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RESEARCH PAPER

Theoretical Investigation of Energy-Saving Potential of Eco-Friendly R430A, R440A and R450A Refrigerants in a Domestic Refrigerator

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Abstract This paper presents theoretical investigation of the energy-saving potentials of the eco-friendly R430A, R440A and R450A refrigerant mixtures in a domestic refrigerator. The results showed that R440A refrigerant mixture produced the highest coefficient of performance (COP). The COPs obtained for R430A and R440A were 5.57 and 10.70% higher, respectively, while the COP of R450A was 3.36% lower than that of R134a. All the three investigated alternative refrigerants exhibited low discharge pressure which is highly desirable in refrigeration system. R430A and R440A refrigerants produced higher refrigerating effect and volumetric cooling capacity (VCC) than R450A and R134a refrigerants. The average VCCs of R430A and R440A are 8.75 and 7.24%, respectively, higher than that of R134a, while the value of R450A is 4.77% lower than that of R134a. The results also showed that R430A and R440A are more energy saving than both R450A and R134a in the refrigeration system. The power per ton of refrigeration obtained for R430A and R440A is 5.48 and 10.46% lower, respectively, than the value of R134a, while the value for R450A is 4.62% higher than that of R134a. Generally, R430A and R440A performed better than both R450A and R134a in that they exhibited lower energy consumption per ton of refrigeration, lower discharge pressure, higher refrigerating effect, COP and volumetric cooling capacity than R450A and R134a. The overall best performance is obtained using R440A in the system.

Keywords Eco-friendly · Energy saving · Alternative refrigerant · Domestic refrigerator · R430A · R440A

Abbreviations

CFC	Chlorofluorocarbon
COP	Coefficient of performance
EOS	Equations-of-state
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
ODP	Ozone depleting potentials
ODS	Ozone depleting substance
PPTR	Power per ton of refrigeration
VCC	Volumetric cooling capacity

List of symbols

h_1	Specific enthalpy of refrigerant at the outlet of evaporator (kJ/kg)
h_2	Specific enthalpy of refrigerant at the outlet of compressor (kJ/kg)
h_3	Specific enthalpy of refrigerant at the outlet of condenser (kJ/kg)
h_4	Specific enthalpy of refrigerant at the inlet of evaporator (kJ/kg)
P_{cond}	Condensing pressure (N/m^2)
P_{evap}	Evaporating pressure (N/m^2)
Q_{cond}	Heat rejected in the condenser per unit mass (kJ/kg)

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Q_{evap}	Refrigerating effect or heat absorbed in the evaporator per unit mass (kJ/kg)
T_2	Discharge temperature at the outlet of compressor (°C)
T_{cond}	Condensing temperature (°C)
T_{evap}	Evaporating temperature (°C)
W_{comp}	Compressor energy input per unit mass (kJ/kg)
ρ_1	Density of the refrigerant at the inlet of the compressor (kg/m^3)

1 Introduction

Global environmental problems are becoming increasingly significant as the world is facing rapid growing populations, migrations to cities, depletion of key resources and growing living standard expectations. The refrigeration industry has contributed significantly to the global environmental problems through anthropogenic chemicals (refrigerants) released into the atmosphere (Love and Cleland 2012). Also, energy consumption is growing at a high speed due to rapid industrialisation, and household energy consumption has become a significant feature on a global scale and it is a major factor in the current worldwide environmental problems. The fast increase in energy costs, the emission of polluting substances and global climate change have all made energy optimisation a crucial issue, not only in the industrial sector but also in the residential sector. Domestic refrigerators and freezers which are part of the main energy users in the private homes were among the first appliances to be targeted for energy efficiency improvements for households. Energy efficiency is the major prime mover in reducing global warming (greenhouse gas emissions). Therefore, new technologies required to conserve energy, use energy effectively, use alternative energy sources and reduce the household energy running costs are under continuous development (Minh et al. 2006; Sheykhlou and Jafamadar 2016).

Refrigeration and air-conditioning are very important for mankind; they find applications in various fields like food processing, preservation and distribution, power plants, vehicles and residential comfort. On the other hand, they have been identified as the main energy-consuming domestic appliances (Qiu et al. 2014; Tahavvor and Hosseini 2015). In spite of their inherent advantages, refrigeration and air-conditioning contribute to the two major environmental problems: ozone layer depletion and global warming. Ozone layer depletion is caused by discharging chlorine-containing refrigerants known as ozone-depleting substances (ODSs) into the atmosphere. These substances deplete the earth's protective ozone layer at a much greater rate than the natural processes of reproducing ozone, which upsets the natural balance and leads to an increase in dangerous ultraviolet radiation reaching the earth's surface. The depletion is dependent on the different ozone-depleting potentials (ODPs) of the chlorofluorocarbon (CFC) and hydro-chlorofluorocarbon (HCFC) refrigerants (Bolaji and Huan 2013a, b).

Global warming arises because of the greenhouse effect. It increases at a high rate by the emission of the greenhouse gases caused by human activity. Greenhouse gases result in an upsurge in the capability of the atmosphere to hold surplus heat radiated from the earth (Restrepo et al. 2008). As a result, the temperature of the earth's surface is increasing and this leads to climate change. There are several ODSs that also have a strong greenhouse effect. The potential effect of different greenhouse gases varies from substance to substance, and it is expressed by a global warming potential (GWP) value. Some of these greenhouse gasses include CFCs, HCFCs, HFCs, CO_2, methane (CH_4) and nitrous oxide (N_2O) (Benhadid-Dib and Benzaoui 2011; Bolaji and Huan 2012).

The discovery of the above two main environmental problems has given rise to a series of international agreements demanding a gradual phaseout of halogenated refrigerants. The Montreal Protocol, an internationally approved agreement to combat ozone depletion, sets a timeline in 1987 for the phaseout of CFCs and HCFCs. The CFCs have been phased out in developed countries since January 1996 and January 2010 in developing countries (Bolaji 2011; UNEP 2013). The ODPs of HCFCs (the initial alternative refrigerants to CFCs) are in relative high levels though less than those of CFCs; their productions will also be phased out in the developed countries by 2020 and 2030 for new equipment and services, respectively. The schedule for developing nations commenced with a production and import freeze in 2016 and will end with total phaseout by 2040. Some European countries have already banned the use of HCFC refrigerants in new equipment and even for service of existing equipment (UNEP 2016).

Hydro-fluorocarbon (HFC) refrigerants which were once considered eco-friendly and the leading alternative refrigerants to CFCs and HCFCs in refrigeration systems are being scrutinised due to their high GWP (Austin 2016). They are regulated by the Kyoto Protocol under the climate change convention. International concern over relatively high global warming potential of HFC refrigerants has caused some European countries to abandon them as CFCs and HCFCs replacements. Hydrocarbons are the alternative refrigerants which are currently favoured in many European countries (Bolaji et al. 2014).

R134a, a HFC refrigerant with GWP of 1430 as compared to that of carbon dioxide (CO_2), is the most widely used alternative refrigerant in refrigeration equipment such as household refrigerators and small air conditioners. This refrigerant was identified as one of the controlled greenhouse gases (Tiwari and Gupta 2011; Joybari et al. 2013). The high GWP of R134a gas and its impact on climate change were not considered serious during the selection of R134a as an alternative refrigerant to R12. Now, R134a, a zero ODP refrigerant but with high GWP, is used worldwide. The sale of R134a has significantly increased during the past two decades. The growing emissions of this refrigerant in the atmosphere are steadily increasing the concentration of greenhouse gases resulting in adverse climate problems (Bolaji and Huan 2013a, b). Consequently, the application of R134a as a long-time alternative working fluid in refrigeration and air-conditioning systems is not acceptable anymore; it needs to be replaced with more eco-friendly refrigerants.

Many researchers have carried out various investigations on the energy performance of refrigeration and heat pump systems with the main aim of reducing the energy consumption by the systems. Ku et al. (2010) investigated the energy efficiency of two different types of compressors for a household refrigerator. One of these is conventional crank-driven compressor which is a positive-displacement compressor that has the piston driven by a crankshaft to discharge gas at high pressure. The other is linear compressor which has no crank mechanism, and its piston is oscillated by linear motor and helical coil spring. The main objective of their study is to reduce the mechanical loss in the conventional crank-driven compressor of the household refrigerator in order to increase the energy efficiency of the system. Vakiloroaya and Ha (2014) conducted a study on the energy-efficient air-cooled direct expansion air-conditioning systems with liquid pressure amplification. The study explored an optimal strategy on energy consumption for a direct expansion air-conditioning system by using a refrigerant pump in the liquid line to allow the system to operate at a lower condensing pressure with the main objective of improving the energy efficiency of the system.

Wall et al. (2015) carried out a design that altered the operation of a refrigeration system by dynamically determining optimal operating temperature set-points and run-time schedules with the aim of reducing energy consumption and operating costs, while maintaining local constraints such as capacity control, defrost cycles, product quality and safety. Afshari et al. (2016) used energy correlations in air-to-water heat pumps to investigate the optimal charge amount for different refrigerants for achieving a better understanding of energy consumption of the systems under various charges and operating conditions. Likewise, Oh et al. (2016) conducted retrofit design to improve the energy efficiency and economics of an industrial refrigeration system. The study considered a retrofit option of using a mixed refrigerant in refrigeration system designed for pure refrigerant with the main goal of decreasing energy consumption of the system by switching refrigerants without requiring extensive and expensive reconfiguration of the equipment.

Some studies have also been conducted in recent years to find suitable alternative refrigerants for R134a in domestic refrigerators. Yana-Motta et al. (2010) studied low GWP alternatives for small refrigeration (plugin) applications. The study reported detailed performance evaluation of HFO refrigerants (R1234yf and R1234ze) in an actual vending system. Overall results show that comparable performance to R134a can be achieved without significant hardware modification. Efficiency of R1234yf was very close to that of R134a, while R1234ze efficiency was lower than that of R134a and R1234yf. The performance of a low GWP R1234yf as an alternative refrigerant in a small refrigeration system was investigated theoretically by Jarall (2012). The study revealed that R1234yf has slightly less values of pressure ratio, discharge temperature, coefficient of performance (COP) and Carnot efficiency as well as higher values of evaporation and convection heat transfer coefficients than R134a.

Feiza (2013) carried out a theoretical analysis on the environmental and thermodynamic basis of a vapour compression refrigeration system in order to investigate the possibility of using R152a as an alternative to R134a refrigerant. The results showed better performance of R152a in comparison with R134a. In order to determine the best suitable mass ratio of propane (R290) and iso-butane (R600a) mixture as working fluid in small refrigerator, Bolaji and Huan (2013a, b) carried out thermodynamic analysis of the performance of a household refrigerator using various ratios of R290 and R600a blends as alternative refrigerants to R134a. The results showed that the COPs of the various blends investigated were slightly higher than that of R134a and the highest COP was obtained using the blend of the same mass proportion of R290/R600a (50/50) in the system. Also, a theoretical investigation on two mixtures of R290 and R600a as possible alternatives to R134a in vapour compression refrigeration system was carried out by Memet (2014). The two mixtures were in the ratios 30/70 and 40/60 mass proportions. The results of the study revealed that the cooling capacity of mixture 40/60 mass proportion was higher than that of 30/70 mass proportion.

Bilen et al. (2014) theoretically investigated the possible alternative replacement of R134a with R152a in the air-conditioning system of an automobile. The study presented and compared the properties of R152a with three different refrigerants (R 134a, R22 and R12). The results obtained showed that R152a and R134a do not lead to any significant difference on the performance of the refrigeration system. Baskaran and Mathews (2015) investigated the performance of R152a and RE170 mixtures as alternatives to R134a in refrigeration system. The results showed that the COP obtained working with 60% RE170 and 40% R152a was 4.88% higher than that of R134a but with 9.35% higher compressor power consumption. Gohel and Kapadia (2016) also studied the thermodynamic cycle of a mobile air-conditioning system using R1234yf as an alternative replacement for R134a. The results showed that the energy performance parameters obtained for R1234yf are slightly lower than those obtained with R134a at low condensing temperature.

Various studies reviewed above have shown that it is difficult to find pure fluids as alternatives to replace existing refrigerants unless a major change including a compressor redesign is carried out. One of the ways of avoiding a major system change is the use of refrigerant mixtures, since by mixing two or more refrigerants a different working fluid with the preferred characteristics can be created. For instance, the composition of a blend having high-pressure and low-pressure refrigerants can be modified in order to tailor the vapour pressure of the resulting fluid to match that of the halogenated refrigerants being replaced. New blends that are nonflammable but still contain flammable refrigerants could be formed through blending of refrigerants.

Mixtures of two or more refrigerants have made it possible to improve system characteristics such as compressor discharge temperature and vapour volume. R430A is a non-azeotropic mixture composed of R152a and R600a (76 and 24% in weight, respectively), also, R440A is a non-azeotropic mixture composed of R290, R134a and R152a (0.6, 1.6 and 97.8% in weight, respectively), and R450A is a near-azeotropic mixture composed of R134a and R1234ze (42 and 58% in weight, respectively). It has a very low temperature glide of about 0.4 °C (Mendoza-Miranda et al. 2016). According to Park and Jung (2009), R430A is a good long-term drop-in eco-friendly substitute refrigerant for R134a in domestic water purifiers. It has excellent thermodynamic and environmental properties (Baskaran and Mathews 2012; Shodiya et al. 2015).

Thermal systems such as refrigerators and air conditioners consume a large quantity of electric power. It is necessary to develop energy-efficient refrigerants for refrigeration and air-conditioning systems. In addition to zero ODP and low GWP, the new alternative working fluids in the refrigeration systems must also have similar or higher energy efficiency than the conventional refrigerants so that the new alternative refrigerants do not cause additional CO_2 generation at the power source (indirect global warming). Most of the previous studies on energy-efficient refrigeration involved redesign and modification of the system which is not suitable for the existing domestic refrigerators. Therefore, in this study, the energy-saving potentials of R430A, R440A and R450A refrigerant mixtures were investigated theoretically. The vapour pressure and thermo-physical properties of R430A, R440A and R450A refrigerants are similar to that of conventional refrigerant (R134a) in domestic refrigerating systems, and hence, they can be used as drop-in replacement without any modification in the existing systems. The performance parameters of the system working with the three refrigerant mixtures were evaluated and compared with those of the baseline refrigerant (R134a). The compositions of the refrigerant mixtures together with their environmental and thermo-physical properties are shown in Table 1.

2 Materials and Methods

2.1 Theoretical Analysis of Refrigeration Cycle

Larger percentage of the modern refrigeration and air-conditioning systems operate on the principles of vapour compression refrigeration system. Figure 1 shows the schematic diagram of a simple vapour compression refrigeration system. It uses circulating fluid refrigerant which absorbs and removes heat from the evaporating chamber and subsequently rejects that heat at the condenser. It consists of four major components: an evaporator, a compressor, a condenser and an expansion or a throttling device. The evaporator is the chamber or space that needs to be cooled by the working fluid (refrigerant); the compressor is the heart of the refrigeration system. It supplies the necessary force required to circulate the refrigerant through the system and to keep the system running. It increases the refrigerant pressure and consequently the temperature that facilitate the 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 regulates or controls the flow of the liquid refrigerant. The expansion device also reduces the pressure of the refrigerant to the low pressure existing in the evaporator.

The theoretical analysis of vapour compression refrigeration cycle is normally conducted using *P*–*h* diagram that shows four basic processes (Fig. 2): two constant-pressure (isobaric) processes, one constant-enthalpy (isenthalpic) process and the fourth is the constant entropy (isentropic) process. Process 1–2 is an isentropic compression process in the compressor. The compressor energy input (W_{comp}, kJ/kg) is obtained as:

$$W_{\mathrm{comp}} = (h_2 - h_1) \tag{1}$$

where h_1 = specific enthalpy of refrigerant at the outlet of evaporator and h_2 = specific enthalpy of refrigerant at the

Table 1 Environmental and thermo-physical properties of the investigated refrigerants (Calm and Hourahan 2011; Lemmon et al. 2013)

Properties	Refrigerants			
	R430A	R440A	R450A	R134a
Composition	R152a (76%) R600a (24%)	R290 (0.6%) R134a (1.6%) R152a (97.8%)	R134a (42%) R1234ze (58%)	–
Molar mass (kg/kmol)	63.96	66.23	108.67	102.03
Critical temperature (°C)	106.98	112.66	101.98	101.06
Normal boiling point, NBP (°C)	− 27.6	− 25.4	− 24.0	− 26.1
Liquid density, kg/m^3 at 25 °C	759.78	897.62	1169.00	1206.70
Vapour density, kg/m^3 at 25 °C	19.69	18.68	31.28	32.35
ODP	0	0	0	0
GWP	104	150	547	1430
GWP percentage of baseline refrigerant (%)	7.27	10.49	38.25	100

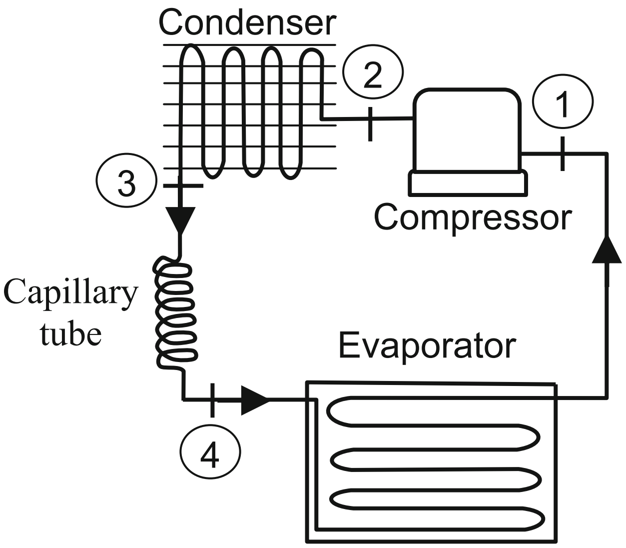

Fig. 1 Schematic diagram of a simple vapour compression refrigeration system

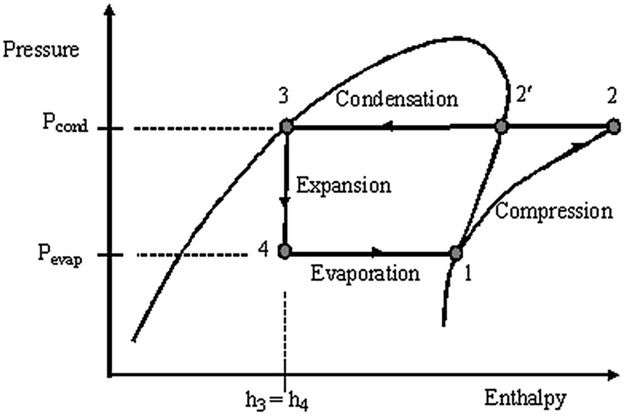

Fig. 2 Vapour compression refrigeration cycle on *p*–*h* diagram

outlet of compressor. Process 2–3 consists of de-superheating at constant condensing pressure (P_{cond}) from compressor discharge temperature (T_2) at point 2 to condensing temperature (T_{cond}) at point 2′ followed by condensation at constant condensing temperature (T_{cond}) and pressure (P_{cond}) from point 2′ to point 3. The heat rejected in the condenser (Q_{cond}, kJ/kg) is obtained as:

$$Q_{\mathrm{cond}} = (h_2 - h_3) \tag{2}$$

where h_3 = specific enthalpy of refrigerant at the outlet of condenser. Expansion of refrigerant at constant enthalpy occurs in process 3 to 4:

$$h_3 = h_4 \tag{3}$$

where h_4 = specific enthalpy of refrigerant at the inlet of evaporator. Process 4–1 is an evaporation process at constant evaporating pressure (P_{evap}) and temperature (T_{evap}) which takes place 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:

$$Q_{\mathrm{evap}} = (h_1 - h_4) \tag{4}$$

The coefficient of performance (COP) is the refrigerating effect produced per unit of energy required. COP is a major parameter used in refrigeration system to determine the performance of the system. It is computed as the ratio of the refrigerating effect (Eq. 4) to the compressor energy input (Eq. 1).

$$\mathrm{COP} = \frac{Q_{\mathrm{evap}}}{W_{\mathrm{comp}}} \tag{5}$$

Power per ton of refrigeration (PPTR) is obtained as (Bolaji et al. 2014):

$$\mathrm{PPTR} = \frac{3.5W_{\mathrm{comp}}}{Q_{\mathrm{evap}}} \tag{6}$$

The volumetric cooling capacity (VCC, kJ/m^3) is the refrigerating effect per unit volume of refrigerant at the inlet of the compressor. It is expressed as:

$$\mathrm{VCC} = \rho_1 \cdot Q_{\mathrm{evap}} \tag{7}$$

where ρ_1 = density of the refrigerant at the inlet of the compressor (kg/m^3).

2.2 Thermodynamic Properties of Refrigerants

The vital thermal properties of the working fluids that are required to describe their operating characteristics and performance in the refrigeration system are the pressure–volume–temperature (PvT) in an equilibrium state. Other properties could be obtained from a PvT correlation (equation-of-state) utilising specific heat (Bolaji 2014). These properties are useful for determining the applicability of refrigerants under design operating conditions. A widely used refrigerant database software known as REFPROP (Lemmon et al. 2013) which includes state-of-the-art equations-of-state (EOS) representations for a wide variety of fluids and can generate a wide range of thermo-fluid properties for both pure and various mixtures of fluids was used to compute the properties of the investigated refrigerants.

3 Results and Discussion

The saturation vapour pressure curves for R134a and the three alternative refrigerants are shown in Fig. 3. As shown in the figure, the saturation vapour pressure curves for R430A, R440A and R450A refrigerants are very close to the vapour pressure curve of R134a with deviations of 2.83, 6.69 and 5.54%, respectively, in the temperature range of − 30 to 60 °C. This shows that the three alternative refrigerants can exhibit similar properties and could be used as substitutes for R134a. The curves of the refrigerating effects of R134a, R430A, R440A and R450A at varying evaporating temperature for condensing temperatures of 40, 50 and 60 °C are shown in Fig. 4. As shown in these figures, the refrigerating effect increases as the evaporating temperature increases for all the investigated refrigerants. Increase in the evaporating temperature increased the latent heat energy of the refrigerant which also increased the refrigerating effect. Very high latent heat energy is desirable since it will reduce the required refrigerant's mass flow rate per unit capacity. The influence of the condensing temperature on the refrigerating effect for R134a, R430A, R440A and R450A is shown in Fig. 5.

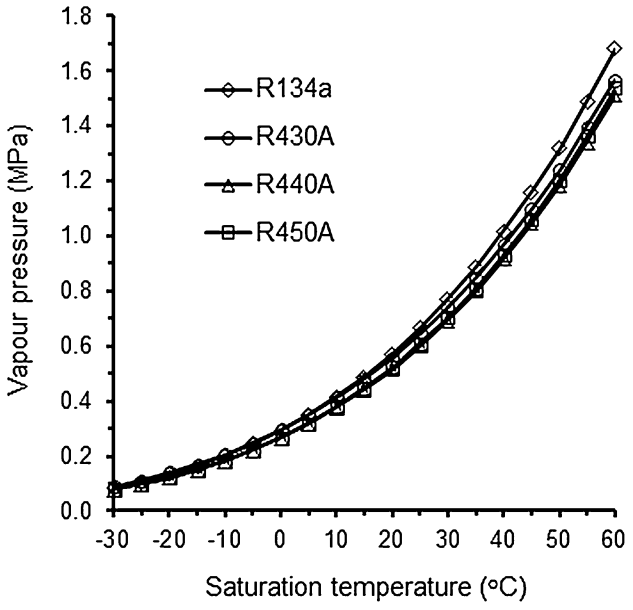

Fig. 3 Saturation vapour pressure curves

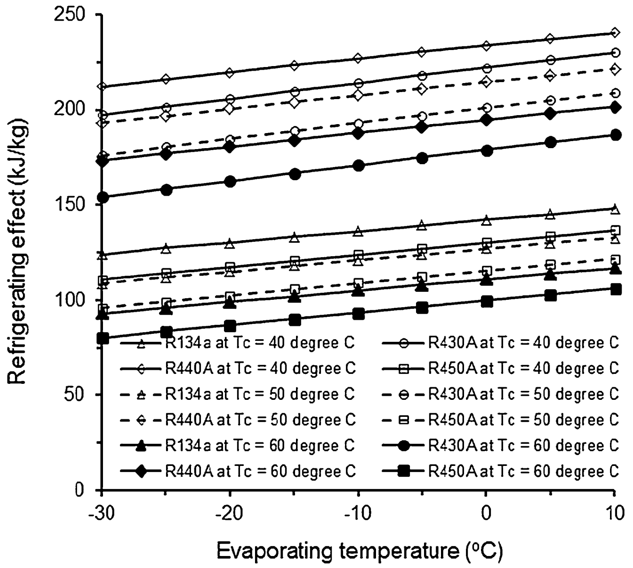

Fig. 4 Refrigerating effect versus evaporating temperature at the condensing temperatures of 40, 50 and 60 °C

Refrigerating effect for the investigated refrigerants reduces as the condensing temperature increases. For a constant enthalpy of refrigerant at compressor inlet (h_1), increase in the condensing temperature will increase the enthalpy of refrigerant at the inlet to the evaporator (h_4) and thereby reduce the refrigerating effect ($h_1 - h_4$). The average refrigerating effect of R450A is 9.94% lower, while those of R430A and R440A are 59.49 and 71.73%, respectively, higher than that of R134a.

Figure 6 shows the influence of the condensing temperature on the discharge pressure for R134a and the three

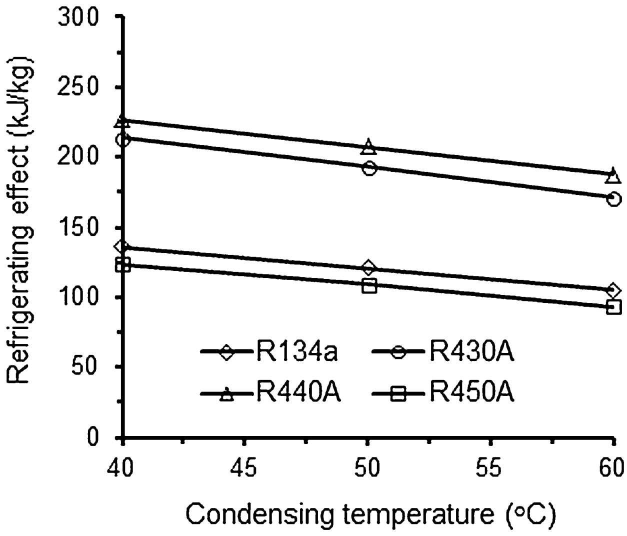

Fig. 5 Variation of refrigerating effect with condensing temperature

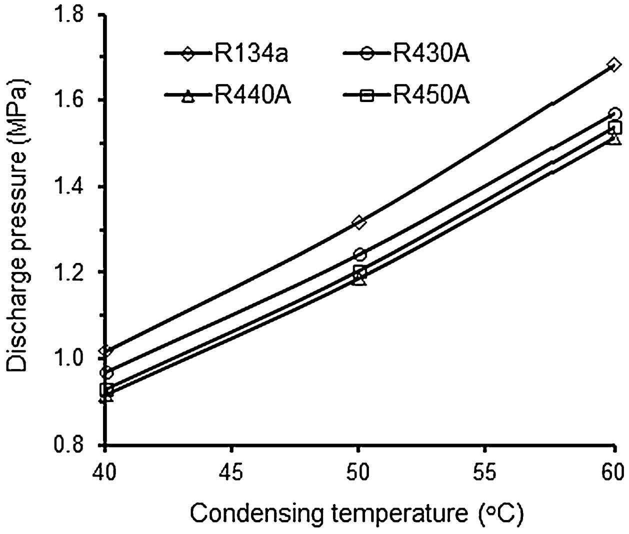

Fig. 6 Influence of the condensing temperature on the discharge pressure

investigated alternative refrigerants. Refrigerants with lower discharge pressure are desirable in refrigeration system, and they are better than those with high discharge pressure because high discharge pressure reduces the performance of the system, and it influences the stability of the lubricants and compressor components. As shown in Fig. 6, condensing temperature is directly proportional to discharge pressure; condensing temperature increases as discharge pressure increases for the four investigated refrigerants. The lowest discharge pressure was obtained using R440A in the system. The discharge pressure for R430A, R440A and R450A is 5.86, 9.94 and 8.57%, respectively, lower than that of R134a.

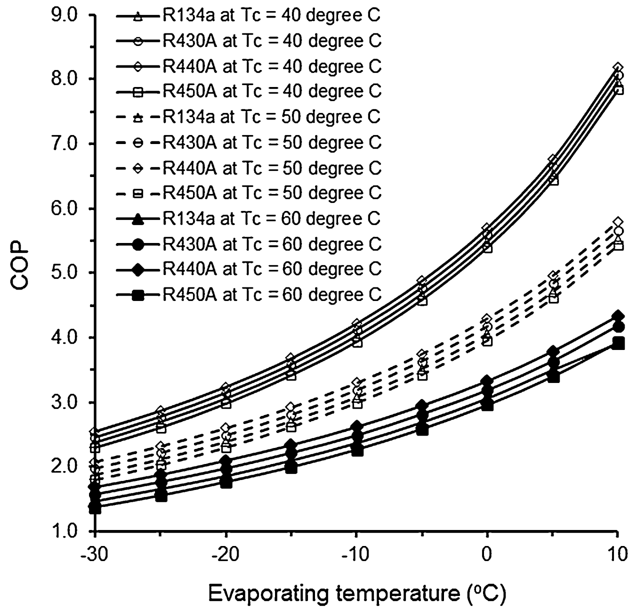

Fig. 7 Effects of the evaporating temperature on the coefficient of performance (COP) for the condensing temperatures of 40, 50 and 60 °C

The curves of the coefficient of performance (COP) for R430A, R440A, R450A and R134a at varying evaporating temperature for the condensing temperatures of 40, 50 and 60 °C are shown in Fig. 7. The COP of a refrigeration cycle reflects the cycle performance. These figures clearly show that COP increases with increase in the evaporating temperature. R450A has the lowest COP with a value of 3.36% lower than that of R134a at condensing temperature of 60 °C, while the COPs of R430A and R440A are 5.57 and 10.70%, respectively, higher than that of R134a at the same condensing temperature. Also, the influence of the condensing temperature on the COP for R134a and its three investigated alternatives is shown in Fig. 8. The figure shows that COP reduces as the condensing temperature increases. Increase in condensing temperature increases the power input through compressor and thereby reduces the COP of the system. The average COPs obtained for R430A and R440A were 3.40 and 6.66%, respectively, higher than that of R134a.

Figure 9 shows the power per ton of refrigeration (PPTR) as a function of evaporating temperature at the condensing temperatures of 40, 50 and 60 °C for the four investigated refrigerants. Influence of the condensing temperature on the PPTR is shown in Fig. 16. The PPTR is the energy consumption for a unit refrigeration capacity of a system. It shows the energy-saving potential of the working fluid used in the refrigeration system. As shown in the figures, the PPTR reduces as the evaporating temperature increases (Fig. 9), but it increases as the condensing temperature increases (Fig. 10) for all the refrigerants.

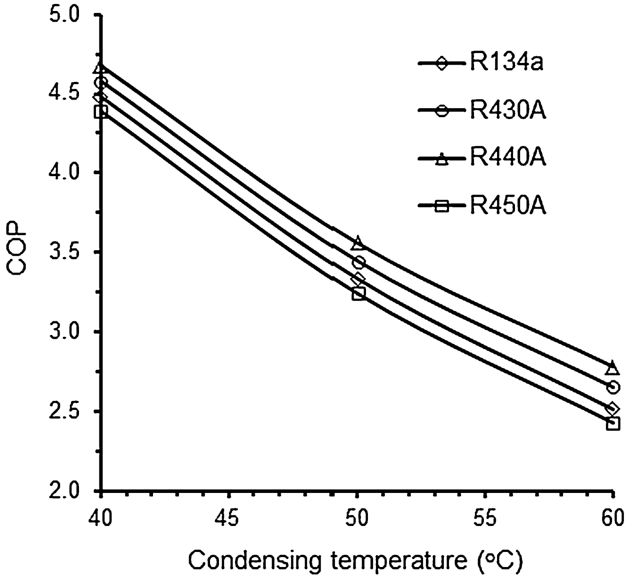

Fig. 8 Influence of the condensing temperature on the coefficient of performance (COP)

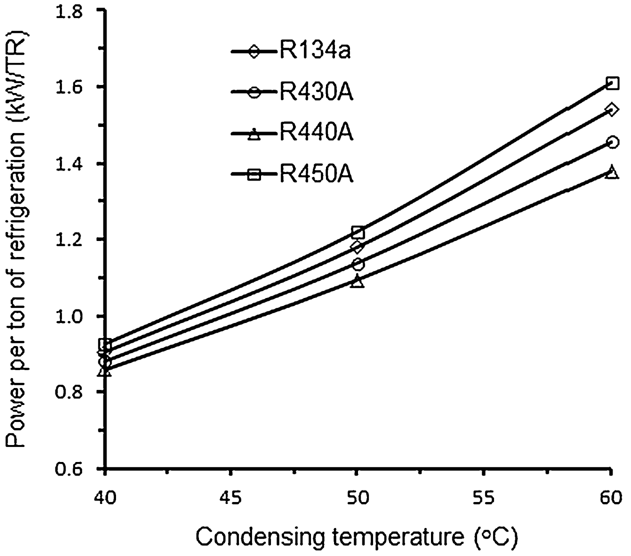

Fig. 10 Influence of the condensing temperature on the power per ton of refrigeration

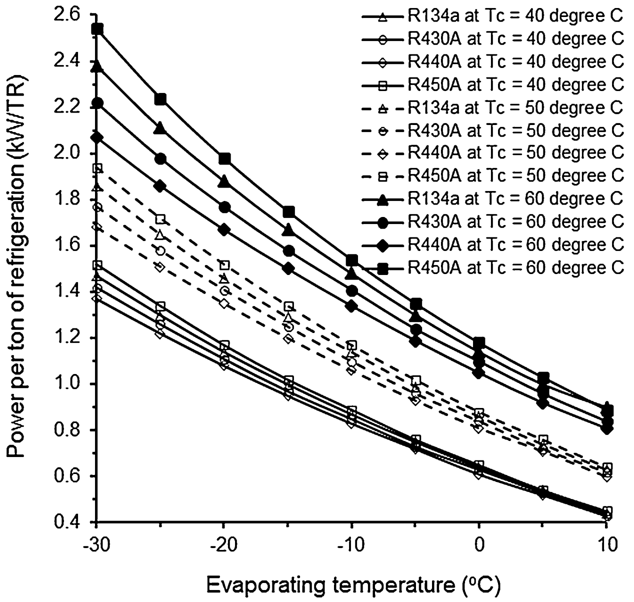

Fig. 9 Power per ton of refrigeration versus evaporating temperature at the condensing temperatures of 40, 50 and 60 °C

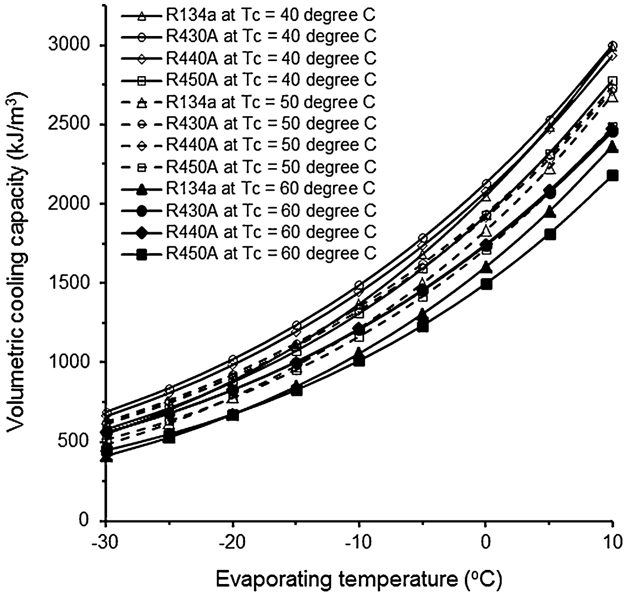

Fig. 11 Effects of the evaporating temperature on the volumetric cooling capacity (VCC) for the condensing temperature of 40, 50 and 60 °C

R430A and R440A refrigerants exhibited lower energy consumption than R450A and R134a. The average PPTR obtained for R430A and R440A is 5.48 and 10.46%, respectively, lower than that of R134a, while the value for R450A is 4.62% higher than that of R134a. This result indicates that R440A is the most energy saving among all the investigated refrigerants.

The effects of the evaporating temperature on the volumetric cooling capacity (VCC) for R430A, R440A, R450A and R134a refrigerants at condensing temperatures of 40, 50 and 60 °C are shown in Fig. 11. Refrigerants with high volumetric capacities are desirable in refrigeration systems because they will produce high cooling capacity. The figures show that the VCC increases with increase in the evaporating temperature. This is as a result of decrease in the specific volume and increase in the cooling effect. The VCC curves for all the four investigated refrigerants are very close to each other with slight deviations between them. Also, the influence of the condensing temperature on the VCC is shown in Fig. 12. As shown in this figure, the

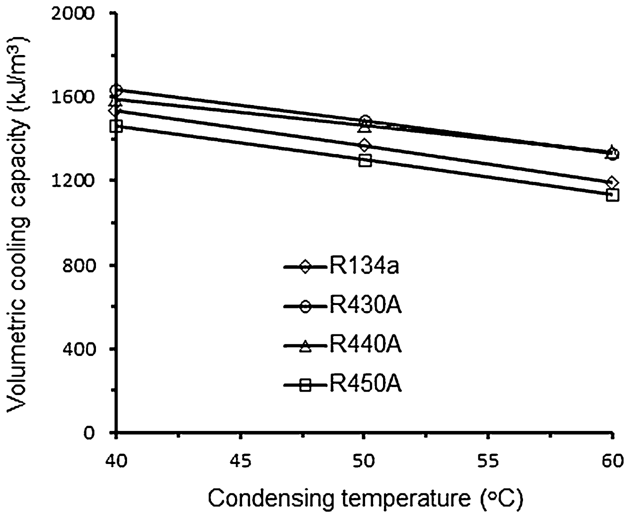

Fig. 12 Influence of the condensing temperature on the volumetric cooling capacity

VCC reduces as condensing temperature increases. The average VCCs obtained for R450A are 4.77% lower, while the values for R430A and R440A are 8.75 and 7.24%, respectively, higher than that of R134a.

4 Conclusions

Thermal systems such as refrigerators and air conditioners consume large quantity of electric power. Hence, in addition to zero ozone depletion and low global warming potentials, the new alternative working fluids in the refrigeration systems must also have similar or higher energy efficiency than the conventional refrigerants so that the new alternative refrigerants do not cause additional CO_2 generation at the power source. Therefore, in this study, the energy-saving potentials of R430A, R440A and R450A refrigerant mixtures were investigated theoretically. The following conclusions were drawn from the analysis and discussion of the results:

1. The vapour pressure and temperature characteristic profiles for R430A, R440A and R450A are very close to that of R134a with deviations of 2.83, 6.69 and 5.54%, respectively, in the temperature range of − 30 to 60 °C. This shows that they possess similar properties and they could be used as replacements for R134a.
2. R430A and R440A refrigerants produced very high refrigerating effect. The average refrigerating effect of R430A and R440A is 59.49 and 71.73%, respectively, higher, while that of R450A is 9.94% lower than that of R134a.
3. All the three investigated alternative refrigerants exhibited low discharge pressure which is highly desirable in refrigeration system. The lowest discharge pressure was obtained using R440A in the system.
4. R440A produced the highest coefficient of performance (COP), while R450A has the lowest COP. The COP of R450A was 3.36% lower than that of R134a at condensing temperature of 60 °C, while the values of R430A and R440A are 5.57 and 10.70%, respectively, higher than that of R134a at the same condensing temperature.
5. The power per ton of refrigeration (PPTR) reduces as the evaporating temperature increases, but it increases as the condensing temperature increases. The average values of PPTR obtained for R430A and R440A are 5.48 and 10.46%, respectively, lower than the value of R134a, while the value for R450A is 4.62% higher than that of R134a. R440A is the most energy efficient among all the investigated refrigerants.
6. The volumetric cooling capacities obtained for R430A and R440A are very close throughout all the operating conditions. Their average values are 8.75 and 7.24%, respectively, higher than the value of R134a, while the value of R450A is 4.77% lower than that of R134a.

In general, R430A and R440A performed better than both R450A and R134a in that they exhibited lower energy consumption per ton of refrigeration, lower discharge pressure, higher refrigerating effect, COP and volumetric cooling capacity than R450A and R134a. The overall best performance is obtained using R440A in the system.

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