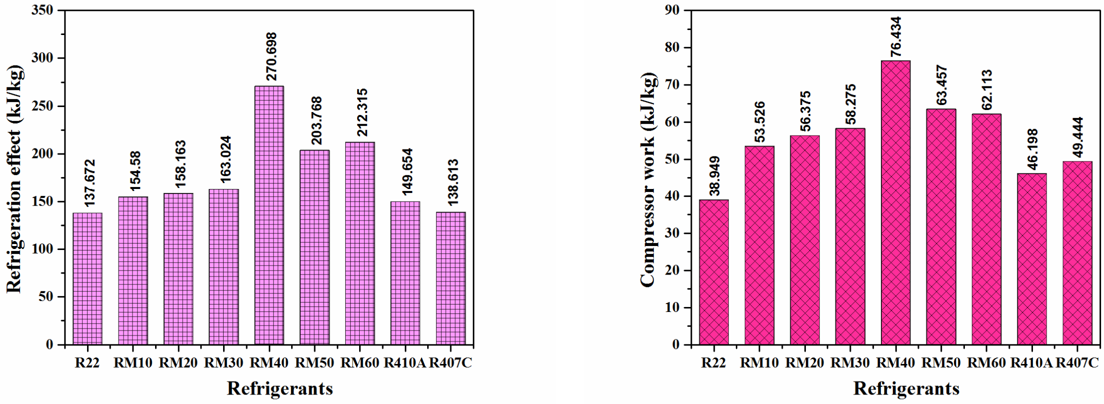
Table 7: Comparison of performance characteristics of R22 with Dalkilic results

S.NO	Performance characteristics	Dalkilic A.S. et.al for R22	Present computer MATLAB program for R22	Deviation (%)
1	P_k (Mpa)	1.943	1.9427	-0.015
2	P_e (Mpa)	0.355	0.35481	-0.053
3	RE (kJ/kg)	138	137.9490	-0.036
4	W_c (kJ/kg)	43.40	43.7740	0.861
5	COP	3.180	3.1514	-0.899
6	PPTR (kW/TR)	1.101	1.1106	0.871
7	VCC (kJ/m³)	1273.912	1280.525	0.5191

5. RESULTS AND DISCUSSIONS

5.1 Refrigeration Effect and Compressor Work

Figure 3(a) illustrates the cooling effect produced by the various alternative refrigerants. From the figure 3(a) it is evident that refrigerants (RM10 to RM60) possess higher refrigeration effect compared to R410A, R407C and R22. Since these refrigerants (RM10 to RM60) have high latent heat of vapourization compared to R410A, R407C and R22. Figure 3(b) illustrates the the work input required to the compressor for various alternative refrigerants in order to produce required cooling effect. From the figure 3(b) it is clear that refrigerant mixtures (RM10 to RM60) possess higher compressor work compared to R410A, R407C and R22. Since these refrigerant blends (RM10 to RM60) have higher vapour enthalpy values compared to R410A, R407C, and R22.

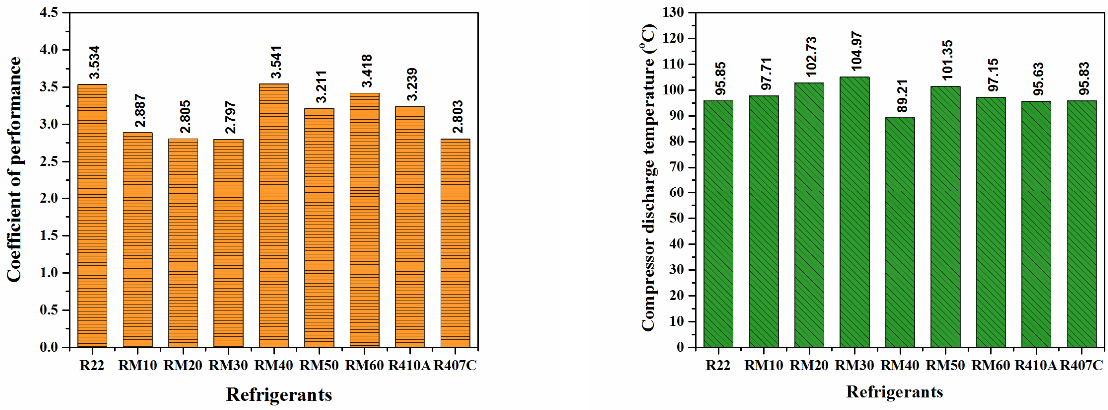


(a) (b)

Figure 3 : (a) Refrigeration effect of R22 alternatives (b) Compressor work of R22 alternatives

5.2 Coefficient of Performance and Compressor Discharge Temperature

Figure 4(a) illustrates the Coefficient of performance (COP) of various R22 alternative refrigerants. İt can be considered as an energy efficiency index of the equipment when it is operating with particular refrigerant. From the figure 4(a) it is evident that COP of refrigerant mixture RM40 is 0.2% higher compared to R22 and eight studied blends.Since COP depends on the cooling effect as well as work of compression. Figure 4(b) illustrates the discharge temperature of compressor for various considered R22 alternatives. Compressor discharge temperature imparts the life span of the compressor motor. Hence it is essential to compute the discharge temperature of compressor operating with various refrigerants. The excessive discharge temperature causes the burnt out of windings of the compressor motor. Hence discharge temperature should be low from the compressor life point of view. From the figure 4(b) it is found that discharge temperature of refrigerant mixture RM40 is 6.64^{o}C lower compared to R22 and eight investigated refrigerant mixtures. Since RM40 possess lower pressure ratio compared to R22 and other considered refrigerants.



(a) (b)

Figure 4 : (a) Coefficient of performance of R22 alternatives (b) Compressor discharge temperature of R22 alternatives

5.3 Heat rejected through the condenser

Figure 5 illustrates the condenser heat rejection of various R22 alternatives. From the figure 5 it is observed that heat rejected through the condenser for the refrigerant mixtures (RM10 to RM60) is higher than the R410A, R407C and R22. Since these refrigerant blends are have high latent heat of condensation compared to R410A, R407C and R22.

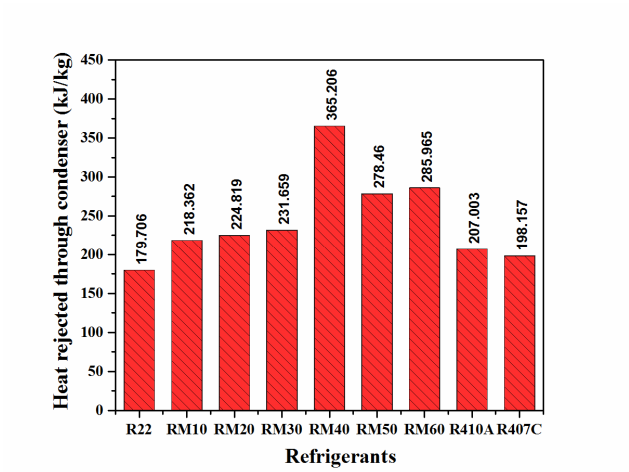
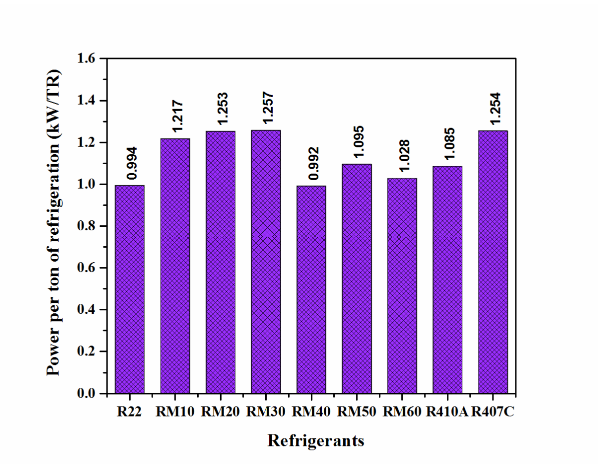


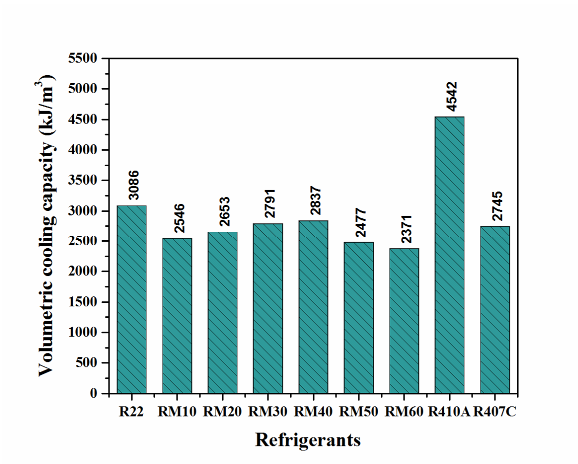
Figure 5 : Heat rejected through the condenser of various R22 alternatives

5.4 Compressor Power per Ton of Refrigeration and Volumetric Cooling Capacity

Compressor power required per ton of refrigeration is inversly proportional to COP. From the figure 6(a) it is clear that electrical power consumed by the compressor for RM40 is 0.2% lower compared to R22 and eight studied refrigerants. Since COP of RM40 is higher compared to R22 and eight studied refrigerants. Figure 6(b) illustrates the volumetric cooling capacity of various refrigerants. Volumetric cooling capacity indicates the size of compressor required to produce the required cooling effect. It depends upon on vapour density occurs at the exit of evaporator and also on the refrigeration effect. From the figure 6(b) it is observed that the volumetric cooling capacity of RM40 (2837 kJ/m3) is higher than R407C (2745 kJ/m^3) and it is quite similar to R22 (3086 kJ/m^3). Hence similar compressor can be used for RM40 as that of R22. However volumetric capacity of R410A is very high among the R22, R407C and other considered refrigerants. Hence R410A requires the redesign of compressor.



(a)



(b)

Figure 6 : (a) Compressor power per ton of refrigeration of R22 alternatives (b) Volumetric cooling capacity of R22 alternatives

6. CONCLUSIONS

From the performance study of various R22 developed alternatives, the conclusions can be made as follows.

- The coefficient of performance of RM40 was 0.2% higher compared to R22 and eight studied blends. The GWP of RM40 (10) was very low compared to that of GWP of R22 (1760).
- Power consumed by the compressor for RM40 was 0.2% lower compared to R22 and eight considered blends.
- Discharge temperature of RM40 was lowest among the R22 and eight studied refrigerants. And it was reduced by 6.64°C when compared to R22. Hence RM40 exhibited better lifespan of compressor motor.
- Volumetric cooling capacity of RM40 (2837 kJ/m^3) was higher than R407C (2745 kJ/m^3) and it was quite similar to R22 (3086 kJ/m3). Therefore similar compressor would be used for RM40 as that of R22. But R410A demands the redesign of compressor. Since its volumetric cooling capacity was very high compared to R22 and eight investigated refrigerants.
- Overall the thermodynamic performance of new refrigerant mixture RM40 (R290/R152a 95/5 composition mass %) is better than the base line refrigerant R22. Hence RM40 is a new sustainable replacement to R22 used in air conditioners.

NOMENCLATURE

ARI	Air conditioning and refrigeration institute	
BP	Boiling point	
GWP	Global warming potential	
ODP	Ozone depletion potential	
h	Enthalpy	(kJ/kg)
h_1	Enthalpy at compressor inlet	(kJ/kg)
h_{1g}	Enthalpy at evaporator outlet	(kJ/kg)
h_2	Enthalpy at compressor outlet	(kJ/kg)
h_{2f}	Enthalpy at condenser inlet	(kJ/kg)
h_{3e}	Enthalpy at condenser outlet	(kJ/kg)
h_4	Enthalpy at evaporator inlet	(kJ/kg)
m	Mass flow rate of the refrigerant	(kg/min)
MW	Molecular weight	(kg/kmol)
P	Pressure	(MPa)
P_c	Critical pressure	(MPa)
P_{cm}	Critical pressure of the mixture	(MPa)
P_e	Evaporator pressure	(MPa)
P_k	Condenser pressure	(MPa)
R	Universal gas constant	(J/mol K)
T_{bub}	Bubble point temperature	(°C)
T_c	Critical temperature	(K)
T_{cm}	Critical temperature of the mixture	(K)
T_d	Compressor discharge temperature	(°C)
T_{dew}	Dew point temperature	(°C)
T_e	Evaporating temperature	(°C)
T_{glide}	Temperature glide	(°C)
T_k	Condensing temperature	(°C)
Q_c	Refrigeration capacity	(kW)
v	Specific volume	(m^3/kg)
V_{cm}	Critical volume of the mixture	(m^3)
ρ_{1g}	Density at exit of evaporator	(kg/m^3)

Greek Letters

ρ	Density	(kg/m^3)

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