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Analytical computation of thermodynamic performance parameters of actual vapour compression refrigeration system with R22, R32, R134a, R152a, R290 and R1270

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Abstract. The present work focuses on analytical computation of thermodynamic performance of actual vapour compression refrigeration system by using six pure refrigerants. The refrigerants are namely R22, R32, R134a, R152a, R290 and R1270 respectively. A MATLAB code is developed to compute the thermodynamic performance parameters of actual vapour compression system such as refrigeration effect, compressor work, COP, power per ton of refrigeration, compressor discharge temperature and volumetric refrigeration capacity at condensing and evaporating temperatures of 54.4oC and 7.2oC respectively. Analytical results exhibited that COP of both R32 and R134a are 15.95% and 11.71% higher among the six investigated refrigerants. However R32 and R134a cannot be replaced directly into R22 system. This is due to their higher compressor discharge temperature and poor volumetric capacity respectively. The discharge temperature of both R1270 and R290 are lower than R22 by 20-26oC. Volumetric refrigeration capacity of R1270 (3197 kJ/m3) is very close to that of volumetric capacity of R22 (3251 kJ/m3). Both R1270 and R290 shows good miscibility with R22 mineral oil. Overall R1270 would be a suitable ecofriendly refrigerant to replace R22 from the stand point of ODP, GWP, volumetric capacity, discharge temperature and miscibility with mineral oil although its COP is lower.

Keywords: Discharge temperature; Ecofriendly; Miscibility; R1270; Volumetric capacity

1 Introduction

Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) was extensively used in vapour compression based refrigeration industries from past several years due to their better thermophysical and thermodynamic properties [1]. However CFCs and HCFCs contains ODP (ozone depletion potential) and high GWP (global warming potential) and hence CFCs and HCFCs were eventually phase out in all the developing nations by the year 2010 and in all the developed nations by the year 2030 respectively in accordance to Monetreal protocal [2-3]. Therefore it is essential to develop new ecofriendly refrigerants.

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Formerly several theoretical and experimintal studies were carried to find an appropriate fluids to replace R22 and R134a respectively. Experimental peformance tests were carried out in a vapour compression plant with R134a, R152a, R290, R600a, R1234yf and R1234ze(E) respectively [4]. Tests results revealed that refrigerants R152a and R1234yf were suitable drop in replacements to R134a. Expermimental studies were done in a vapour compression test setup with R513A and R134a [5]. Results reported that superior peformance of R513A would be obtained only with the adjustment of thermostatic expansion valve. Peformance tests were conducted in a heat pump tester under various test conditions with hydrocarbons like R290 and R1270 [6]. Experimental results showed that performance of both R1270 and R290 were better than the R22. Particulary R290 exhibited 6-12% higher COP under various test conditions compared to R22. Therotical thermodynamic analyis was carried out in a standard vapour compression system with RE170, R290, R1270, R600a, R32, R134 and R152a respectively [7]. Reults exhibited that peformance of RE170 was higher among other studied refriferants and hence it was a viable alternative to R134a. Theoretical and experimintal investiagtions were done in an air conditioner under different operating conditions with R161 and R22 [8]. Both theoretical and exprimental results exhibited that energy efficiency ratio of R161 was superior than the R22. A thorough review study reported that hydrcarbons and its mixtures were viable refrigerants to refrigeration related industries [9]. Therortical performance studies were carried out in a simple saturation vapour compression system with R1234yf, R161, R152a and R134a respectively [10]. Results revealed that R152a would be a better choice to replace R134a from the stand point of COP, power savings, volumetric capacity and GWP. The present work emphasis on performance computation of six pure refrigerants based on actual vapour compression cycle in order to find an appropriate candidate to replace R22.

2 Properties of investigated refrigerants

In this study six pure refrigerants like R22, R32, R134a, R152a, R290 and R1270 are considered and thermodynamic properties of all the six pure refrigerants are must require to do the thermodynamic analysis of vapour compression refrigeration system. Hence a computer MATLAB program is written to develop the thermodynamic properties of six pure refrigerants by using Martin-Hou equation of state [11].

$$P = \frac{RT}{v-b} + \frac{a_2 + b_2 T + c_2 e^{\frac{-5.475T}{T_C}}}{(v-b)^2} + \frac{a_3 + b_3 T + c_3 e^{\frac{-5.475T}{T_C}}}{(v-b)^3} + \frac{a_4}{(v-b)^4} + \frac{b_5 T}{(v-b)^5} \quad (1)$$

The developed properties of all the six studied refrigerants shows good agreement with the experimental reported properties available in ASHRAE hand book [12]. The deviation of computed properties of all the six pure refrigerants from that of ASHRAE are within 1.5 to 3% for the given operating conditions. Hence the developed MATLAB code is reliable and therefore the same developed thermodynamic properties are used in this study. The basic physical and critical characteristics of six pure refrigerants are taken from the ASHRAE hand book and it is given below in table 1.

Table 1. Basic properties of pure refrigerants

Refrigerant	M (kg/kmol)	T_b (°C)	P_c (MPa)	T_c (K)	ODP	GWP (100 years)
R22	86.5	-40.81	4.99	369.3	0.055	1760
R32	52.024	-51.651	5.782	351.25	0	677
R134a	102.03	-26.074	4.0593	374.21	0	1300
R152a	66.051	-24.023	4.5168	386.41	0	140
R290	44.096	-42.11	4.2512	369.89	0	3
R1270	42.08	-47.62	4.5548	364.21	0	3

3 Thermodynamic performance analysis

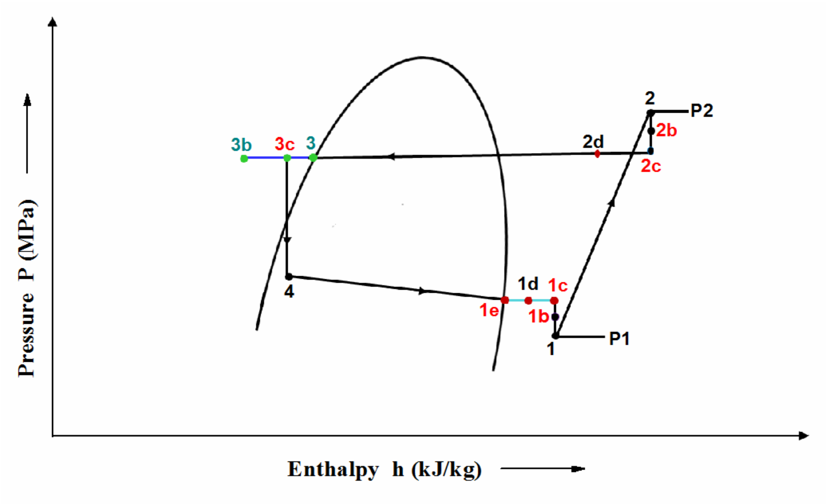

Fig 1. P-h diagram of actual vapour compression refrigeration cycle.

In the present methodology analytical computation of thermodynamic performance of six pure refrigerants (R22, R32, R134a, R152a, R290 and R1270) is done based on actual vapour compression refrigeration cycle. In this cycle superheating, subcooling, various pressure and heat losses or heat gain occurred at different components of the system are considered and they are given in table 2 and 3 respectively [13-14].The p-h diagram of actual vapour compression refrigeration cycle is shown in figure 1 [15-16]. A MATLAB code is developed to compute the thermodynamic performance parameters of six pure refrigerants at ARI conditions (Tk=54.4oC and Te=7.2oC) respectively. The various performance parameters are refrigeration effect, compressor work, coefficient of performance, compressor discharge temperature, power per ton of refrigeration and volumetric refrigeration capacity. The capacity and operating conditions of the system considered for all the six refrigerants are Q=1.5 TR, Tk=54.4oC and Te=7.2oC respectively.

Table 2. Explanation of different state points of the cycle

State points of the cycle	Explanation
4-1e	Pressure drop in the evaporator
1e-1d	Superheating of refrigerant vapour occurred in the evaporator
1d-1c	Heat gain and refrigerant superheating in the suction pipe line
1c-1b	Pressure drop through suction line
1b-1	Pressure drop across suction valve
1-2	Compressor work
2-2b	Pressure drop across discharge valve
2b-2c	Pressure drop in the discharge line
2c-2d	Heat loss and refrigerant desuperheating in the discharge pipe line
2c-3	Pressure drop in the condenser
3-3b	Subcooling
3b-3c	Heat gain occurred in the liquid pipe line

Table 3. Description of various losses considered in the cycle

S. No.	Description	Values
1	Pressure loss across suction valve	0.2 bar
2	Pressure loss across discharge valve	0.4 bar
3	Pressure drop occurred in the suction line	0.1 bar
4	Pressure loss occurred in the discharge line	0.1 bar
5	Pressure drop in the evaporator	0.1 bar
6	Rise in temperature due to heat gain at the inlet of compressor	5°C
7	Temperature drop due to heat loss at the outlet of compressor	5°C
8	Degree of superheating	10°C
9	Degree of subcooling	5°C

4 Mathematical computations

The mathematical computations involved in the thermodynamic analysis of investigated refrigerants are given below.

Refrigerant mass flow rate is computed by

$$\dot{m} = Q/RE \qquad (2)$$

Isentropic compressor work is computed as

$$W_c = h_2 - h_1 \qquad (3)$$

Refrigerating effect (Cooling effect) is calculated as

$$RE = h_{1d} - h_4 \qquad (4)$$

.
Coefficient of performance (COP) is calculated as

$$COP = RE/W_c \qquad (5)$$

Energy (Power) consumption by the compressor per ton of refrigeration is computed by

$$PPTR = 3.5167/COP \quad (6)$$

Volumetric cooling capacity is calculated as

$$VRC = \rho_{1d} \times RE \quad (7)$$

The compressor discharge temperature (T_d) is computed using superheated property tables and interpolating for the degree of superheat corresponding to the entropy difference.

Table 4. Summary of results for the pure refrigerants

Refrigerant code	$\dot{m}$ (kg/min)	RE (kJ/kg)	W_c (kJ/kg)	COP	T_d (°C)	PPTR (kW/TR)	VRC (kJ/m³)
R22	2.236	141.502	38.642	3.661	91.40	0.960	3251
R32	1.302	242.923	57.220	4.245	110.18	0.828	5929
R134a	2.230	141.915	34.693	4.090	76.08	0.859	2103
R152a	1.447	218.678	61.441	3.559	92.22	0.988	1903
R290	1.334	237.232	71.110	3.336	65.19	1.054	2582
R1270	1.300	243.373	71.260	3.415	70.42	1.029	3196

5 Analytical validation

In the present study a MATLAB code was developed and it is used to compute the thermodynamic performance of R22 and its alternatives. To validate the MATLAB code, results are compared with the previously published data [7, 17]. Dalkilic AS and Wongwises S has computed the thermodynamic analysis of simple saturation vapour compression system with R22 at Tk = 50°C and Te=-10°C whereas Baskaran A and Koshy Mathews P has computed the thermodynamic performance of standard vapour compression system with R134a at Tk = 50°C and Te=-10°C by considering degree of superheating and subcooling as 10°C and 5°C respectively. For the validation of present MATLAB code, the same refrigerants R22, R134a and operating conditions are used as that of the previous authors. The results of thermodynamic performance parameters of refrigerants R22 and R134a obtained from the MATLAB code are compared with published data results and they are given in table 5 and 6 respectively. The deviation of MATLAB code results with Dalkilic AS, Wongwises S, Baskaran A, and Koshy Mathews P for both the R22 and R134a is less than 1%. Therefore the developed MATLAB code is reliable and hence it can be used for the computation of thermodynamic performance of any refrigerants.

Table 5. Comparison of thermodynamic performance parameters of MATLAB code results with Dalkilic AS and Wongwises S results for the refrigerant R22

S.NO	Performance parameters	Dalkilic AS and Wongwises S results for R22	MATLAB code results for R22	Deviation (%)
1	Evaporator pressure (MPa)	1.943	1.9427	-0.015
2	Condenser pressure (MPa)	0.355	0.35481	-0.053
3	Pressure ratio	5.476	5.4753	-0.012
4	Refrigeration effect (kJ/kg)	138	137.9490	-0.036
5	Compressor work (kJ/kg)	43.40	43.7740	0.861
6	COP	3.180	3.1514	-0.899
7	Power per ton of Refrigeration (kW/TR)	1.101	1.1106	0.871
8	Volumetric cooling capacity (kJ/m^3)	1273.912	1280.525	0.5191

Table 6. Comparison of thermodynamic performance parameters of MATLAB code results with Baskaran A and Koshy Mathews P results for the refrigerant R134a

S.NO	Performance parameters	Baskaran A and Koshy Mathews P results for R134a	MATLAB code results for R134a	Deviation (%)
1	Evaporator pressure (kPa)	200.6	200.41	-0.094
2	Condenser pressure (kPa)	1317.9	1317.0	-0.068
3	Pressure ratio	6.57	6.5715	0.022
4	Refrigeration effect (kJ/kg)	137.28	138.2360	0.696
5	Compressor work (kJ/kg)	41.42	41.5229	0.248
6	COP	3.315	3.3292	0.428
7	Power per ton of Refrigeration (kW/TR)	1.057	1.0563	-0.066
8	Volumetric cooling capacity (kJ/m^3)	1314	1317.8	0.289

6 Results and discussions

The results and discussions of various thermodynamic performance parameters of six pure studied refrigerants are given below.

6.1 Refrigeration effect

Figure 2 shows the cooling effect (refrigeration effect) of various refrigerants. From the figure 2 it is noticed that refrigeration effect of refrigerants like R32, R152a, R290 and R1270 are higher than the R22. This is due to their high latent heat of vaporization when compared to R22.

6.2 Compressor work

Figure 3 shows the compressor work of six studied refrigerants. Referring to figure 3 it is observed that the compressor work of both R290and R1270 refrigerants are higher than the R22. This is due to high vapour enthalpies of refrigerants (R290 and R1270) compared to R22.

6.3 Coefficient of performance

Figure 4 shows shows the coefficient of performance of various considered refrigerants. COP is measured as an energy efficiency index of the device charged with particular refrigerant. From the table 4 it is seen that both cooling (refrigeration effect) effect and compressor work increase for the refrigerants R32, R152a, R290 and R1270 respectively. Therefore net effect of refrigeration effect and compressor work of these refrigerants on coefficient of performance may be either increases or decreases or remains same which depends on the type of the refrigerant and also on the operating conditions of the device. From the figure 4 it is clear that the COP of R32 and R134a is 15.95% and 11.71% higher than R22 respectively.

6.4 Compressor discharge temperature

Before introducing the new refrigerant into the device, it is essential to study the steadiness and lifetime of compressor. This can be done by computing the compressor discharge temperature of all the studied refrigerants. Referring to figure 5 it is noticed that compressor discharge temperature of both R1270 and R290 are lower than R22 by 20-26^{o}C. This is due to lower adiabatic index of refrigerants. The lower compressor discharge temperature is advantageous from the stand point of durability of the compressor life. Hence both R290 and R1270 fluids exhibits better reliability and lifespan of compressor motor. However R32 is not preferable from the stand point of compressor life because its discharge temperature is very high.

6.5 Power per ton of refrigeration

Figure 6 shows shows the power (energy) per ton of refrigeration for various studied refrigerants. It indicates the electrical work input required to the compressor to produce per ton of refrigeration. Referring to figure 6 it is observed that energy spent by the compressor per ton of refrigeration for the refrigerant R32 is 13.75 % lower among six investigated refrigerants. This is due to refrigerant type and also due to operating conditions of the given device.

6.6 Volumetric cooling capacity

Figure 7 shows shows the volumetric refrigeration capacity of various refrigerants. Volumetric refrigeration capacity depends on density of refrigerant vapour and refrigeration effect of the given fluid. It denotes the cooling capacity per unit volume of vapour refrigerant at the outlet of evaporator .And also it denotes the volume of refrigerant handled by the compressor for the given fluid. From the figure 7 it is evident that volumetric refrigeration capacity of R134a and R152a are lower than R22 and hence these refrigerants requires larger size of compressor whereas volumetric capacity of R32 is very high among six studied refrigerants. Therefore R32 requires redesign or smaller size of compressor.

Volumetric cooling capacity of refrigerant R1270 is very close to R22 and hence same size of compressor can be used for R1270 as that of R22. Volumetric capacity of R290 is in between R22 and R1270.

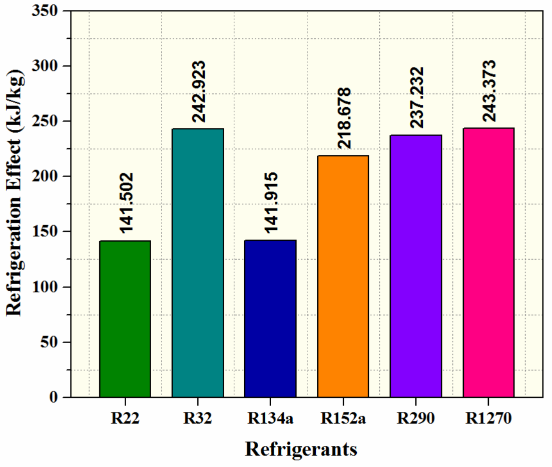

Fig 2. Refrigeration effect of various refrigerants

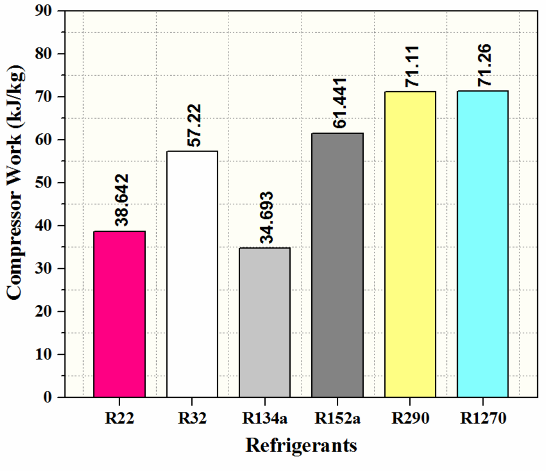

Fig 3. Compressor work of various refrigerants

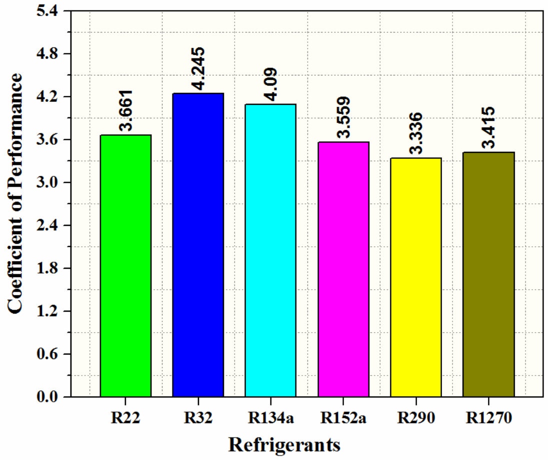

Fig 4. COP of various refrigerants

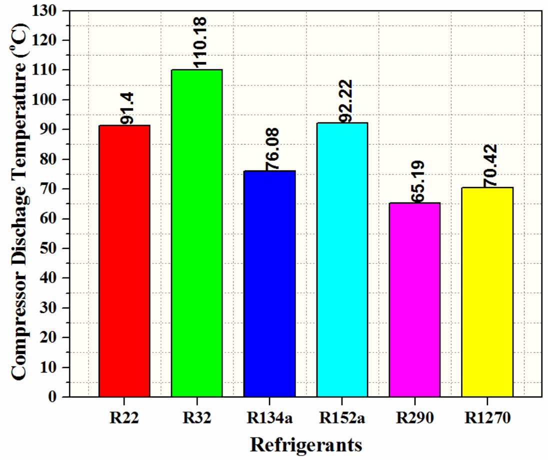

Fig 5. Compressor discharge temperature of various refrigerants

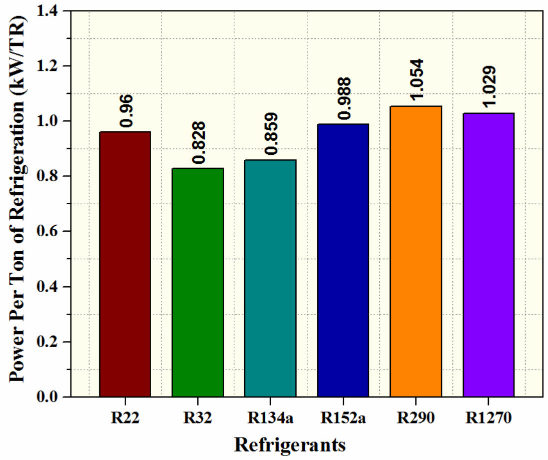

Fig 6. Power per ton of refrigeration of various refrigerants

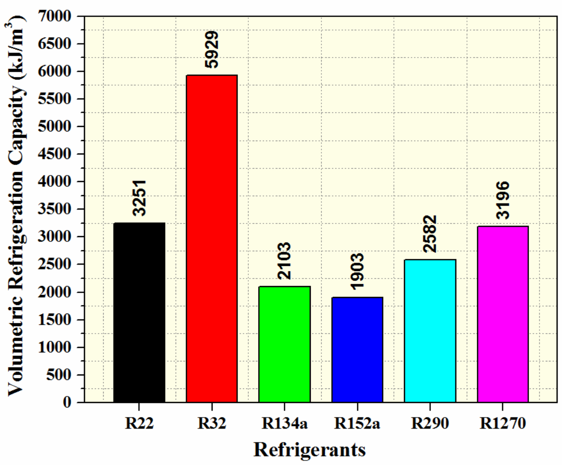

Fig 7. Volumetric refrigeration capacity of various refrigerants

7 Conclusions

From the thermodynamic performance computation of six pure refrigerants the following conclusions can be drawn.

- Eventhough COP of R32 and R134a were 15.95% and 11.71% higher among the six investigated refrigerants, they cannot be replaced directly into R22 system. This is due to their higher compressor discharge temperature and poor volumetric capacity respectively.
- Among the six investigated refrigerants the discharge temperature of both R1270 and R290 were lower than R22 by 20-26°C. Hence both R290 and R1270

exhibits better reliability and lifespan of compressor motor. Refrigerants R290 and R1270 shows better miscibility with R22 mineral oil.

- Volumetric refrigeration capacity of R32 (5929 kJ/m3) was 82.3% higher than the R22 (3251 kJ/m3). Therefore R32 requires redesign or smaller size compressor compared to R22 whereas volumetric capacity of R134a and R152a were 35.2-41.4% lower compared to R22. Hence both R134a and R152a requires larger size of compressor compared to R22. Due to above factors R32, R134a and R152a cannot be replaced directly into R22.
- The volumetric capacity of R1270 (3196 kJ/m^3) was very close to that of volumetric capacity of R22 (3251 kJ/m3) and hence same size of compressor can be used for R1270 as that of R22.
- Overall R1270 would be a suitable ecofriendly alternative refrigerant to replace R22 from the stand point of ODP, GWP, volumetric refrigeration capacity, discharge temperature and miscibility with mineral oil although its COP was fairly lower.

Nomenclature

ARI	Air conditioning and refrigeration institute
GWP	Global warming potential
ODP	Ozone depletion potential
RE	Refrigeration effect (kJ/kg)
TR	Ton of refrigeration (kW)
h_1	Enthalpy at the compressor entry (kJ/kg)
h_2	Enthalpy at the compressor exit (kJ/kg)
h_{1d}	Enthalpy at the evaporator inlet (kJ/kg)
$\dot{m}$	Mass flow rate of refrigerant (kg/min)
M	Molecular weight (kg/kmol)
P_c	Critical pressure (MPa)
Q	Refrigeration capacity (kW)
R	Universal gas constant (J/molK)
T_b	Boiling point (°C)
T_c	Critical temperature (K)
T_d	Discharge temperature (°C)
T_e	Evaporating temperature (°C)
T_g	Temperature glide (°C)
T_k	Condensing temperature (°C)
v	Specific volume (m^3/kg)
W_c	Compressor work (kJ/kg)

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