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Performance Evaluation of Vapor Compression Refrigeration Cycle for Air Conditioning Applications with R-22, R-290 and R-600a as Refrigerants

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ABSTRACT

R-22 also called Freon-22 is the most widely used refrigerant, and its applications are found in residential, commercial, industrial and transport sectors, and spans cooling capacities in wide ranges. As per Montreal protocol R-22 is being phased out by 2040 in developing countries like India, hence there is a need to search for an alternate refrigerant. In the present paper, R-290(Propane) and R600a (Isobutene) both of these refrigerants are considered under hydrocarbon group are selected to study and compare these refrigerants performance with that of R-22 air conditioning system of 1.5 Ton capacity.

After detailing the earlier research work in this area, the behavior of Air conditioning systems employing R-22 and other alternate refrigerants the properties of these refrigerants are also listed. This paper presents simulation results on the performance of air conditioning system (1.5Ton/5.276 kW /18000 BThU/Hr/ capacity) with R-22, R290 and R600a.All the simulations are carried out by using cool pack software. The simulation results are compared at constant Evaporator temperature of 7.2ºC, and at different Condensing temperatures ranging from 35ºC to 70ºC.The various parameters selected for the comparison of the air conditioning system performance are condenser heat rejection rate, compressor power consumption, compressor displacement volume flow rate, mass flow rate of refrigerant, COP, Pressure ratio and saturation pressure etc.

KEY WORDS: Air-conditioning system, R-22, R-290, R-600a, COP

1. INTRODUCTION

In practice there are different types air conditioning systems available in the range from 2kW to 33 MW (0.5ton to 9500 tons). Most of the air conditioners are operating on standard vapor compression refrigeration cycle. The standard vapor compression refrigeration system consists of a compressor, condenser, capillary and an expansion valve. Compressor is hermetically sealed type, condenser is a forced convection type with fins and a fan mounted, and capillary tube is a constant area expansion device, which is very commonly used in small refrigeration system and air conditioning systems, it is a simple tube with inner diameter of a few millimeters as it has advantages of simplicity, inexpensiveness, and also the requirement of low starting torque of a compressor motor, and an evaporator of forced convection type with a blower mounted on it. As CFC (chlorofluorocarbon) and HCFC (hydro chlorofluorocarbon) refrigerants which have been used as refrigerants in a vapor compression refrigeration system were known to provide principal cause to ozone layer depletion and global warming. HCFC-22 is one of the important refrigerants used in air-conditioning all over the world.HCFC-22 is a controlled substance under the Montreal protocol. It has to be phase 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, such as chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs). Although a replacement for CFCs has been found, the search for good alternatives for HCFCs especially R-22 is still on. According to literature there is no single compound refrigerant that can replace R-22 Production and use of these refrigerants have been restricted.

Because of environmental and energy efficiency concerns, the air conditioning industry has been forced to look for alternatives to above said long standing refrigerants and at the same time, to examine new technologies that will allow air conditioning systems using next generation of refrigerants, to be more efficient and environmentally friendly. In the present paper, hydrocarbon-based refrigerants R290 (propane) and R600a(Isobutane) have been selected to study their performance on the air conditioning system.

2. LITERATURE REVIEW

Literature is available on some of the feasible alternative refrigerants that replace R-22 in air conditioning applications.

Goldschmidt V W., Hart G. H (1982) developed a heat pump model coupled to a mobile home. The purpose of the model is to predict heat loads in a residential heated space during daily and seasonal changes in ambient conditions. The model predictions are found to be accurate to within 10%.

Domanski P.A., Didion D.A. (1993) presented the performance evaluation of nine R-22 alternatives. The study is conducted using a semi theoretical (cycle_11) model. COP of none of the selected refrigerant exceeded the cop of R-22. Masanobu et al (1994) conducted performance tests with HFC32/HFC-134a (30/70 by wt %). HFC-32/HFC-134a (25/75 by wt %) and HFC-32/HFC-125 (50/50 by wt %) i.e. R-410A. Due to large mass flow rate of R-410A the cooling capacity was greater than other mixtures by more than 50%and due to higher compressor power required for R410A the energy efficiency ratio was lesser than other refrigerants mixture by 1-5%.

Ryuzaburo et al (1997) tested R410A in a split type room air conditioner and found that the efficiency of R410A was almost close to that of HCFC-22 within +/- 1%. Devotta et al (2001) 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. They have concluded that Pressure ratios for R410are slightly lower than that of R-22 but operating pressures are fairly large compare to R-22.

It is observed from the literature review that efforts are on to select alternative and environmentally friendly refrigerants to replace R-22 in room air conditioning systems.

About R290 (Propane)

Abou R600a(Isobutane)

Table 1 Comparison of some Properties of R22 with R290 & R600a.

S. No	Property	R22	R290	R600a
1	Chemical formula/ blend composition	$CHClF_2$ Difluoro-Monochloromethane	$CH_3CH_2CH_3$ propane	$CH_3CH_2CH_2CH_3$ butane
2	Molar mass(kg/kmol)	86.468	44.1	58.12
3	Critical point temperature (ºC)	96.145	96.7	152
4	Critical pressure (bar)	49.9	42.5	38
5	Critical volume(L/kg)	1.949	4.545	4.526
6	Boiling point(ºC)	-40.810	-42.1	-11.67
8	Freezing point (ºC)	-160	-187.1	-159.6
9	ODP	0.05	0	0
10	GWP	1810	~20	~20
11	ASHRAE Safety group	A1	A3	A3

Safety classification of refrigerants

The safety classification consists of two alphanumeric characters (e.g. A2); the capital letter corresponds to toxicity and the digit to flammability.

Toxicity classification

Refrigerants are divided into two groups according to toxicity:

Class A signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 ppm

Class B signifies refrigerants for which there is evidence of toxicity at concentrations below 400 ppm

Flammability classification

Refrigerants are divided into three groups according to flammability:

Class 1 indicates refrigerants that do not show flame propagation when tested in air at 21°C and 101 kPa

Class 2 indicates refrigerants having a lower flammability limit of more than 0.10 kg/m^3 at 21°C and 101 kPa and a heat of combustion of less than 19 kJ/kg

Class 3 indicates refrigerants that are highly flammable as defined by a lower flammability limit of less than or equal to 0.10 kg/m^3 at 21°C and 101 kPa or a heat of combustion greater than or equal to 19 kJ/kg

3.1 Working of a simple vapor compression Refrigeration cycle

The simple vapor compression refrigeration cycle is shown in Fig. 1 It consists of four essential parts 1.Compressor, 2. Condenser, 3. Expansion valve and Evaporator. Compressor compresses the vapor refrigerant to the condenser with high pressure and temperature, in the condenser condensation takes place by rejecting heat in the form latent heat of condensation through cooling medium either water or air here the phase change of refrigerant takes place from vapor to liquid refrigerant and enters in to the expansion valve as in high pressure liquid refrigerant and exits as a low pressure liquid refrigerant and finally the low pressure liquid refrigerant enters in the evaporator where it absorbs heat from load and leaves the evaporator in the form of vapor refrigerant. The P-h chart is shown in Fig. 2

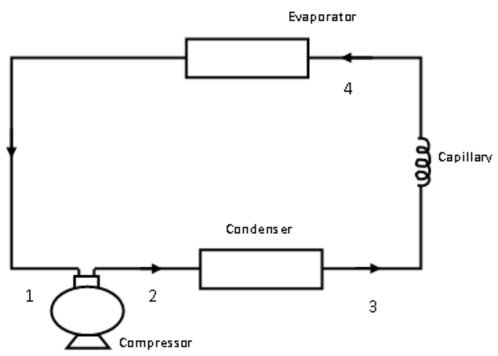

Figure 1: Simple vapor compression refrigeration cycle.

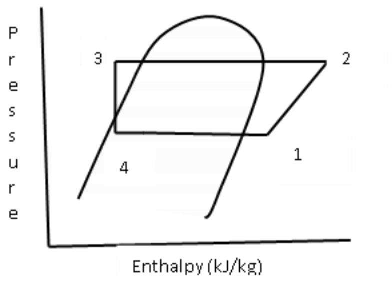

Figure 2: P-h Chart

Thermodynamic cycle analysis

The main objective of the analysis is to study the performance of air conditioning system using hydrocarbon refrigerants R290 and R600a and to compare with the existing refrigerant R22.The important properties of these refrigerants have been prepared and tabulated in Table no 1.the model used is cool pack and it is developed by Denmark university (6). This software is a collection of simulation programs for refrigeration. The programs in Cool Pack cover the following simulation purposes

Cycle analysis – e.g., comparison of one- and two-stage cycles. To make it easier to get an overview of the programs in Cool Pack the program is divided into three main groups (Refrigeration Utilities, EES Cool Tools and Dynamic).

Calculation of refrigerant properties (property plots, thermodynamic and Thermo physical data, Refrigerant Comparisons.Cycle Analysis-Comparison of single stage and Multistage.

System dimensioning- Calculation of component sizes from general configuration criteria.

System Simulation-Calculating operating conditions in a system with known components with their operating parameters.

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 3. 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 rating conditions are an evaporating temperature of 7.2ºC and a condensing temperature which is varying between 30ºC and 70ºC. In this study the condenser sub cooled temperature is selected as 8ºC and super heat is fixed to 6ºC.Pressure losses in the condenser and evaporator is 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 also suction line unuseful super heat is considered as zero. Standard evaporator temperature is considered as 7.2ºC and condensing temperature is considered as 40.5ºC.

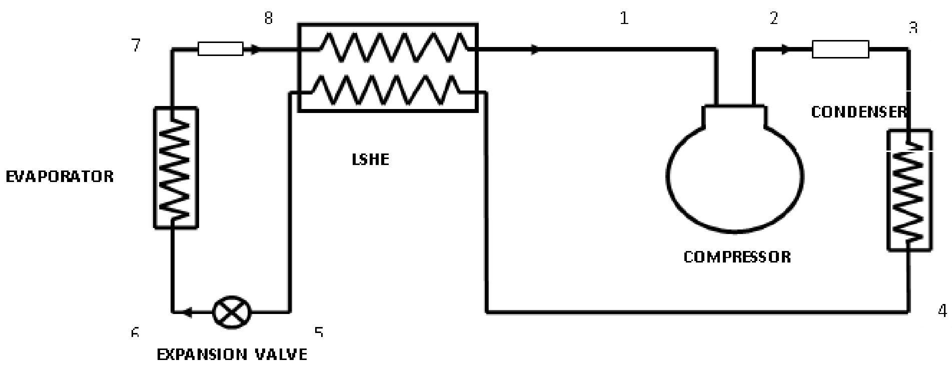

Figure 3: Simulation cycle with different states.

The various stages in the above Figure 3 are as follows:1-2 Isentropic compression in the compressor,2-3 discharge line, condensation in the condenser,4-5 refrigerant passes through liquid suction heat exchanger (LSHE), if selected otherwise refrigerant directly enters in to the expansion system at 5 itself. 5-6 expansion process in the expansion system, 6-7 Evaporation in the evaporator,7-8 suction line. 8-1 again liquid suction heat exchanger if selected otherwise refrigerant directly enters in to the suction line at 1 itself. A sample of cycle specifications has been shown in Fig 4.

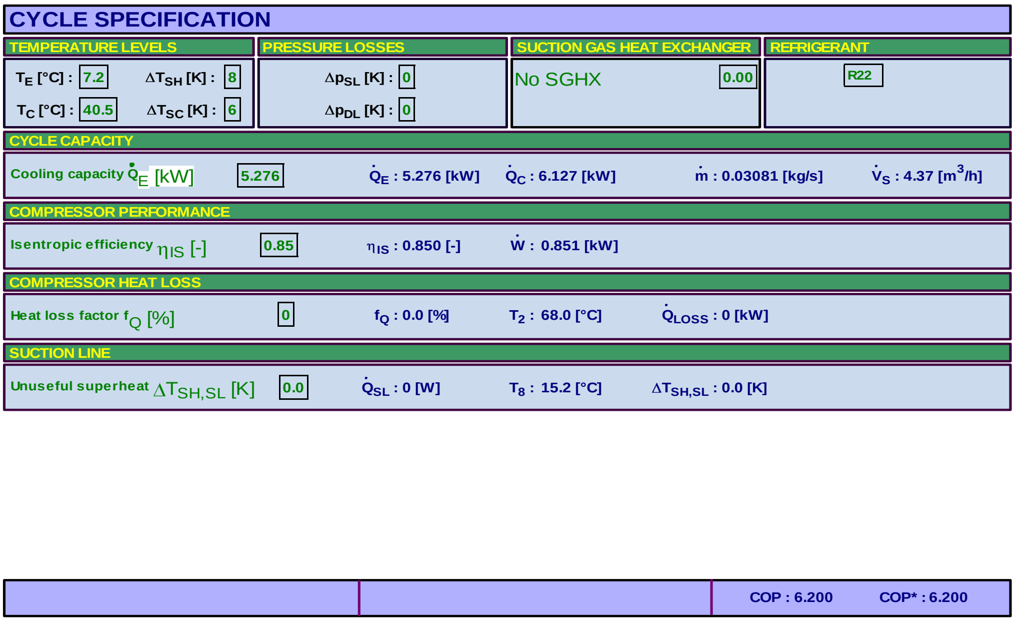

Figure 4: Cycle specifications

Thermodynamic cycle analysis

The variation of the condensing pressure with condensing temperature is shown in Figure 5 for three refrigerants. It is observed from the figure that condensing pressures with R290 and R600a are lower than R22.At standard operating conditions it is observed that there is a decrease in saturation pressure by 12% for R290 and 66.23% for R600a as compared R22. Fig. 6 show the Variation of Pressure ratio with condensing temperature. It is observed that the pressure ratio of R600a is higher at all condensing temperatures and pressure ratio of R290 is smaller at all condensing temperatures in comparison with that of R22. At standard operating conditions it is found that there is a drop in Pressure ratio by 6.25% with R290 and Rise in pressure ratio by 5.52% with R600a.

The Variation of discharge temperature with condensing temperature is shown in Fig. 7 and it is pointed out that the discharge temperature of R22 is much higher than both the refrigerants. R600a allows lowest and R290 gives a lower discharge temperature. Lower discharge temperatures are always acceptable as it safe guards the motor winding and hence life of the motor itself. At standard operating conditions it is observed that the percentage decrease in discharge temperature with R290 is 21% and with R600a is 30%.

Figure 8 gives the variation of mass flow rate of refrigerant with condensing temperature and it is found that R22 requires larger mass flow rate of refrigerant in comparison with R290 and R600a. At all condensing temperatures there is large variation of mass flow rate of R22 where as R290 and R600a requires almost similar mass flow rates. At standard operating conditions it is observed that the reduction in the mass flow rate with R290 is 44% and with R600a is 40.5%.

Variation of Displacement volume with condensing temperature is shown in Fig.9.This indicates that R600a needs a largest displacement volume per hour and where as R22 needs very small Displacement volume per hour. At standard operating conditions it is observed that the rise in displacement volume flow of R600a is 188% where as for R290 the rise in displacement volume flow is by 44%.

Figure10. Shows the variation of power input to compressor, at lower condensing temperatures all the three refrigerants require almost same power input to compressor where as R600a requires relatively smaller power input with increase in condensing temperatures. At standard operating conditions it is observed that R600a requires slightly higher power in put to the compressor.

Figure 11 Shows the Variation COP with condensing temperature. COP of the system is decreasing with increase in condensing temperatures for all the three refrigerants and at lower condensing temperatures COP of R600a system is slightly higher than R22 & R290 systems. At standard operating conditions it is observed that R600 gives a slight increase in COP by 3.65%. Figure 12 Gives Variation heat rejection rate with condensing temperature. It is observed that as the condensing temperature increases there is an increase in same heat rejection rate with all the refrigerants.

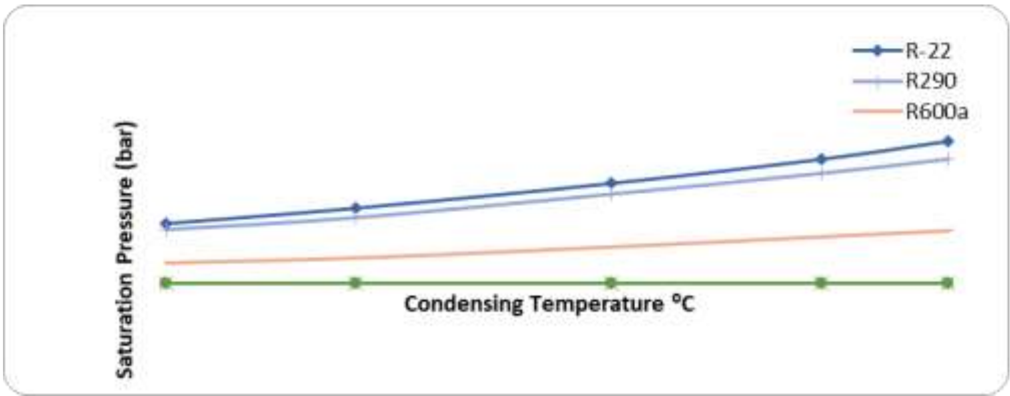

Figure 5: Variation of Condenser pressure with condensing temperature.

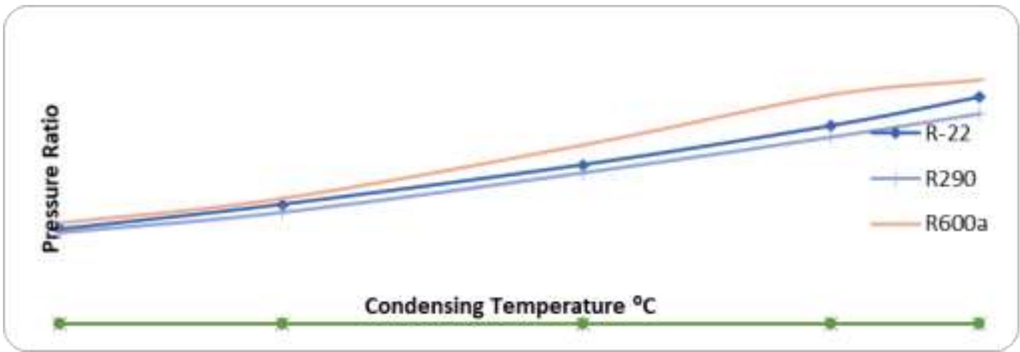

Figure 6: Variation of Pressure ratio with condensing temperature.

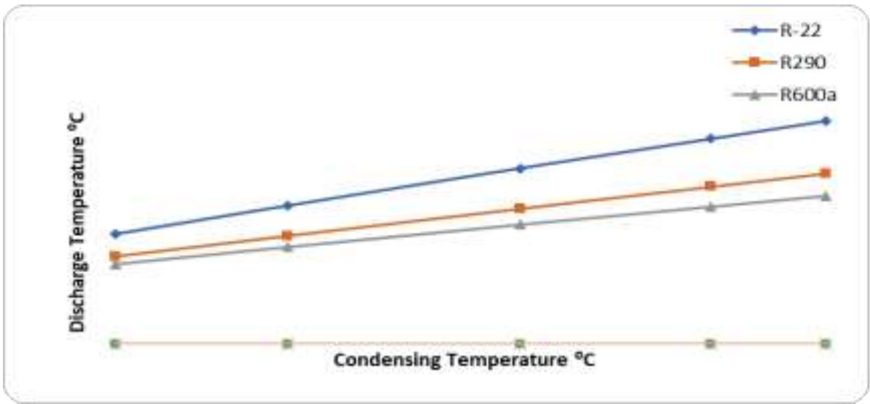

Figure 7: Variation of Discharge temperature with condensing temperature.

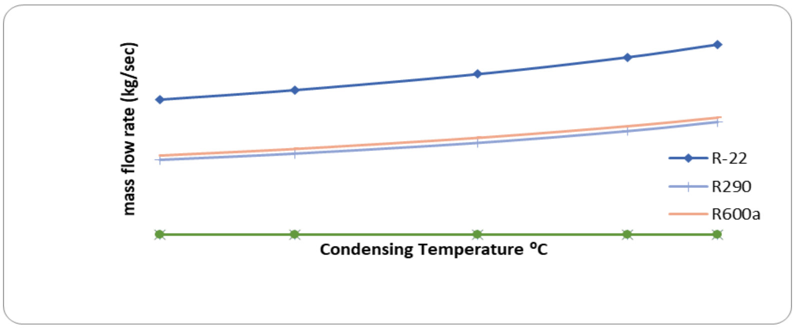

Figure 8: Variation of mass flow rate of refrigerant with condensing temperature.

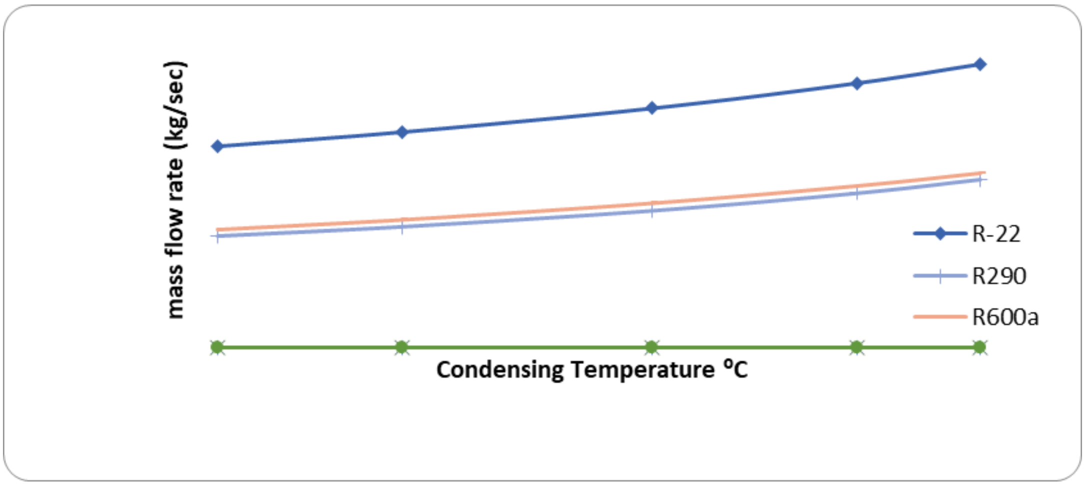

Figure 9: Variation of Displacement volume with condensing temperature

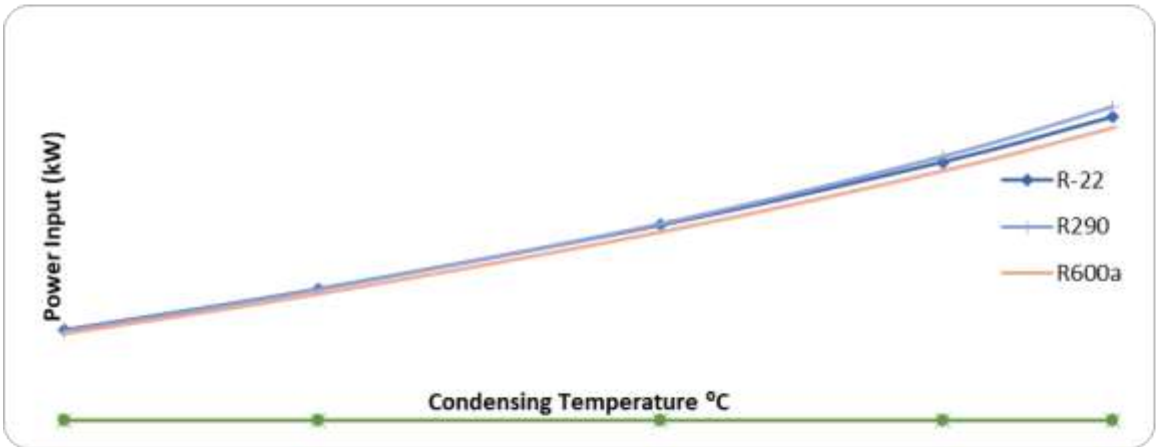

Figure 10: Variation power input with condensing temperature

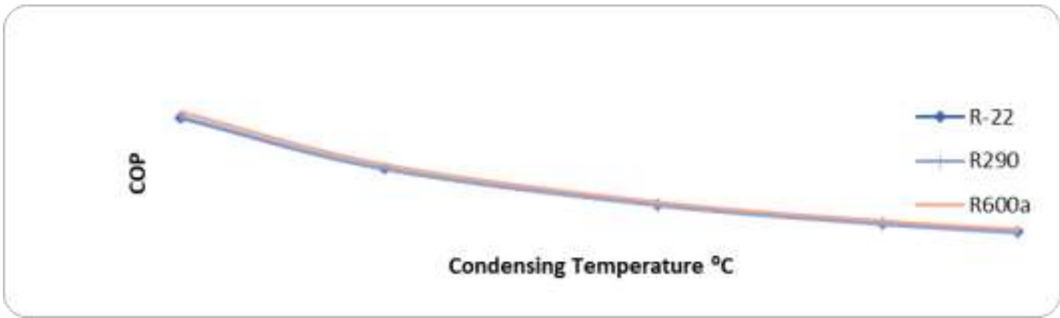

Figure 11: Variation COP with condensing temperature

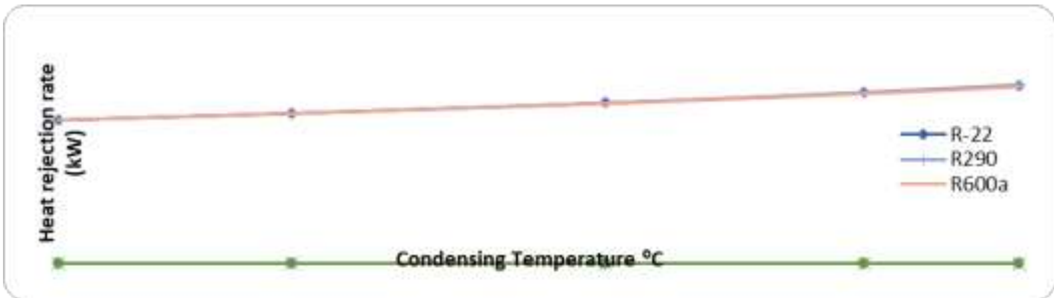

Figure 12: Variation heat rejection rate with condensing temperature

Conclusions

- Condensing pressures obtained with R290 and R600a are lower than R22 and pressure ratios obtained with R290 are lowest which leads to improve the compressor performance.
- R600a allows lowest discharge temperature and R290 experience a lower discharge temperature as compared to R22 which is good for compressor motor winding life.
- The mass flow rate observed with R290 & R600a are lower as compared with R22.
- Displacement volume flow observed is higher for R290 and Highest for R600a.
- R290&R600a requires almost same power input to compressor which is similar to R22 compressor power input.
- R600a has highest COP and R290 &R22 similar COP.

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