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Analysis of Alternative Refrigerants to R22 for Air-Conditioning Applications at Various Evaporating Temperatures

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ABSTRACT
This paper presents the simulation results of a 1.5 ton capacity room air conditioning system with some selected refrigerants that have been assessed for their suitability as alternative refrigerants to R22 for air conditioning applications. The refrigerants with zero Ozone depletion potential only are selected in this study. The performance of selected refrigerants viz, R22, R134a, R404A, R407C, R410A, R507A, R290 and R600a is considered in the present analysis. The thermodynamic analysis of these refrigerants has been carried out on these selected refrigerants using COOLPACK software. The analysis mainly focuses on obtaining results of parameters with fixed condenser temperature but with variable evaporator temperatures. The parameters like heat rejection rate, mass flow rate of refrigerant, displacement volume, power input, discharge temperature, cop, saturation pressure and pressures ratio are analyzed. The thermodynamic analysis of eight selected refrigerants is carried out using the simulation software COOL PACK version 1.49 and a comparative study of the different refrigerants is made.
Key words: Alternate refrigerant, R-22, Room Air-conditioner, evaporator temperature, COOLPACK software.

I. INTRODUCTION

Air conditioning systems are available in the wide range of capacities from 2kW to 33 MW (0.5ton to 9500 tons). Majority of the air conditioners are operating on standard vapor compression refrigeration cycle. HCFC-22 is one of the most important refrigerants used in air-conditioning all over the world. HCFC-22 is a controlled substance under the Montreal protocol [1] The Kyoto Protocol was initially adopted on December 1997 and entered in to force on February 2005. This protocol intends a reduction of four green house gases (Carbon dioxide, methane, nitrous oxide, Sulphur hexafluoride) and two groups of gases (hydroflurocarbons and per fluorocarbons). It has to be phased out by 2030 in developed countries and 2040 in developing countries. The growing awareness of the need to sustain the ecology of the planet has resulted in the phase out of the harmful refrigerants containing chlorine atoms including HCFC. The search for good alternatives for HCFCs especially R-22 is still on, engaging intense research efforts.

II. LITERATURE SURVEY

Major earlier investigations in the area of alternate refrigerants are reviewed below from the point of view of their ability to match the performance of the widely used (HCFC-22) R22 refrigerant.

Zaghdoudi et al [2] have simulated the performance of ten alternate refrigerants to replace R22 in an air conditioner of 9000BTU/hr(0.75TR) capacity by using NIST Cycle_D software and these refrigerants include R134a, R290, R600, R404A, R407A, R407C, R407D, R410A, R410B and R417. It was concluded that no single refrigerant possesses all the characteristics of R22.

Devotta et al [3] also assessed the suitability of various alternative refrigerants to R-22 for air conditioning applications. They have selected only zero ozone depleting potential refrigerants. NIST Cycle_D has been used for the comparative thermodynamic analysis. The objective of the analysis is to identify fluids that are likely to be close to HCFC-22 operating conditions. Among the refrigerants studied are HFC-134a, HC290, R407C, R410A, and three blends of HFC-32, HFC134a and HFC-125.They have concluded that the pressure ratios for R410A are slightly lower than that of R-22 but operating pressures are fairly large compared to R-22 at evaporator temperature of 7.2ºC and condenser temperature of 55ºC. Domanski and Didion [4] evaluated the performance of nine R-22 alternatives and the study is conducted using a semi theoretical (cycle_11) model. They have tested R22 (100%), R32/125 (60%/40%), R32/125/134a/290 (20%/55%/20%/5%), R32/125/134a (10%/70%/20%), R290 (100%), R32/125//134a (30%/10%/60%), R32/227ca (35%/65%), R32/134a

(30%/70%), R-32/R134a (25%/75%), R-134a (100%). COP of none of the selected refrigerant exceeded the COP of R-22. It is suggested that utilization of the liquid line-suction line heat exchanger may be warranted for some of the alternative refrigerants. Chen et al [5] investigated the feasibility of using hydrocarbon refrigerant mixtures in residential air conditioners and heat pumps. The mixture of HC-290 and HC-600 gave the highest COP. It is considered to represent the best balance between COP and volumetric capacity for hydrocarbons. They also concluded that this mixture has low volumetric capacity and hence it requires larger compressor.

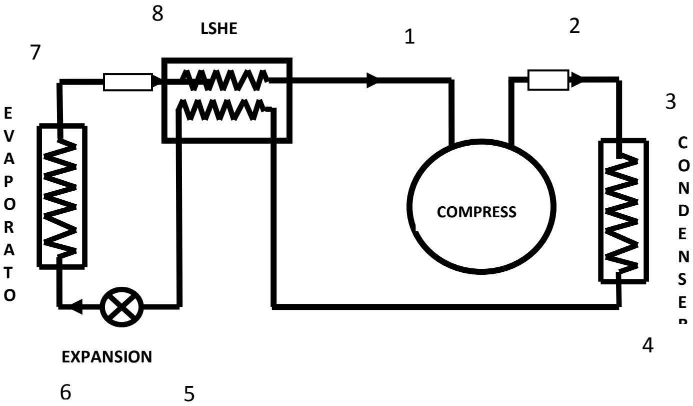
Venkataiah &Venkata rao [6] studied the performance of the eight selected refrigerants viz., R-22, R-134a, R407C, R410A, R404A, R507A, R290, and R600a at a fixed evaporator temperature and varied the condenser temperature using COOLPACK software (version1.49) and also compared the performance of these refrigerants with the similar work carried out by Zaghdoudi et al. Venkataiah &Venkata rao [7] studied the performance of R22 and R410A refrigerants at various evaporating temperatures.

III. Properties of different refrigerants used for the analysis [8]

Table 1.

S. No	Property	R22	R134a	R404A	R407C	R410A	R507A	R290	R600a
1	Chemical formula/ blend composition	$CHClF_2$	CH_2FCF_3	44%R125+52%R125a+4%R134a	23%R32+25%R125+52%R134a	50%R32+50%R125	50%R125+50%R143a	$CH_3CH_2CH_3$ propane	$CH_3CH_2CH_2CH_3$ butane
2	Molar mass(kg/kmol)	86.468	102.03	97.604	86.204	72.585	98.859	44.1	58.12
3	Critical point temperature T_c(ºC)	96.145	101.06	72.046	86.034	71.358	70.617	96.7	152
4	Critical pressure (P_c) (bar)	49.9	40.593	37.289	46.298	49.026	37.050	42.5	38
5	Critical density(kg/m^3)	523.84	511.90	486.583	484.23	459.53	490.77	-	-
6	Boiling point(ºC)	-40.810	-26.074	-46.2	-43.8/-36.7	-51.4	-47.1	-42.1	-0.5
7	ODP	0.05	0	0	0	0	0	0	0
8	GWP	1810	1300	3920	1770	2000	3985	~20	~20

Details of system and software: The cycle consists of a compressor, discharge line, condenser, expansion device, evaporator, compressor suction line, and an optional suction line heat exchanger. The simulation cycle is outlined by different states as shown in the Fig 1. These state points are the following: the suction gas (1) is compressed and discharged into the discharge line (2). The discharge line leads the refrigerant to the inlet of the condenser (3). The condensed and sub cooled refrigerant in the condenser outlet (4) is either lead to the liquid inlet of the suction gas heat exchanger (SGHX) if this has been selected, or directly to the inlet of the expansion valve. If a SGHX is included the exit condition (5) will be different from condition (4). From the expansion valve outlet (6) the refrigerant is lead to the evaporator. The evaporated and superheated refrigerant in the evaporator outlet (7) is lead through the suction line, either to the gas side inlet of the SGHX, if this has been selected, or to the compressor inlet (1). If a SGHX is included the exit condition (8) will be different from condition (1). The P-h diagram of this cycle is shown in fig 2.



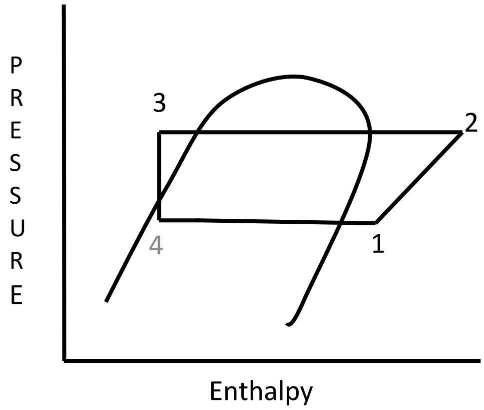


Fig. 2. P-h chart

Fig. 1. Vapor compression refrigeration cycle with different states.

COOL PACK SOFT WARE [9] enables calculation of refrigeration properties (property plots, thermodynamic and thermo physical data, refrigerant comparisons),cycle analysis- comparison of single stage and multi stage systems, system dimensioning-calculation of component sizes from general configuration criteria, system simulation-calculation of operating conditions in a system with known components with their operating parameters, evaluation of operation and evaluation of the system coefficient of performance with less power consumption.

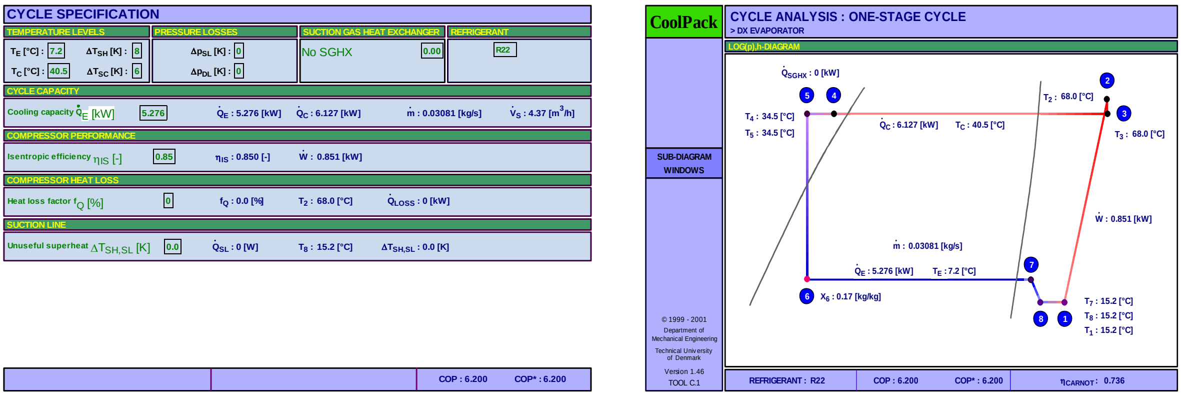


Fig. 3 (a) & (b). Description of model and refrigeration cycle in the software

Thermodynamic Analysis of the refrigeration cycle for various refrigerants.

Presented below are the simulation results of a 1.5Ton (5.276kW/18000 BTU/Hr) capacity room air conditioner with selected refrigerants that have been assessed for their suitability as alternative refrigerants to R-22. The Performance of the refrigerants R-22, R-134a, R407C, R410A, R404A, R507A, R290, and R600a is considered for the analysis.

Cycle Inputs for simulation: The cycle inputs are condensing temperature of 55ºC and evaporating temperature which is varying between -5ºC and 15ºC. Condenser sub cooled temperature is 8ºC and super heat is fixed to 6ºC. Pressure losses in the condenser and evaporator are neglected. Cooling capacity in the evaporator is selected as 5.276kW (1.5Ton), isentropic efficiency of compressor is taken as 0.85, compressor heat loss factor is considered as zero and also suction line super heat is considered as zero.

IV. Results

The results of analysis of performance of eight selected refrigerants viz R22, R134a, R404A, R407C, R410A, R507A, R290 and R600a are plotted below. The various performance parameters such as heat rejection rate, mass flow rate of refrigerant, displacement volume, power input, discharge temperature, cop, saturation pressure and pressures ratio are plotted against various evaporating temperatures varying from -5°C to 15°C.

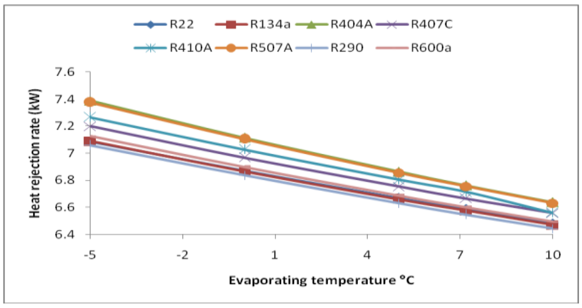


Fig 4.(a) Variation of heat rejection rate with increase in evaporating temperature

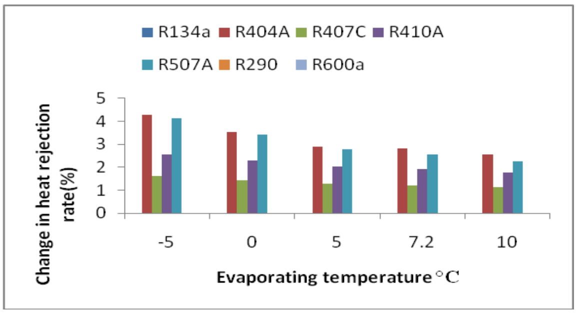


Fig 4 (b) Change in % of heat rejection with evaporating temperature in comparison with R22

Fig 4.a. Shows the variation of heat rejection rate with evaporating temperature as evaporating temperature increases from -5°C to 10°C. The heat rejection rate decreases for all the selected refrigerants with increase in evaporator temperature.

Fig 4 (b). Depicts the percentage change in heat rejection rate in comparison with R22 is as follows: at 7.2°C temperature, R404A rejects with highest value of of 2.82% and R507A with a value of 2.56% and all other refrigerants follow almost similar values for R22.

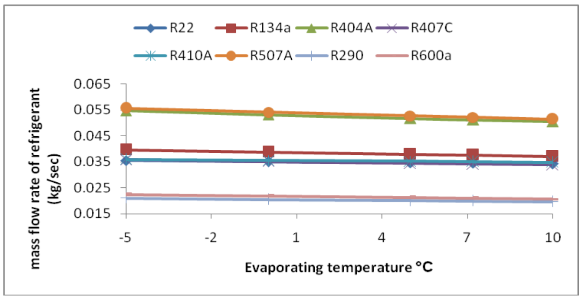


Fig 5.(a). Variation of mass flow rate of refrigerant with increase in evaporating temperature.

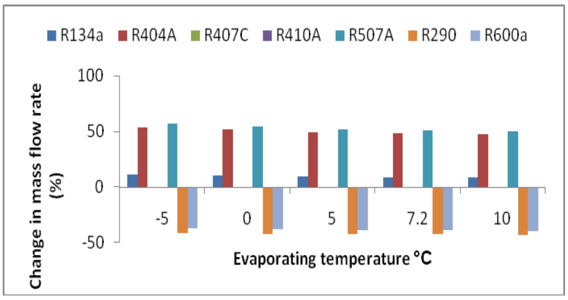


Fig 5 (b) Change in % of mass flow rate of refrigerant with evaporating temperature in comparison with R22

Fig 5.a) Shows the variation of mass flow rate of refrigerant with increase in evaporating temperature and the trend is similar for almost all the selected refrigerants, as eveporating temperature increases the mass flow rate of all the refrigerants are decreasing.

Fig 5 b) Shows the chage in % of mass flow rate of refrigerant with evaporating temperature in comparison with R22 and it is observed that at an evapoartor temperature of 7.2°C, R507C requires 51.2%,R404A requires 48.47%,R134a requires 8.988% higher refrigerant than that of R22, where as R290 requires -42.6% and R600a requires -39.22% lesser refrigerant as compared to R22.

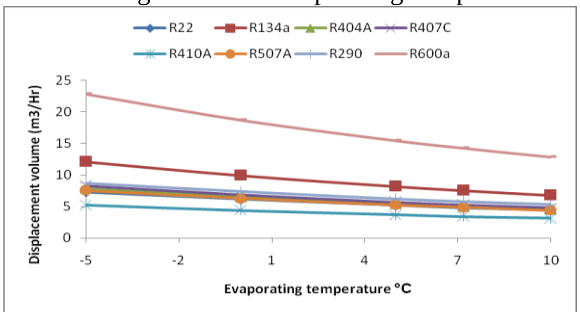


Fig 6.(a). Variation of displacement volume of compressor with increase in evaporating temperature

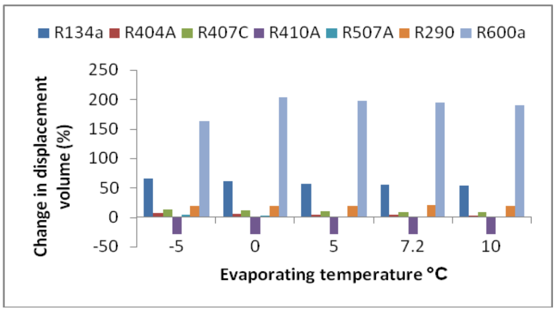


Fig 6 (b). Change in % of displacement volume of compressor with evaporating temperature in comparison with R22.

Fig 6.a) shows the variation of displacement volume of the compressor with increase in evaporating temperature and it can be concluded that as the evaporating temperature increases, the displacement volume flow of compressor decreases for all the refrigerants.
Fig 6 b) shows the variation of % of change in displacement volume with evaporating temperature in comparison with R22. It can be concluded that at an evaporating temperature of 7.2°C, R600a requires 194.4%, R134a requires 53.27%, R290 requires 19.83%, R407C requires 8.88%,R404A requires 3.71% higher displacement volume compressor in comparison with R22 wher as R410A requires -29.132% smaller displacement volume compressor in comparison with R22.

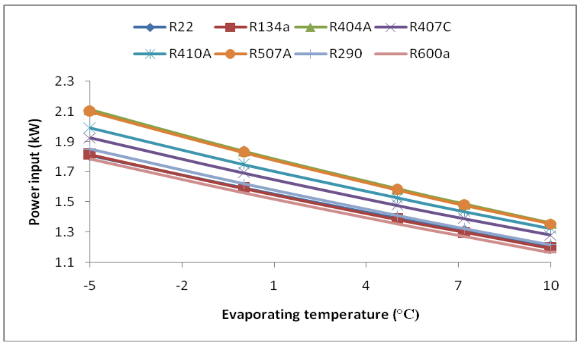


Fig 7.(a) Variation of power input of compressor with increase in evaporating temperature.

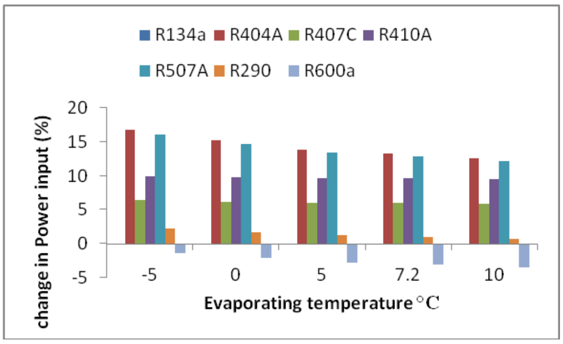


Fig 7 (b) Change in % of power input with evaporating temperature in comparison with R22.

Fig 7.a) shows the variation of power input of compressor with increase in evaporating temperature and it is observed that as the evaporating temperature increases the power required to run the compressor decreases for all the refrigerants.

Fig 7 b) shows the variation % of change in power input with evaporating temperature in comparison with R22. At 7.2°C It is concluded that the percentage increasing order of power input for various refrigerants as follows R290(1.068%),R407C(6.03%), R410A (9.610%), R507A (12.82%)R404A (13.35%) where as R600a requires -3.47% of lesser power input than that of R22.

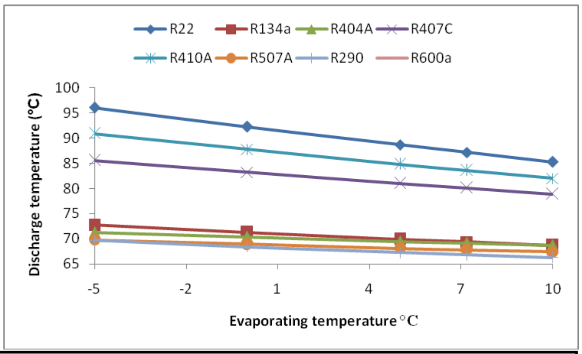


Fig 8.(a). Variation of discharge temperature with increase in evaporating temperature.

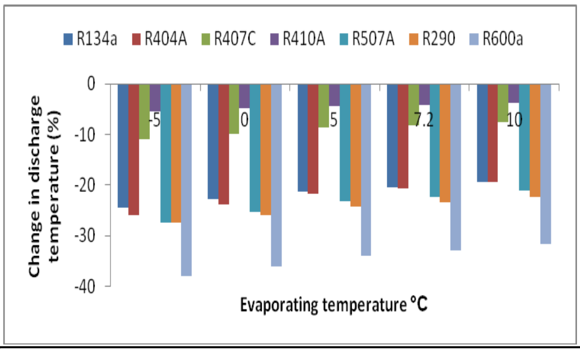


Fig 8 (b). Change in % of discharge temperature with evaporating temperature in comparison with R22.

Fig 8.a) shows the variation of discharge temperature with increase in evaporating temperature. It is observed that as the evaporating temperature increases, the discharge temperature decreases for all the selected refrigerants.

Fig 8 b) shows the variation of % change in discharge temperature with evaporating temperature in comparison with R22. at 7.2°C temperature, it is observed that the discharge temperature is decreasing with increase in temperature. The percentage decrease in the discharge temperature in comparison with R22 in the order as follows, R410A(-4.12%),R407C(-8.14%), R134a(-20.41%),R404A(-20.62%), R507A(-22.24%),R290(-23.39%),R600a(-32.79%).

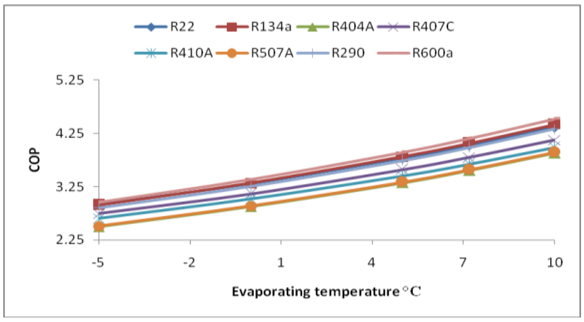


Fig 9.(a) Variation of COP with increase in evaporating temperature

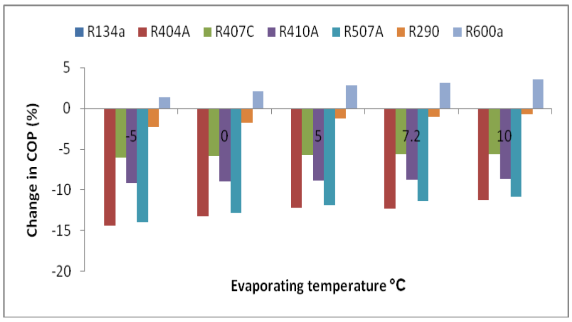


Fig 9. (b) Change in % of COP with evaporating temperature in comparison with R22.

Fig 9.a) Shows the variation of COP with increase in evaporating temperature and it is observed that as the evaporating temperature increases the COP is increasing for all the selected refrigerants.

Fig 9 b) Shows the variation of % change in COP with evaporating temperature in comparison with R22. At a temperature of 7.2°C it can be concluded only R600a gives 3.17% higher COP than R22,R134a &R290 indicating same as that of R22 where as for the remaining refrigerants the decreasing order of COP is R404A (-11.22%), R507A(-10.84%), R410A(-8.69%), R407C(-5.63%).

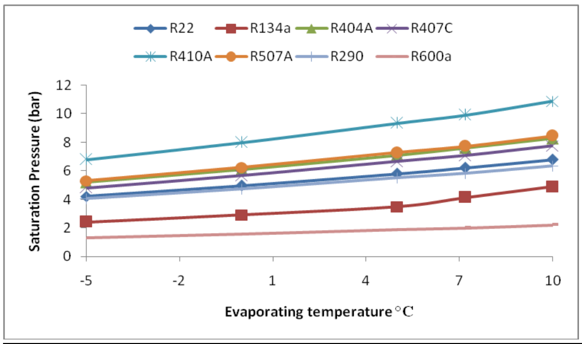


Fig 10.(a) Variation of saturation pressure with an increase in evaporating temperature

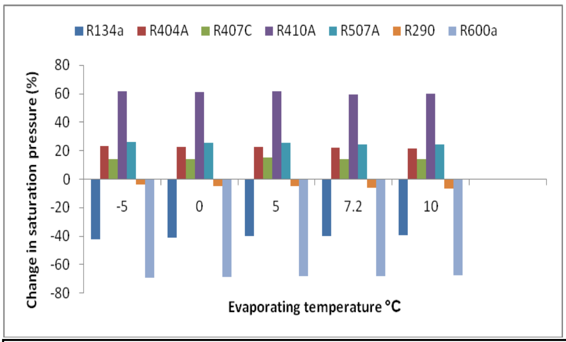


Fig 10.(b) Change in % of saturation pressure with evaporating temperature in comparison with R22

Fig 10.a) shows the variation of saturation pressure with increase in evaporating temperature it indicates that as the evaporator temperature increases the saturation pressure increases linearly for all the selected refrigerants.

Fig 10.b) shows the % of change in saturation pressure with evaporating temperature in comparison with R22 and at 7.2°C it can be concluded that the % increasing order of saturation pressure for variuos refrigerants is R407C(13.8%), R404A(22%) R507(24.23%) and R410A(59.3%), and the decreasing order of saturation pressure for the rerigerants is R290(-6.26%), R134a(-39.80) and R600a(-67.64%).

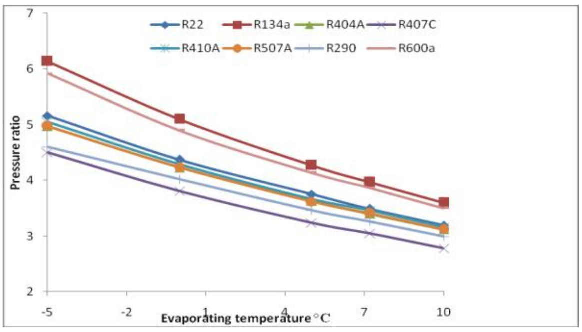


Fig 11.(a) Variation of pressure ratio with increase in evaporating temperature

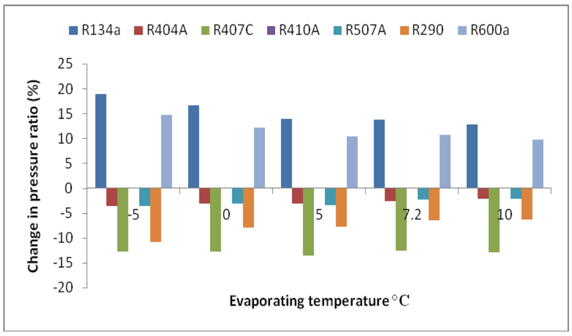


Fig 11. (b)Change in % of pressure ratio with evaporating temperature in comparison with R22

Fig 11.a) shows the variation of pressure ratio with increase in evaporating temperature it indicates that as the evaporator temperature increases the pressure ratio decreasing continuously for all the selected refrigerants.

Fig 11.b) shows the % change in pressure ratio with evaporating temperature in comparison with R22 and at 7.2°C it can be concluded that the percentage increasing order of the pressure ratio is R600a(10.63%) and R134a(12.85%) where as for the rerigerants the decreasing order of the percentage of pressure ratio is R404A(-2.19%),R407A(-2.29%),R290(-6.27%) and R407C(-12.85%) and there is not much variation in the pressure ratio for the refrigerant R410A.

V. DISCUSSION OF THE RESULTS

The results available in the literature[3] and those from the present analyses are compared at an evaporator temperature of 7.2°C and a condensing temperature of 55°C. A comparative statement prepared thus is shown in Table-2 and also a comparison of the same as a percentage relative to R22 is shown in Table 3.

Table No.2

S.No.	**Parameter**	**Results of Devotta et al[3]**	**Results of present paper**
1	Refrigerants selected for the analysis	R22,R134a,R290, R407C R410A, R32/R134a(30/70),R32/R125(60/40), R32/R125/R134a(30/10/60)	R22,134a,R404A,R407C,R410A,R507A,R290 and R600a.
2	Software used	Cycle_D	Cool Pack version 1.49
3	Saturation Pressure	Data not available	Highest for R410A and lowest for R600a.
4	Pressure ratio	Highest for R134a and lowest for R290	Highest for R134a and lowest R407C
5	Discharge temperature	Highest for R22 and Lowest for R290	Highest for R22 and Lowest for R600a,next lowest R290
6	Compressor power consumption	Highest for R410A and Lowest for R134a	Highest for R404A and Lowest for R600a
7		Specific compressor displacement Largest for R134a and lowest for HFC32/HFC125((60/40 by wt%)	Displacement volume :Largest for R600a and lowest for R410A(R32/R125)(50/50%)
8	COP	Highest for R134a and lowest for R410A.	Highest for R600a and lowest for R404A.
9	Heat rejection rate(kW)	Data not available	Highest for R404A and lowest for R290
10	Mass flow rate of refrigerant(kg/sec)	Data not available	Highest for R507A and lowest for R600a

Table No.3

Summary of data obtained from simulation results at 7.2°C and condensing temperature 55°C.

			% Relative to R22					
Refrigerant	Heat rejection rate	Mass flow rate	Displacement volume.	Compressor power	Discharge temperature	COP	Saturation pressure	Pressure ratio
R134a	0.00	8.968	55.57	0.00	-20.41	0.0	-39.8	13.75
R404A	2.82	48.47	3.71	13.35	-20.62	-12.24	22	-2.57
R407C	1.2	0.00	8.88	6.03	-8.14	-5.66	13.8	-12.6
R410A	1.913	0.00	-29.132	9.61	-4.12	-8.76	59.3	0.00
R507A	2.56	51.2	0.00	12.82	-22.24	-11.37	24.23	2.29
R290	0.00	-42.6	19.83	1.068	-23.39	-1.018	-6.26	-6.45
R600a	0.00	-39.22	194.4	-3.053	-32.79	3.17	-68	10.63

VI. CONCLUSIONS

It is found from the present study and after comparison with similar earlier studies that

a) The heat rejection rate of all the refrigerants is almost same b). R290 &R600a need smaller mass flow rate of refrigerant and R507 and R404A require larger mass flow rate of refrigerant

c) R600a needs the largest compressor displacement volume and R410A needs smallest compressor displacement volume d) R404a and R507a consume largest power input to the compressor e) Discharge temperature of all the selected refrigerants is lower than that for R22

f) COP of all the refrigerants is less than that for R22 except for R600a g) Saturation pressure of R410A is highest and that for R600a has lowest value and h) Pressure ratio of R407C is lowest and R410A is highest. It can be concluded that there is no single refrigerant which satisfies all the characteristics of R22.

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