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COMPUTATIONAL ANALYSIS OF THE PERFORMANCE OF OZONE-FRIENDLY R22 ALTERNATIVE REFRIGERANTS IN VAPOUR COMPRESSION AIR-CONDITIONING SYSTEMS

Performance of two ozone-friendly refrigerants (R410A and R419A) was investigated theoretically using computational thermodynamic analysis. The results obtained showed that the performance of R410A was very close to that of R22 in all the operating conditions. Both R22 and R410A performed better than R419A in terms of their COP and refrigerating effect. Compared with R22, the average COP and refrigerating effect of R419A are lower by 13.78 and 33.96%, respectively. Generally, R410A refrigerant has approximately the same performance with R22, therefore, it is considered as a good drop-in substitute for R22 in vapour compression air-conditioning system.

1. INTRODUCTION

Theoretically, the coefficient of performance (COP) of an ideal Carnot vapour compression cycle is independent of the refrigerant. However, the irreversibilities inherent in the ideal cycle cause the COP and other performance parameters of practical cycle to depend on the refrigerant [1]. Therefore, refrigerant represents one of the important ingredients of any vapour compression refrigeration system. It immensely influences design, operation and performance of the system [2].

The linkage of the CFC refrigerants to the destruction of the ozone layer, which has been established recently, is attributable to their exceptional stability because of which they can survive in the atmosphere for decades and ultimately diffusing to the rarefied heights where the stratospheric ozone layer resides. The inventors of these refrigerants could not have visualized the ravaging effects of the refrigerants on the ozone layer. They intentionally pursued refrigerants with the exceptional stability that was

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imposed as one of the necessary requirements of the ideal refrigerant they were called upon to invent [3].

In the past, refrigerants have been selected on the basis of suitable qualifying properties such as non-flammability, non-toxicity, stability and good materials compatibility. Also considered are a qualitative assessment of transport and thermodynamic properties such as the desirability of a low viscosity, high latent heat, and operation away from the critical point. The performance of refrigerants which satisfied these criteria were then calculated for various applications and compared with each other [4].

Chlorofluorocarbon (CFC) and hydro-chlorofluorocarbon (HCFC) refrigerants fulfilled all the primary requirements and heralded an unprecedented revolution in the refrigeration and air-conditioning industry. Today, the litany of the requirements imposed on an ideal refrigerant has increased. The additional primary requirements now include zero ozone depletion potential (ODP) and low global warming potential (GWP) [5]. The continuous depletion of the ozone layer, which shields the earth's surface from the biologically damaging ultraviolet sunlight called UV-B radiation, has resulted in a series of international treaties demanding a gradual phase out of CFC and HCFC refrigerants. The CFCs have been phased out in developed countries since 1996, and 2010 in developing countries [6]. Initial alternative to CFCs included some hydro-chlorofluorocarbons (HCFCs), but they will also be phased out internationally by year 2020 and 2030 in developed and developing nations, respectively [7, 8].

Since R22 came into common use as a refrigerant in 1936, it has been applied in systems ranging from smallest window air-conditioners to the largest chillers and heat pumps. Individual equipment using this versatile refrigerant ranges from 2 kW to 33 MW in cooling capacity. No other refrigerant has achieved such a wide range of applications [9]. However, R22 is one of a class of chemicals, HCFCs, being phased out due to the environmental hazard of ozone depletion [10, 11].

Ozone friendly alternative refrigerants in air-conditioners and heat pumps can be grouped into three categories; the first category is hydro-fluorocarbons (HFCs) that are used in conventional vapour compression cycles such as R134a, R413A, R410A, R407C. The second category is natural fluids, which includes propane (R290) and ammonia (R717). Although these refrigerants have zero ozone depletion potential (ODP) and minimum global warming impact due to direct emissions but there are safety and environmental factors associated with them that would limit their widespread use as refrigerants. The third category is alternative cycles that include absorption systems, and use of trans-critical fluid CO₂ (R744) and air cycles. In general, these alternative cycles do not currently offer the same energy efficiency as the vapour compression cycle using HFC refrigerants and so, they increase indirect global warming emissions via increased fossil fuel usage through increased electrical energy consumption [12, 13].

Blends of the HFC refrigerants, in the first category of alternative refrigerants, have been considered the favourite candidates for R22 alternatives. HFCs are synthetic

fluids entirely harmless to the ozone layer since they do not contain chlorine and hence have zero ODP. These fluids are the most used substitutes for CFCs and HCFCs [14]. The research on refrigerant replacement for R22 has been one of hot topics in the refrigeration and air-conditioning industry. Many refrigerants were assessed through the Alternative Refrigerant Evaluation Program (AREP) as potential replacements for R22. The most promising alternative refrigerants that emerged were R410A, R407C, R134a, and R290. This list has since been revised to include R419A, R404A and R507 [6, 15].

Table 1

Environmental impacts of the investigated refrigerants [10]

Refrigerant	Ozone depletion potential (ODP)	Global warming potential (GWP) (100 year horizon)
R22	0.055	1700
R410A	0	1725
R419A	0	1985

Table 1 shows the environmental impacts of the investigated refrigerants. It is clearly shown in the table that both R410A and R419A have zero ODP, therefore, they do not contribute to the depletion of ozone layer. R419A has the highest GWP, while the GWP of R410A is very close to that of R22 [10]. Beside the environmental factors, the successful replacement and use of these alternative refrigerants required investigations of their suitability in the system by evaluating and comparing their performance with performance of existing refrigerant in the system [16].

Therefore, the paper presents the results of computational analysis of thermodynamic properties of R22 and two of its ozone-friendly alternatives HFC mixtures (R419A and R410A) in a standard air-conditioning system. R419A is a non-azeotropic mixture composed of R125, R134a and RE170 (dimethylether) (77, 19 and 4 wt. %, respectively), and R410A is a near azeotropic mixture composed of R32 and R125 (60 and 40 wt. %, respectively). The performance parameters of the system working with these alternative refrigerants were evaluated and compared with those of R22.

2. MATERIALS AND METHODS

Vapour compression refrigeration system. Figure 1 shows vapour compression refrigeration cycle on the P - h diagram. The refrigeration system is made up of four major components: condenser, evaporator, compressor and expansion device. In the evaporator, the liquid refrigerant vaporizes by absorbing latent heat from the material being cooled, and the resulting low pressure vapour refrigerant then passes from the evaporator to the compressor. Compressor is the heart of the refrigeration system. It pumps and circulates refrigerant through the system, and supplies the necessary force to

keep the system operating. It raises the refrigerant pressure and hence the temperature, to enable heat rejection at a higher temperature in the condenser. 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 low pressure existing in the evaporator. Expansion device regulates or controls the flow of liquid refrigerant to the evaporator.

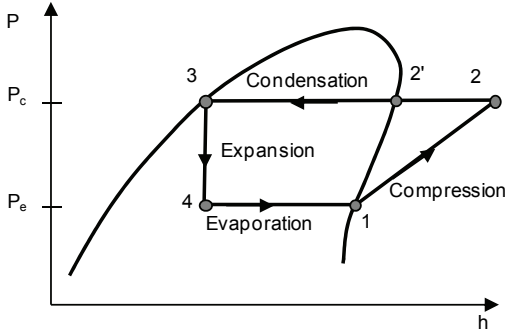


Fig. 1. Vapour compression refrigeration cycle on the P - h diagram

Considering the cycle on the P - h diagram in Fig. 1, the following assumptions are made:

1. Evaporation under constant pressure (P_e) and at constant temperature (T_e) in the evaporator from point 4 to point 1. The heat absorbed by the refrigerant in the evaporator or refrigerating effect (Q_{evap} , kJ/kg) is given as:

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

where h_1 is the specific enthalpy of refrigerant at the outlet of evaporator (kJ/kg), h_4 – the specific enthalpy of refrigerant at the inlet of evaporator (kJ/kg).

2. An isentropic compression process in the compressor, from point 1 to point 2. The compressor work input (W_c , kJ/kg) is

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

where h_2 is the specific enthalpy of the refrigerant at the outlet of compressor (kJ/kg).

3. De-superheating under constant pressure (P_c) from the compressor discharge temperature (T_2) at point 2 to the condenser temperature (T_c) at point 2', followed by condensation at both constant temperature (T_c) and constant pressure (P_c) from point 2' to point 3. The heat rejected in the condenser (Q_c , kJ/kg) is

$$Q_c = h_2 - h_3 \quad (3)$$

where h_3 is the specific enthalpy of refrigerant at the outlet of the condenser (kJ/kg).

4. Expansion at constant enthalpy (isenthalpy) in the throttling valve from point 3 to point 4. Therefore,

$$h_3 = h_4 \quad (4)$$

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):

$$\text{COP}_{\text{ref}} = \frac{Q_{\text{evap}}}{W_{\text{comp}}} \quad (5)$$

Computational analysis. The most fundamental of a working fluid 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 [17, 18]. It 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 [19]. This software was used in this work to compute the properties of investigated refrigerants.

3. RESULTS AND DISCUSSION

The refrigerating effects of R22 and its two potential alternative refrigerants at varying evaporator temperature for condensing temperatures of 30, 40 and 50 °C are shown in Figs. 2a–c, respectively. As shown in these figures, refrigerating effect increases as the evaporator temperature increases for all the investigating refrigerants. This is due to the increase in latent heat value of the refrigerant. A very high latent heat value is desirable since the mass flow rate per unit of capacity is lower. When the latent value is high, the efficiency and capacity of the compressor are greatly increased. This decreases the power consumption and also reduces the compressor displacement requirements that permit the use of smaller and more compact equipment.

The curves of R410A, as clearly shown in Fig. 2, are very close to those of R22 with advantage of higher values, while the curves for R419A are far below that of R22, which indicate very low refrigerating effect. The refrigerating effect for varying condensing temperature is shown in Fig. 3. Refrigerating effect for the three refrigerants reduces as the condensing temperature increases. This is due to an increase in the enthalpy of refrigerant at inlet to the evaporator as a result of the increase in the condensing temperature, which reduces the refrigerating effect. The highest refrigerating effect was obtained using R410A with average value of 3.44% higher than that of R22, while R419A has an average value of 33.96% lower compared with that of R22.

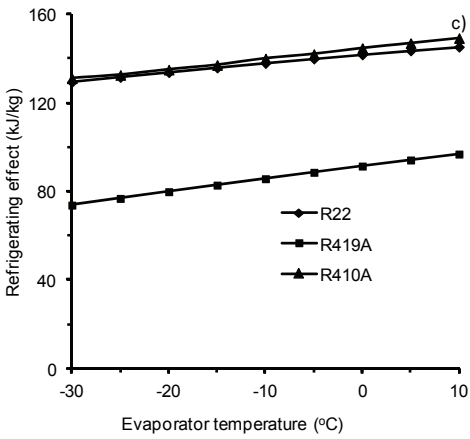
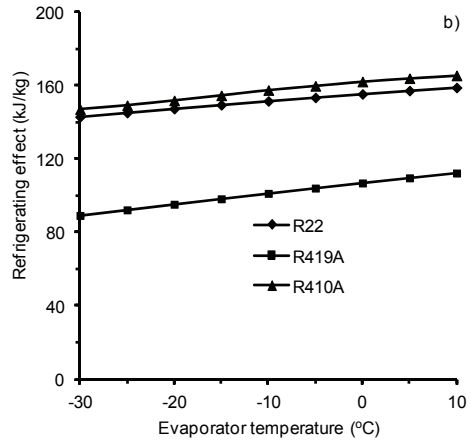
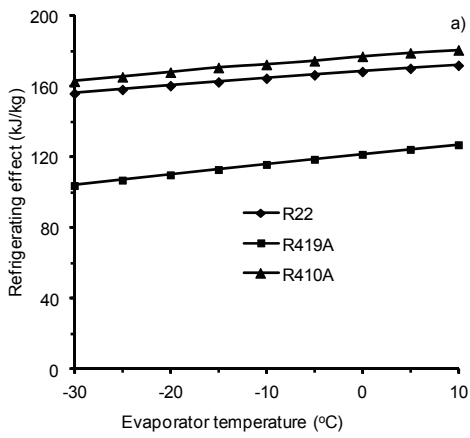


Fig. 2. Refrigerating effect upon evaporator temperature at condensing temperature of: a) 30 °C, b) 40 °C, c) 50 °C

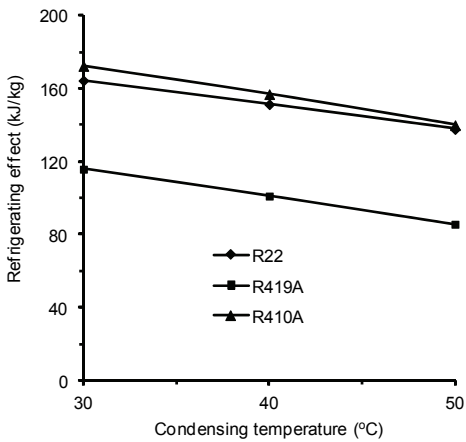


Fig. 3. Refrigerating effect upon varying condensing temperature

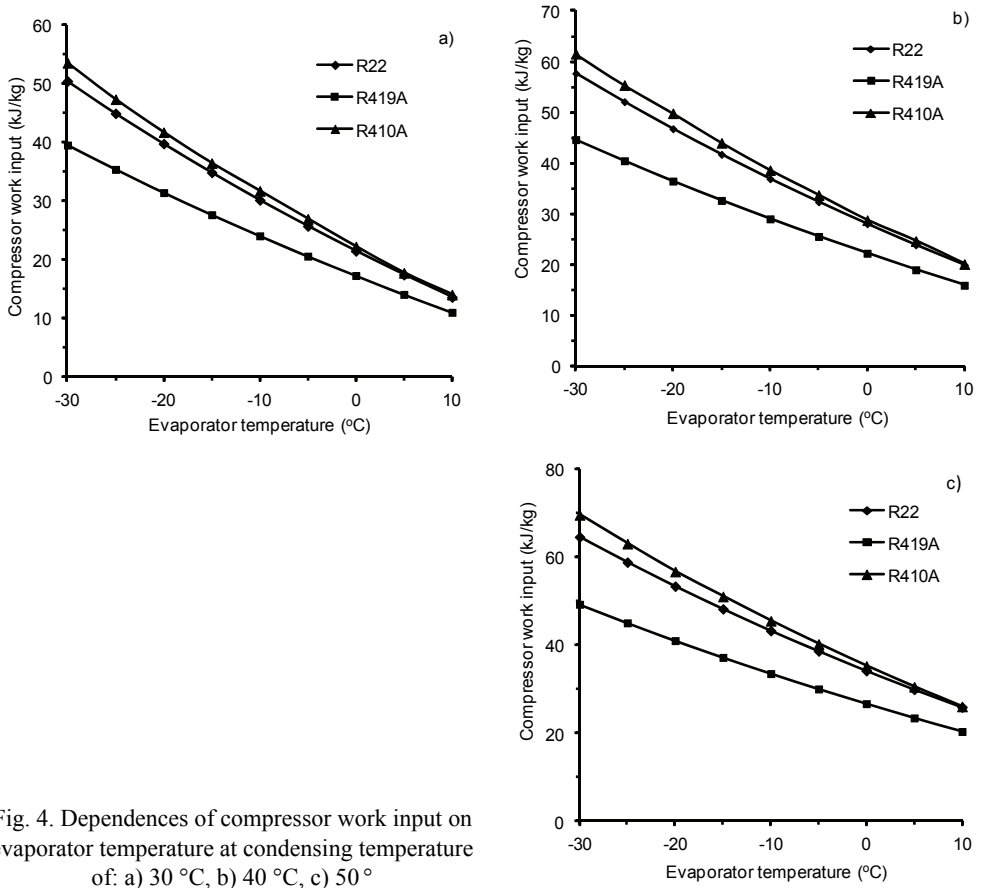


Fig. 4. Dependences of compressor work input on evaporator temperature at condensing temperature of: a) 30 °C, b) 40 °C, c) 50 °

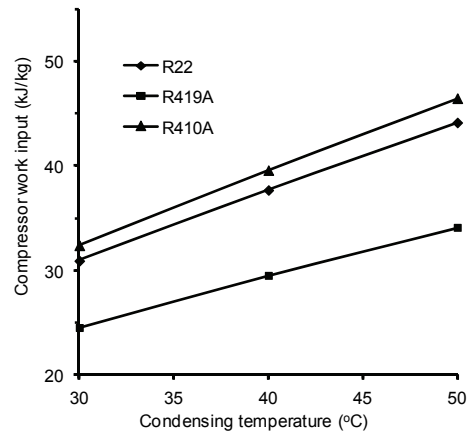


Fig. 5. Dependences of compressor work input on condensing temperature

The compressor work input for R22 and its two potential alternatives at varying evaporator temperature for condensing temperature of 30, 40 and 50 °C are shown in Figs. 4a–c, respectively. These figures clearly revealed that compressor work input increases with increase in the evaporator temperature. Similar trend and variations of compressor work input were obtained for both R410A and R22 for all cases of condensing temperatures studied. R419A exhibited lower compressor work input than both R22 and R410A. Figure 5 shows the variation of compressor work input as a function of condensing temperature. As shown in the figure, the average compressor work input of R410A is very close to that of R22 with average value of 5.04% higher than that of R22, while R419A has an average value of 21.80% lower than that of R22.

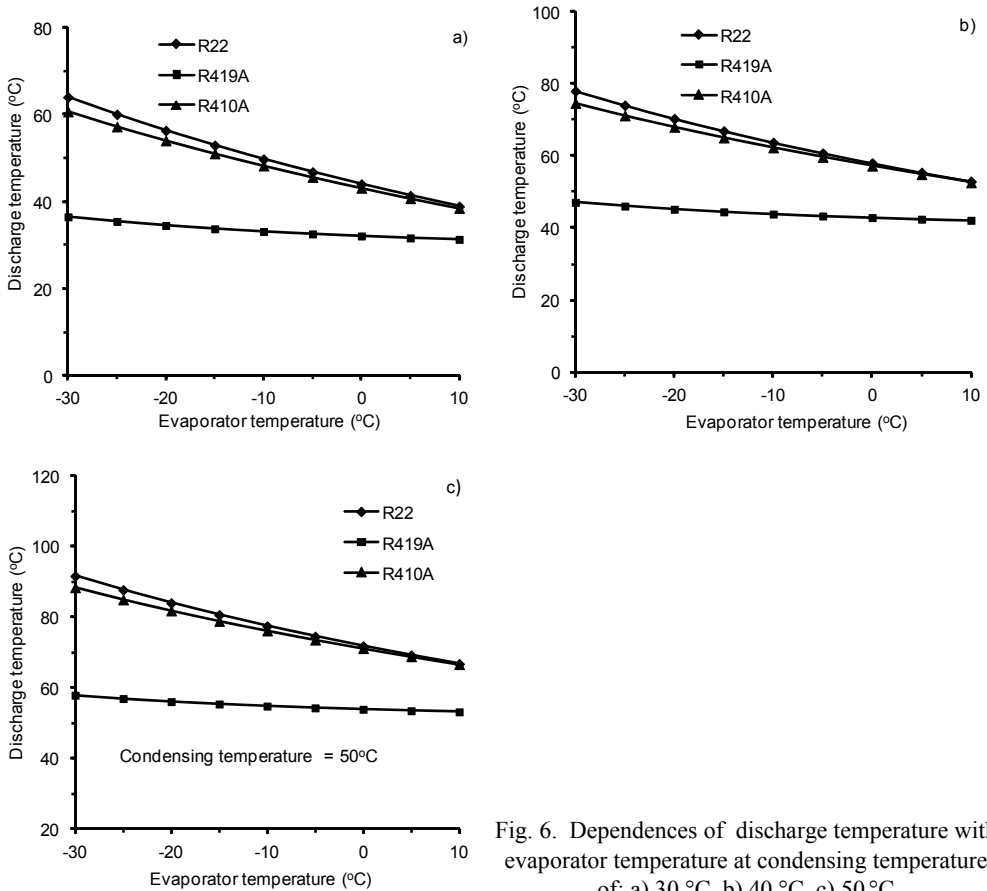


Fig. 6. Dependences of discharge temperature with evaporator temperature at condensing temperature of: a) 30 °C, b) 40 °C, c) 50 °C

Figures 6a–c show the dependence of the discharge temperature for the three investigated refrigerants on the evaporator temperature for the condensing temperatures

of 30, 40 and 50 °C, respectively. The alternative refrigerants (R410A and R419A) exhibited lower values of the discharge temperature than R22, though the curves for R410A are almost the same with those of R22, which depicts the same performance in the system.

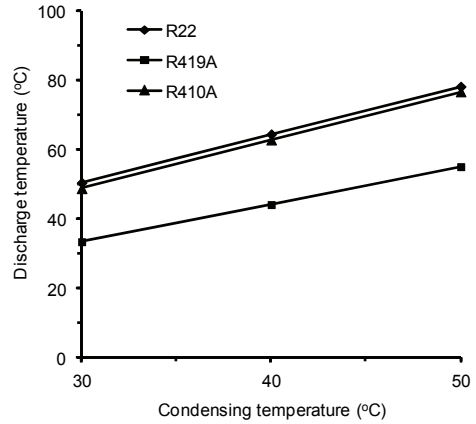


Fig. 7. Dependences of discharge temperature on condensing temperature

High discharge temperature is detrimental to the performance of the system, therefore, low discharge temperature is required, which means that there will be less strain on the compressor and hence a longer compressor life. The lowest value of discharge temperature, which is suitable for the refrigeration system, was obtained using R419A. Figure 7 shows the dependences of the discharge temperature on the condensing temperature. As shown in the figure, discharge temperature increases upon increasing condensing temperature, which is expected due to the direct relationship between the two temperatures. The average discharge temperature obtained for R410A and R419A were 2.46% and 31.26% lower than that of R22, respectively.

The coefficient of performance (COP) for R22 and its two potential alternatives at varying evaporator temperature for condensing temperature of 30, 40 and 50 °C are shown in Figs. 8a–c, respectively. Similar trends were observed in the three figures, for all the refrigerants considered, COP increases with increase in evaporator temperature. The COPs of the three refrigerants are very close. Also, variation of the COP with condensing temperature is presented in Fig. 9 for the three investigated refrigerants. It is clearly shown in this figure that when condensing temperature increases the COP reduces for both R22 and its alternative refrigerants. COP is inversely proportional to the power input through the compressor, therefore, increase in compressor power due to increase in condensing temperature reduces the COP of the system. R22 has the highest COP closely followed by R410A. Compared with

R22, the average COP of R410A reduced by 3.26%, while that of R419A reduced by 13.78%.

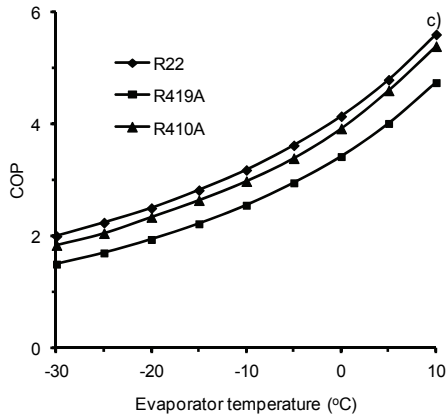
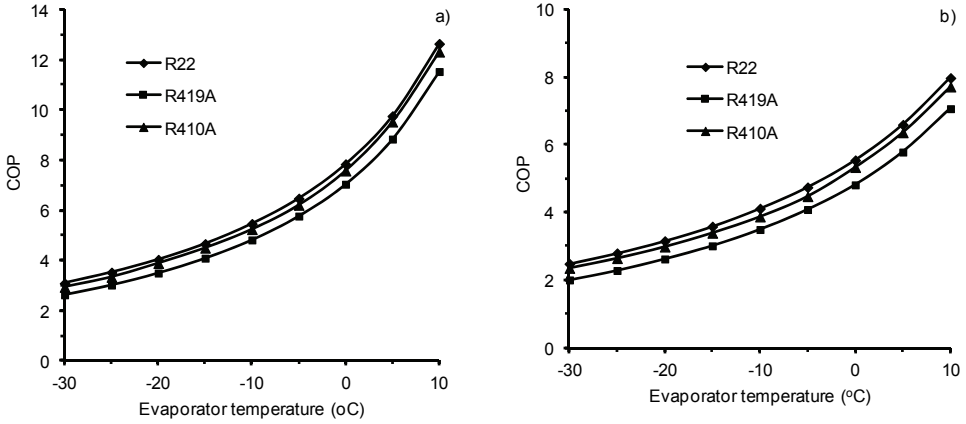


Fig. 8. Dependences of the coefficient of performance (COP) on evaporator temperature at condensing temperature of: a) 30 °C, b) 40 °C, c) 50 °

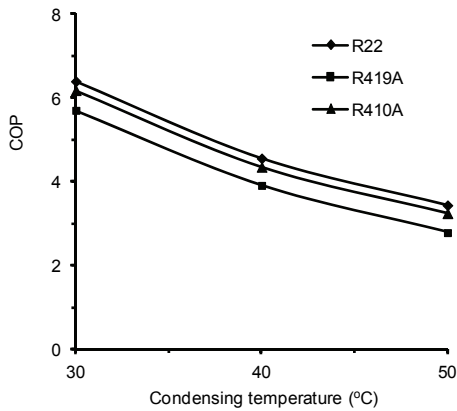


Fig. 9. Dependences of the coefficient of performance (COP) on condensing temperature

4. CONCLUSIONS

R22 that is commonly used as working fluid in vapour compression air-conditioning systems all over the world is being phased out due to its environmental hazard of ozone depletion. The performances of two ozone friendly, hydro-fluoro-carbon (HFC) refrigerant mixtures (R410A and R419A) were investigated theoretically using computational thermodynamic analysis and compared with the performance of baseline refrigerant (R22) in a vapour compression air-conditioning system. Based on the results of investigation, the following conclusions have been drawn:

- Performance of R410A was very close to that of R22 in all the operating conditions and performance characteristics considered.
- Performance of R410A is slightly better than that of R22 in terms of refrigerating effect and discharge pressure. Compared with R22, the average refrigerating effect of R410A is higher by 3.44%, while discharge pressure is lower by 2.46%.
- The COP and refrigerating effect of both R22 and R410A are far better than those of R419A. Compared with R22, the average COP and refrigerating effect of R419A are lower by 13.78 and 33.96%, respectively.
- R419A performed better than both R22 and R410A in terms of compressor work input and discharge temperature. It exhibited very low values of these parameters, which are of great interest in refrigeration systems. Compared with R22, the average compressor work input and discharge temperature of R419A are lower by 21.80 and 31.26%, respectively.
- The overall evaluation of the performances of the two alternative refrigerants in the standard vapour compression air-conditioning system favoured the use of R410A as a drop-in substitute to R22 in the existing system. It will also perform better as long term substitute for R22 in new systems.
- The second alternative refrigerant (R419A) exhibited wide gap between its performance and that of R22, the direct substitution of R22 to R419A will require major changes to the existing equipment. Nevertheless, due to its very low compressor work input and discharge temperature it can be considered in new designs in which its performance can be optimized.

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