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A THEORETICAL COMPARISON OF TWO ECO-FRIENDLY REFRIGERANTS AS ALTERNATIVES TO R22 USING A SIMPLE VAPOUR COMPRESSION REFRIGERATION SYSTEM

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Summary

The paper presents a theoretical investigation into the performance of R432A and R433A refrigerants as alternatives to the ozone depleting R22 refrigerant. The two refrigerants have zero ozone depleting potential and a negligible global warming potential. The results obtained showed that the properties of the three investigated refrigerants are similar. The saturation vapour pressures for R432A and R433A, between the saturation temperatures of -30 to 40°C, are 99.6 and 99.3% the same as that of R22. The performance of R22 in terms of power per ton of refrigeration (PPTR), volumetric refrigeration capacity (VRC) and coefficient of performance (COP) is slightly better than the performance of the two alternative refrigerants. The average COPs obtained for R432A and R433A were lower by only 4.5 and 5.4%, respectively, than those of R22, but the two alternative refrigerants equally exhibited better pressure ratios, discharge temperatures and pressures than R22. Both R432A and R433A have higher refrigerating effects than R22. The VRC and COP of R432A are higher by 3.8% and 0.9%, respectively, than those of R433A. Generally, the performance of the two alternative refrigerants is quite similar in all operation conditions and they have shown satisfactory performance as good long term alternatives to R22 refrigeration systems.

Key words: *eco-friendly, alternative refrigerants, performance, R432A, R433A*

1. Introduction

Nowadays, ozone depleting and global warming issues are recognized as critical aspects of the most serious global environmental problems [1,2]. For many years, chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) have been used successfully as refrigerants, blowing agents, cleaning solvents, and aerosol propellants. These refrigerants seem to be an ideal choice due to their unique thermodynamic and thermo-physical properties, as well as chemical stability in various refrigeration and air-conditioning applications [3]. However, they also have harmful effect on the Earth's protective ozone layer

[4]. Therefore, they have been phased out due to the environmental concerns about their ozone depletion potential (ODP) and high global warming potential (GWP). CFCs have been banned in developed countries since 1996, and from January 1st, 2010, the production and use of CFCs are prohibited completely all over the world [5, 6].

R22 has been used in virtually all residential air-conditioners and heat pumps because of its inherent efficiency and high refrigeration capacity; it also has the largest sales volume among all refrigerants. However, it belongs to the family of hydro-chlorofluorocarbon (HCFC) refrigerants, which contain the ozone depleting chlorine atom and are now substances controlled by the Montreal protocol. HCFC refrigerants will be phased out by 2020 in developed countries and 2030 in developing countries [7, 8]. However, in the European Union, HCFC has been phased out since 2010. Exceptions are recycled and reclaimed refrigerants which should be phased out by the end of 2014. Therefore, the industry and researchers in this field are in search of long-term solutions.

The research on refrigerant replacement for R22 has been one of dominant topics in the refrigeration and air-conditioning industry. No single-component fluid has been identified as a replacement for R22 that would meet all performance, environmental, and safety requirements [9]. In the search for ideal alternatives for R22, initially, pure HFCs, such as R134a, R125, R32 or R143a, were tested. However, only R134a was fairly suitable as single fluid refrigerant substitute for R22 in air-conditioning and medium temperature applications, however, with poorer performance [8]. Several alternatives, including binary, ternary and quartet blends of hydro-fluorocarbons (HFCs) have been considered as potential replacement fluids, since mixing two or more refrigerants can create a new working fluid with desired characteristics.

Many refrigerants were assessed through the Alternative Refrigerant Evaluation Program (AREP) as potential replacements for R22 [10, 11]. The most promising alternative refrigerants that emerged were R410A, R407C and R134a. R407C and R410A were found to be suitable substitutes in air-conditioning and medium temperature applications [12]. In the mid-1990s the application of R407C in residential air conditioners and heat pumps has received wide acceptance in the European market. R407C is a ternary mixture refrigerant composed of R32/R125/R134a (23/25/52% in weight). The operation pressure and temperature of R407C are equivalent to those of R22, therefore, just slight modifications on existing R22 air-conditioners are needed for changing to R407C air-conditioners directly.

Some researchers have carried out theoretical and experimental investigations to assess azeotropic and zeotropic mixtures as R22 substitutes. A theoretical development of the thermodynamic properties of two mixtures of HFC refrigerants (R407C and R410A) was carried out by Monte [13]. Aprea and Greco [14] evaluated the performance of R22 and R407C in a vapour compression plant with a reciprocating compressor. Aprea et al. [15] evaluated performances of R22 substitutes in a vapour compression plant with regulated refrigeration capacity by means of a variable speed compressor. Han et al. [16] studied experimentally the cycle performance of R32/R125/R161 refrigerant mixture as an alternative to R407C. Park et al. [17] studied the thermodynamic performance of R433A as an alternative to R22 used in residential air-conditioners and heat pumps. Also, Fatouh et al. [8] assessed the performance of a direct expansion air-conditioners working with R407C as an R22 alternative and showed that the best performance in terms of operating parameters as well as coefficient of performance (COP) are obtained by using R22.

Most of these studies recommended R407C and R410A as potential substitutes for R22. But these refrigerants are HFC mixtures and the global warming of HFCs has become a hurdle to accept them as long-term solutions (Table 1). Now, the focus is on the use of natural refrigerants, such as hydrocarbons. Hydrocarbons have many advantages including environmental friendliness, chemical stability, high heat transfer coefficients and low refrigerant charge. They are compatible with common materials found in refrigeration and air-conditioning systems and are soluble in conventional mineral oils [18].

The major disadvantage of hydrocarbons as refrigerants is their flammability. It should be remembered that millions of tonnes of hydrocarbons are used safely every year throughout the world for cooking, heating, powering vehicles and as aerosol propellants. In these industries, procedures and standards have been developed and adopted to ensure the safe use of the product. The same approach has also been adopted by the refrigeration industry. Various applications have been developed to deal with the flammability and safety problems, such as the use of enhanced compact heat exchangers, the optimization of system designs, the reduction in the charge of systems and the establishment of rules and regulations for safety precautions [19-21].

In the present study, the performance of hydrocarbon mixtures (R432A and R433A) with zero ODP and negligible GWP (Table 1) is investigated theoretically in a vapour compression refrigeration system. R432A is a near azeotropic mixture composed of 80% propylene (R1270) and 20% dimethylether (RE170) by weight. R433A is also a near azeotropic mixture composed of 30% propylene (R1270) and 70% propane (R290) by weight. The performance of these refrigerants was evaluated and compared with that of R22.

Table 1 Environmental and thermophysical properties of investigated refrigerants [22, 23]

Environmental and thermophysical properties	Refrigerants				
	R22	R432A	R433A	R407C	R410A
Critical temperature (^oC)	96.2	97.3	94.4	86.0	71.4
Normal boiling point, NBP (^oC)	-40.8	-46.6	-44.6	-44.0	-51.0
Temperature glide (^oC)	-	1.0	0.4	5	0.2
Composition	-	R1270 (80%) RE170 (20%)	R1270 (30%) R290 (70%)	R32 (23%) R125 (25%) R134a (52%)	R32 (50%) R125 (50%)
Molar mass (kg/kmol)	86.5	42.8	43.5	86.2	72.6
ODP	0.05	0	0	0	0
GWP	1500	4	4	1525	1725

2. Materials and Methods

2.1 Vapour compression refrigeration system

Fig. 1 shows the vapour compression refrigeration cycle on a p-h diagram. The refrigeration system is made up of four major components: a condenser, an evaporator, a compressor and an expansion device. In the evaporator, the liquid refrigerant vapourizes by absorbing latent heat from the material being cooled, and the resulting low pressure vapour refrigerant then passes from the evaporator to the compressor. The compressor is the heart of the refrigeration system. It pumps and circulates the refrigerant through the system, and supplies the necessary force to keep the system operating. It raises the refrigerant pressure and consequently the temperature, to enable heat rejection in the condenser at a higher temperature. The condenser is a device used for removing heat from the refrigeration system to a medium which has lower temperature than the refrigerant in the condenser. The high pressure liquid refrigerant from the condenser passes into the evaporator through an expansion device or a restrictor that reduces the pressure of the refrigerant to the low pressure existing in the evaporator. The expansion device regulates or controls the flow of the liquid refrigerant to the evaporator.

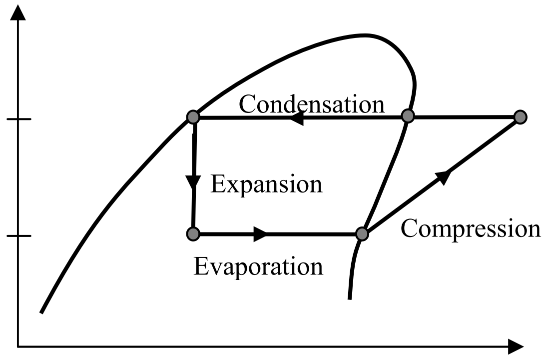

Fig. 1 Vapour compression refrigeration cycle on a p-h diagram

2.2 Determination of thermodynamic properties of refrigerants

The most fundamental of a working fluid's thermal properties that are needed for the prediction of a refrigerant system's performance are the pressure-volume-temperature (PvT) in an equilibrium state. Other properties, such as enthalpy and entropy as well as the Helmholtz and Gibbs functions, may be derived from a PvT correlation utilizing specific heat. There exists a myriad of equations-of-state, which have been classified into families. These equations have been used to develop the most widely used refrigerant database software known as REFPROP [22, 24]. This software was developed and is maintained by the National Institute of Standards and Technology and is currently in its ninth edition. It uses several equations-of-state to correlate 33 single component refrigerants and 29 predefined mixtures, along with the ability to construct virtually any desired mixture of up to five components [25]. This software was used in this work to compute the properties of the investigated refrigerants.

2.3 Data reduction

After the thermodynamic properties of each state of the cycle are determined, the equations for the cycle analysis are obtained by means of mass and energy conservation. The data reduction of the theoretical results is analysed with the equations stated below. Considering the cycle on the p-h diagram in Fig. 1, the heat absorbed by the refrigerant in the evaporator or refrigerating effect (Q_{evap}, kJ/kg) is calculated as:

$$Q_{evap} = (h_1 - h_4) \quad (1)$$

where, h_1 = specific enthalpy of the refrigerant at the outlet of the evaporator (kJ/kg); and h_4 = specific enthalpy of the refrigerant at the inlet of the evaporator (kJ/kg). The compressor work input (W_c, kJ/kg) is obtained as:

$$W_c = (h_2 - h_1) \quad (2)$$

where, h_2 = specific enthalpy of the refrigerant at the outlet of the compressor (kJ/kg). The flow of the refrigerant in the throttling valve from point 3 to point 4 is at constant enthalpy (isenthalpy). Therefore,

$$h_3 = h_4 \quad (3)$$

where, h_3 = specific enthalpy of the refrigerant at the outlet of the condenser (kJ/kg). The pressure ratio (P_R) of the cycle is obtained as:

$$P_R = \frac{P_{cond}}{P_{evap}} \tag{4}$$

where, P_{cond} = condensing pressure (MPa) and P_{evap} = condensing pressure (MPa). Power per ton of refrigeration (*PPTR*) is obtained as:

$$PPTR = \frac{3.5W_c}{Q_{evap}} \tag{5}$$

The volumetric refrigerating capacity (*VRC*, kJ/m^3) is the cooling capacity per unit of vapour volume at the exit of the evaporator and is calculated as follows:

$$VRC = \rho_1 \cdot Q_{evap} \tag{6}$$

where, ρ_1 = density of the refrigerant at the exit of the evaporator (kg/m^3). The coefficient of performance (COP) is the refrigerating effect produced per unit of work required; therefore, COP is obtained as the ratio of Eq. (1) to Eq. (2):

$$COP_{ref} = \frac{Q_{evap}}{W_c} \tag{7}$$

3. Results and Discussion

The curves of the variation of the saturation vapour pressure with the evaporating temperature for the substitute refrigerants (R432A and R433A) compared with the base refrigerant (R22) are shown in Fig. 2. As shown in this figure, there is no significant deviation between the curves for the alternative refrigerants and that of the base refrigerant.

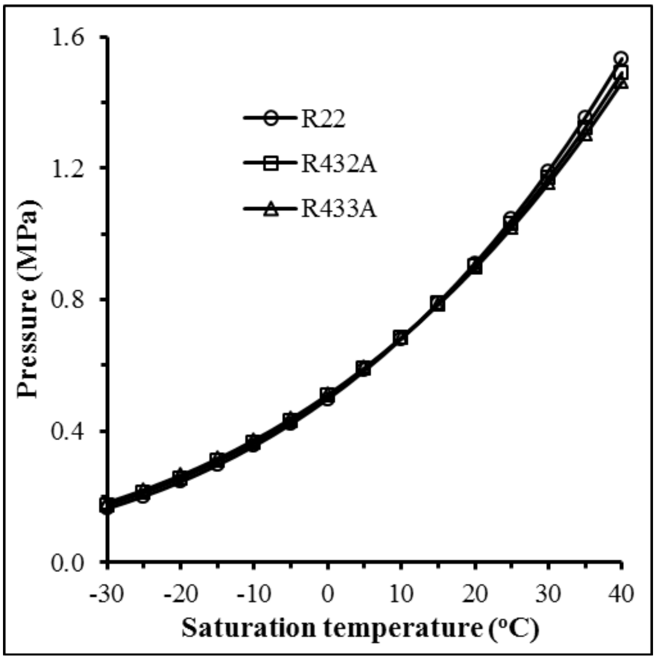

Fig. 2 Saturation vapour pressure curves

The saturation vapour pressures for R432A and R433A, between the saturation temperatures of -30 to 40^{o}C, are 99.6 and 99.3% the same as that of R22. This indicates that R432A and R433A refrigerants exhibit similar properties to R22 and will work successfully as alternative refrigerants for R22.

Fig. 3 shows the influence of the evaporating temperature on refrigerating effects for R432A, R433A and R22 at the condensing temperature of 50^{o}C. As shown in the figure, the refrigerating effect increases as the evaporator temperature increases for all the investigating refrigerants. This is due to the increase in the latent heat energy of the refrigerant. Very high latent heat energy is desirable since the mass flow rate per unit of capacity is lower. When the latent value is high, the energy efficiency and capacity of the compressor are greatly increased. The refrigerating effects of the alternative refrigerants (R432A and R433A), as clearly shown in Fig. 3, are higher than that of R22.

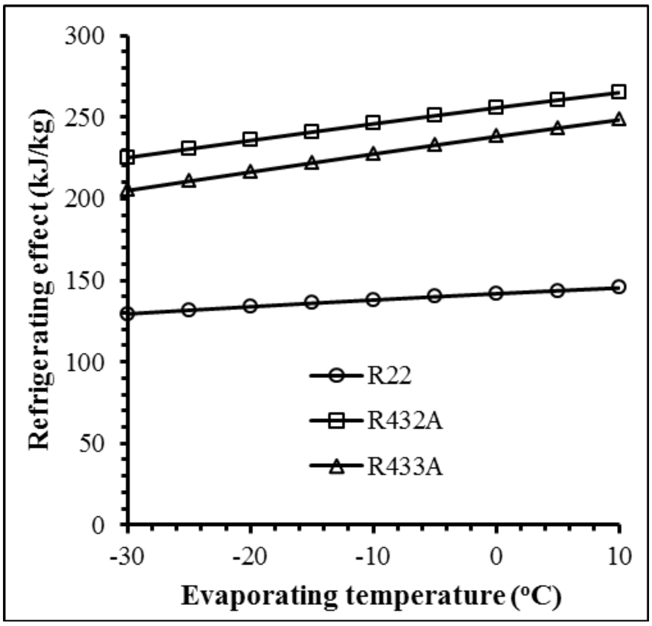

Fig. 3 Influence of evaporating temperature on the refrigerating effect

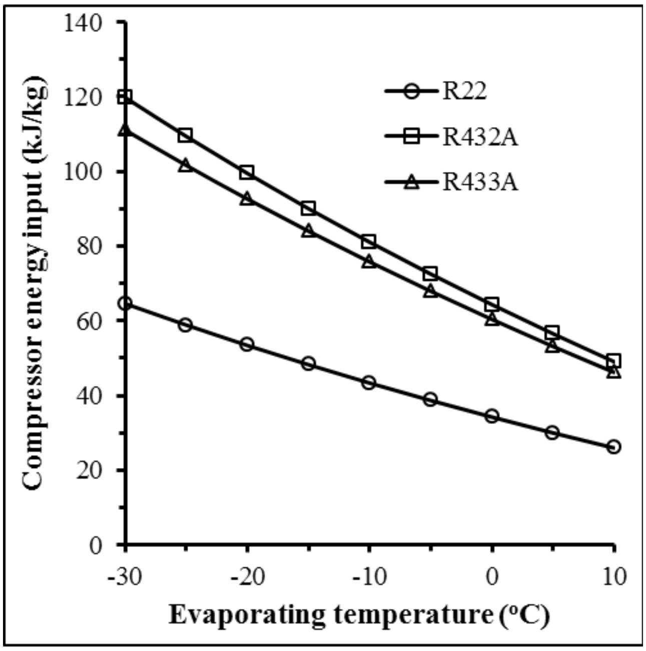

Fig. 4 Compressor energy input versus evaporating temperature

The influence of the evaporating temperature on the compressor energy input for R22 and the two alternative refrigerants at the condensing temperature of 50^{o}C is shown in Fig. 4. The figure shows that the work of compression decreases as the temperature of the evaporator increases. R432A and R433A refrigerants exhibited a higher compressor energy input than R22, but they equally exhibited a very high refrigerating effect (Fig. 3), which is a form of compensation for their high compressor energy input.

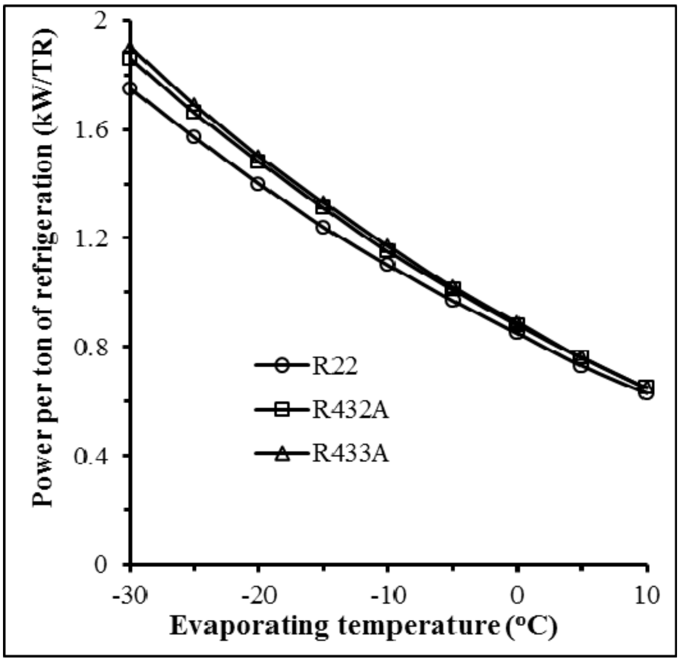

Fig. 5 Influence of evaporating temperature on the power per ton of refrigeration

Fig. 5 shows the power consumption per ton of refrigeration for R22 and the two investigated alternative refrigerants as a function of the evaporating temperature at the condensing temperature of 50°C. The curves for alternative refrigerants are almost the same, which indicate the same performance in the system. The average power consumptions per ton of refrigeration obtained for R432A and R433A were 5.1 and 6.5%, respectively, higher than that of R22.

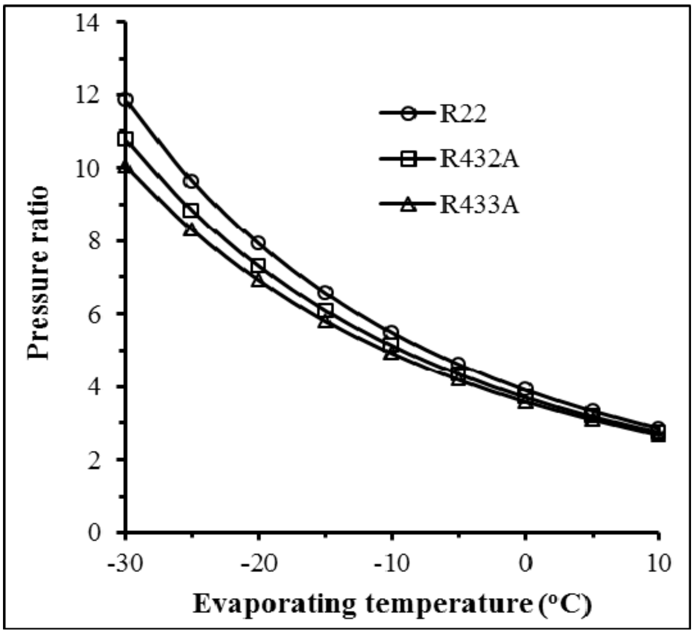

Fig. 6 Influence of the evaporating temperature on the pressure ratio

The influence of the evaporating temperature on the pressure ratio at the condensing temperature of 50^{o}C for R22 and the alternative refrigerants is shown in Fig. 6. From the figure it was observed that the pressure ratios for the investigated refrigerants reduced with the increase in the evaporating temperature. The increase in the evaporating temperature will simultaneously increase the pressure, which will reduce the pressure ratio since the condensing temperature is constant. This justified the curve profile of Fig. 6. The pressure ratio of R22 was found to be the highest, while that of R433A was the lowest. The average pressure ratios obtained for R432A and R433A were 7.3 and 11.9%, respectively, lower than that of R22.

Fig. 7 shows the variation of the discharge temperature for R22 and the two investigated alternative refrigerants as a function of the evaporating temperature at the condensing temperature of 50^{o}C. The alternative refrigerants (R432A and R433A) exhibited lower values of the discharge temperature than R22. High discharge temperature is detrimental to the performance of the system, therefore, the low discharge temperature exhibited by the two alternative refrigerants indicates that using them as drop-in substitutes in R22 systems will produce less strain on the compressor and hence a longer compressor life. The average discharge temperatures obtained for R432A and R433A were 16.5 and 23.7%, respectively, lower than that of R22.

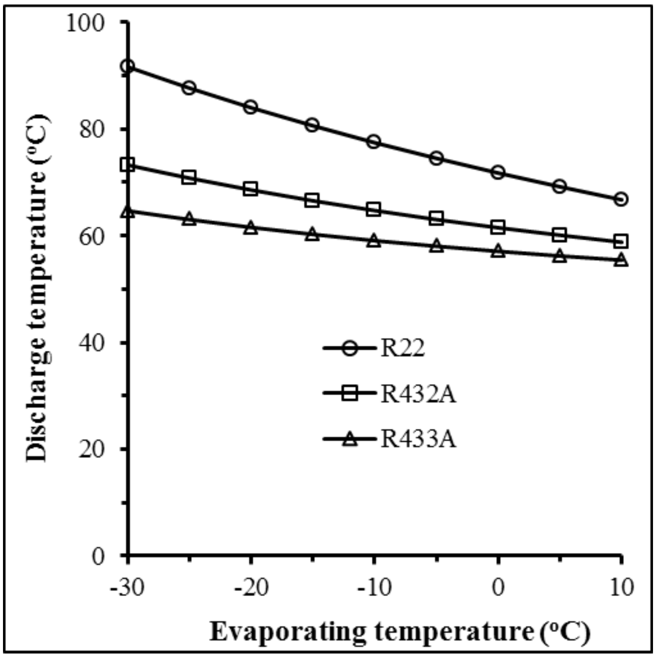

Fig. 7 Influence of the evaporating temperature on the discharge temperature

Fig. 8 shows the discharge pressure at the condensing temperature of 50^{o}C for R22 and its two alternative refrigerants. The discharge pressure is an important parameter that affects the performance of a refrigerating system. It influences the stability of the lubricants and compressor components. Also, high discharge temperature is detrimental to the performance of the system. R432A and R433A exhibited discharge pressure very close to that of R22. R432A and R433A have an advantage of slightly lower discharge pressure than R22 by 3.7 and 5.9%, respectively, of the average values.

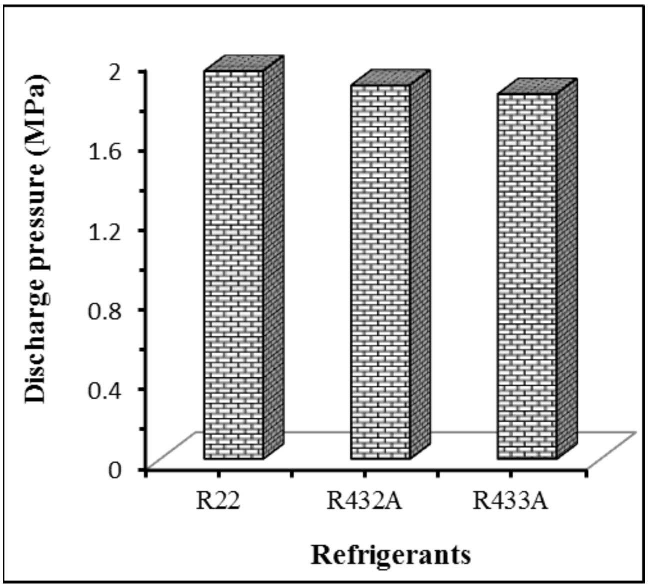

Fig. 8 Discharge pressure of the refrigerants at condensing temperature of 50^{o}C

The influence of the evaporator temperature on the volumetric refrigerating capacity (VRC) at the condensing temperature of 50^{o}C for R22 and the two alternative refrigerants is shown in Fig. 9. As shown in the figure, VRC increases as the evaporator temperature increases for all the investigating refrigerants. This is due to the increase in the density of refrigerant vapour at the exit of the evaporator. A high cooling capacity can be obtained from a high volumetric capacity refrigerant for a given swept volume in the compressor. The VRCs of the two alternative refrigerants are very close to that of R22, which shows that they can use the same compressor size with R22. The average VRCs obtained for R432A and R433A were 9.0 and 12.5%, respectively, lower than that of R22.

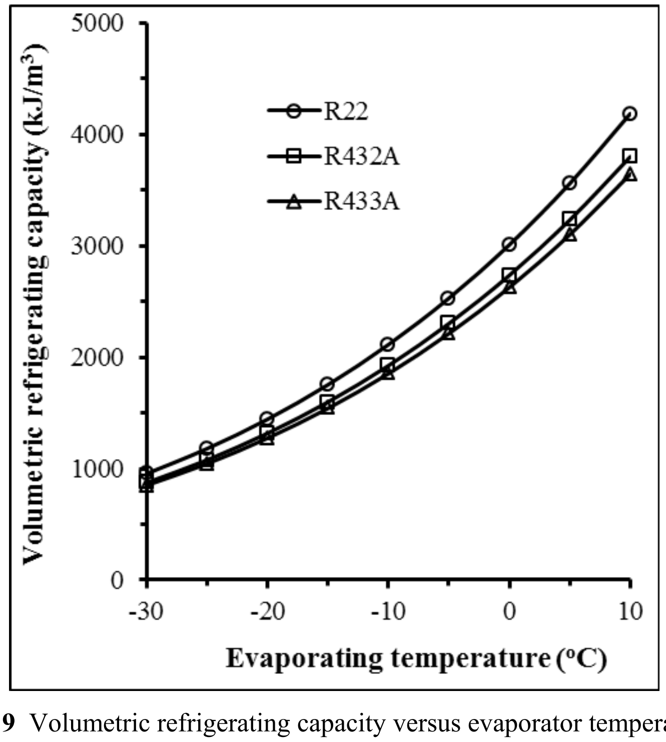

Fig. 9 Volumetric refrigerating capacity versus evaporator temperature

The coefficient of performance (COP) for R22 and its two alternative refrigerant mixtures at varying evaporating temperature at the condensing temperature of 40^{o}C is shown in Fig. 10. Similar trends were observed in the curve profiles for all the investigated refrigerants. The COP increases with an increase in the evaporator temperature. The COPs of the three alternative refrigerants are very close to that of R22. The average COPs obtained for R432A and R433A were 4.5 and 5.4%, respectively, lower than that of R22.

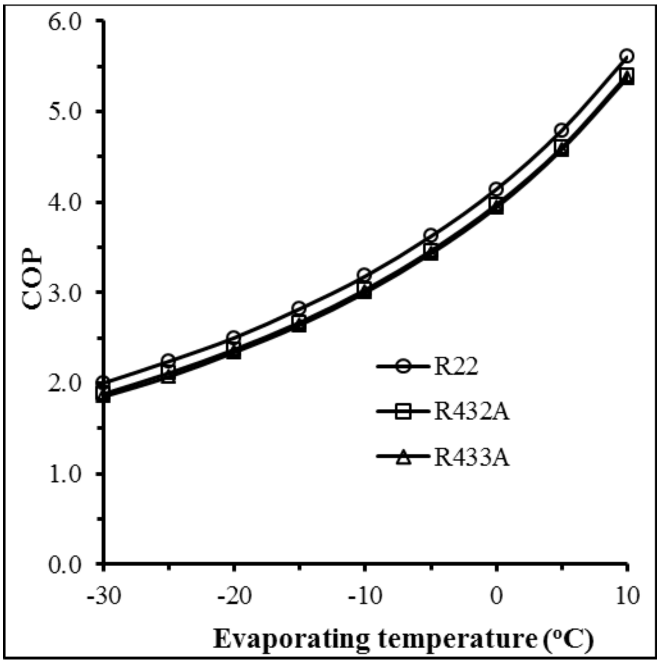

Fig. 10 Influence of the evaporating temperature on the coefficient of performance (COP)

4. Conclusions

In this study, the performance of the eco-friendly R432A and R433A as R22 alternatives was investigated theoretically in a standard vapour compression refrigeration system at the condensing temperature of 50^{o}C. The following conclusions can be drawn from the analysis and discussion of the results:

(i) There is no significant deviation between the saturation vapour pressure profiles for R432A, R433A and R22 refrigerants. The saturation vapour pressures for R432A and R433A, between the saturation temperatures of -30 to 40^{o}C, are 99.6 and 99.3% the same as that of R22. This indicates the existence of similar properties and that both R432A and R433A will work successfully as drop-in substitutes for R22.

(ii) R432A and R433A exhibited a much higher refrigerating effect than R22.

(iii) The Power per Ton of Refrigeration (PPTR), the volumetric refrigeration capacity (VRC) and the coefficient of performance (COP) of the alternative two refrigerants are very close to those of R22, but R22 exhibited better performance of these three parameters than the two alternative refrigerants. Average PPTRs of R432A and R433A are 5.1 and 6.5%, respectively, higher, while their average COPs are 4.5 and 5.4%, respectively, lower than those of R22,.

(iv) The two alternative refrigerants exhibited a better and lower pressure ratio, discharge temperature and discharge pressure than R22.

(v) The performance of the two alternative refrigerants is quite similar in all operation conditions, but the VRC and the COP of R432a are higher by 3.8 and 0.9%, respectively, than those of R433A.

Generally, both R432A and R433A have shown satisfactory performance as good long term alternatives to R22 in vapour compression refrigeration systems.

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