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# Energy Performance of Eco-friendly R152a and R600a Refrigerants as Alternative to R134a in Vapour Compression Refrigeration System

*In this study, the energy performance of eco-friendly refrigerants (R152a and R600a) was investigated theoretically as alternative to R134a in refrigeration system. The results showed that the vapour pressure and specific volume of R152a are very close to those of R134a. R152a emerged as the most energy efficient with average Power Per Ton of Refrigeration (PPTR) of 10.6% less than that of R134a. R152a also exhibited higher Volumetric Refrigerating Capacity (VRC) and Coefficient of Performance (COP) than both R600a and R134a. The average COPs obtained for R152a and R600a were 13.4% higher and 5.4% lower than that of R134a, respectively. Generally, R152a performed better as R134a substitute in that it has the lowest PPTR, highest thermal conductivity, refrigerating effect, VRC and COP.*

***Keywords****: alternative refrigerants, eco-friendly, energy, performance*

## 1. Introduction

The use of chlorofluorocarbons (CFCs) has increased rapidly since their selection in the 1930s because of their many remarkable properties such as thermal and chemical stability, non–toxicity, non–flammable, good material compatibility and appropriate thermodynamic characteristics. They have played an important role in many fields of modern life, especially in the refrigeration and freezer industries. Nowadays, it is well known that chlorine atoms liberated from CFCs act as catalysts in ozone depleting reactions and contribute to the greenhouse effect. The stable structure of these chemical enables them to attack the ozone layer. The inventors of these refrigerants could not have envisaged the damaging effects of the refrigerants on the ozone layer. They purposefully pursued refrigerants with the outstanding stability that was imposed as one of the essential requirements of the ideal refrigerant they were called upon to invent [1, 2].

Therefore, many actions have been performed to reduce the production and consumption of CFCs by different countries and international organizations. In 1987, the Montreal Protocol, an international environmental agreement, established requirements for the worldwide phase out of ozone depleting CFCs. The use and production of CFCs have been phased out in developed and developing countries since January 1996 and 2010, respectively [3, 4]. 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, because their ozone depletion potentials (ODPs) and global warming potentials (GWPs) are in relative high levels though less than those of CFCs [5-7].

Refrigeration and air-conditioning industries have been forced to find alternative chemicals to CFCs and HCFCs. Hydro-fluorocarbon (HFC) refrigerants have been discovered as the prominent replacement refrigerants in refrigeration and air-conditioning systems [8, 9]. The thermophysical properties of HFC refrigerants are very similar to those of CFCs, and they are stable, non-toxic and ozone safe refrigerant. Therefore, R134a a HFC refrigerant was recommended by the American Household Appliances Manufacturers as a potential replacement for R12 in domestic refrigeration [10]. However, while the ODP of R134a is approximately zero, its GWP of 1300 is relatively high (Table 1).

International concern over relatively high GWP of R134a has instigated some European countries to remove R134a from refrigerator/freezers and abandon it as replacement refrigerant in domestic refrigerator. For this purpose, the production and use of R134a may be terminated in the near future [13-15]. Therefore, other replacements will be needed that are thermodynamically attractive as R134a. The European Union (EU) has taken the course of proceeding down the legislative path in order to try to address probable future consequences of global warming. On January 31, 2006, the EU Parliament passed legislation banning the installation of R134a systems in all new vehicle types from January 1, 2011, and in all vehicles from January 1, 2017 (vehicles with R134a systems already fitted will continue to be able to be refilled with R134a). Under the legislation, the replacement refrigerants must have a GWP of less than 150 [16].

R152a has zero ODP and a low GWP of 120, which is less than one-tenth of that of R134a. Also, R152a has very good thermodynamic and transport properties that are very close to R134a, and is currently being considered as a possible alternative for R134a in domestic refrigeration system [17]. Many natural refrigerants have been investigated as alternative refrigerants to R134a. Among these alternatives, hydrocarbon and their mixtures are recognized as strong alternative refrigerants for the existing small and large capacity refrigeration systems [18]. Hydrocarbons have many advantages including environmental friendliness, chemical stability and low refrigerant charge. They are compatible with common materials found in refrigeration and air-conditioning systems and are soluble in conventional mineral oils [19]. R600a, a hydrocarbon refrigerant also has both zero ODP and very low GWP (Table 1).

**Table 1.** Environmental effects of some common refrigerants [11, 12]

| Compositional group | Refrigerants | Ozone depletion potential (ODP) | Global warming potential (GWP) (100 years' horizon) |
|---|---|---|---|
| CFCs | R11 | 1 | 3800 |
| | R12 | 1 | 8100 |
| | R113 | 0.8 | 4800 |
| | R114 | 1 | 9000 |
| | R115 | 0.6 | 9000 |
| HCFCs | R22 | 0.055 | 1500 |
| | R123 | 0.02 | 90 |
| | R124 | 0.022 | 470 |
| | R141b | 0.11 | 630 |
| | R142b | 0.065 | 2000 |
| HFCs | R23 | 0 | 11700 |
| | R32 | 0 | 650 |
| | R125 | 0 | 2800 |
| | R134a | 0 | 1300 |
| | R143a | 0 | 3800 |
| | R152a | 0 | 120 |
| Natural Refrigerants | R290 | 0 | 3 |
| | R600a | 0 | 3 |
| | R1270 | 0 | 3 |
| | R717 | 0 | <1 |
| | R718 | 0 | 0 |
| | R744 | 0 | 1 |

Flammability of R152a and R600a is the most important concern regarding their adoption as alternative refrigerants. 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 is also been followed by the refrigeration industry. Several applications have been developed in handling the flammability and safety problems such as using enhanced compact heat exchangers, optimizing system designs, reducing the charge of systems and establishing rules and regulations for the safety precautions [20, 21]. Therefore, in this study, thermal conductivity and energy performance of environment-friendly R152a and R600a were investigated theoretically as alternative to R134a in a standard vapour compression refrigeration system.

## 2. Materials and Methods

### 2.1 Vapour compression refrigeration system

The standard vapour compression refrigeration system, as shown in Figure 1, 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 refrigeration system. It pumps and circulates refrigerant through the system, and supplies the necessary force to keep the system running. It increases the refrigerant pressure and hence the temperature, to allow heat rejection at a higher temperature in the condenser.

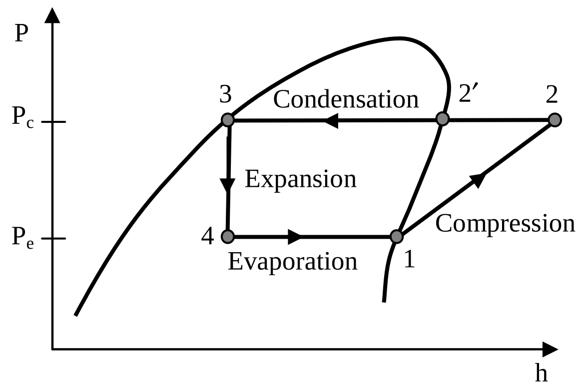


Figure 1: vapour compression refrigeration cycle on p-h diagram

### 2.2 Computational Analysis

The pressure, volume and temperature (PvT) in an equilibrium state are the most fundamental of a working fluid's thermal properties that are needed for the prediction of a refrigerant system's performance. Other properties may be derived from a PvT correlation utilizing specific heat. There exists a numerous of equations-of-state, which have been classified into families. These equations have been used to develop the most commonly used refrigerant database software known as REFPROP 9.0 [22]. 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 [23]. This software was used in this work to compute the properties of investigated refrigerants.

## 2.3 Data Reduction

The data reduction of the theoretical results are analysed with the equations stated below. Considering the cycle on p-h diagram in Figure 1, the heat absorbed by the refrigerant in the evaporator or refrigerating effect ($Q_{evap}$, kJ/kg) is calculated as:

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

where, $h_1$ = specific enthalpy of refrigerant at the outlet of evaporator (kJ/kg); and $h_4$ = specific enthalpy of refrigerant at the inlet of evaporator (kJ/kg). The compressor energy input ($W_{comp}$, kJ/kg) is obtained as:

$$W_{comp} = (h_2 - h_1) \tag{2}$$

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

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

where, $h_3$ = specific enthalpy of refrigerant at the outlet of condenser (kJ/kg).
The Coefficient of Performance (COP) is the refrigerating effect produced per unit of energy required; therefore, COP is obtained as the ratio of Eq. (1) to Eq. (2):

$$COP = \frac{Q_{evap}}{W_{comp}} \tag{4}$$

Power Per Ton of Refrigeration (*PPTR*) is obtained as:

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

The volumetric refrigerating capacity (*VRC*, kJ/m$^3$) is calculated as follows:

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

where, $\rho_1$ = density of the refrigerant at the exit of evaporator (kg/m$^3$).

## 3. Results and Discussion

For any refrigerant to be suitable as substitute for another, it must have similar vapour pressure and specific volume. Figure 2 shows the variation of saturated vapour pressure and temperature for R134a R152a and R600a. The figure revealed that the saturated vapour pressure curve for R152a is very close to the vapour pressure curve of R134a. This indicates that R152a can exhibit similar properties and could be used as substitute for R134a. The saturated vapour pressure curve for R600a is significantly lower than that of R134a by 34.3% of the average value, while the average value of R152a is higher by 8.9%.

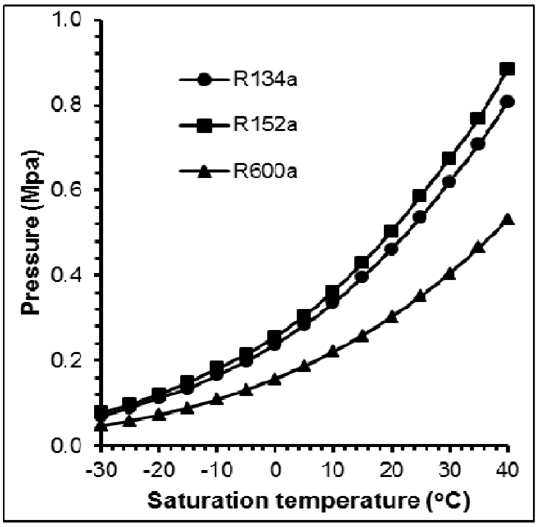


**Figure 2.** Saturation pressure and temperature curves

Figure 3 shows the variation of specific volume of vapour refrigerant with saturation temperature for R134a and its two potential alternative refrigerants. Specific volume increases as saturation temperature reduces. R152a exhibited very close specific volume and temperature characteristic with R134a, which shows that it can use the same compressor size with R134a. Again, the curve of R600a is significantly higher than that of R134a, which shows that it cannot perfectly work with R134a compressor.

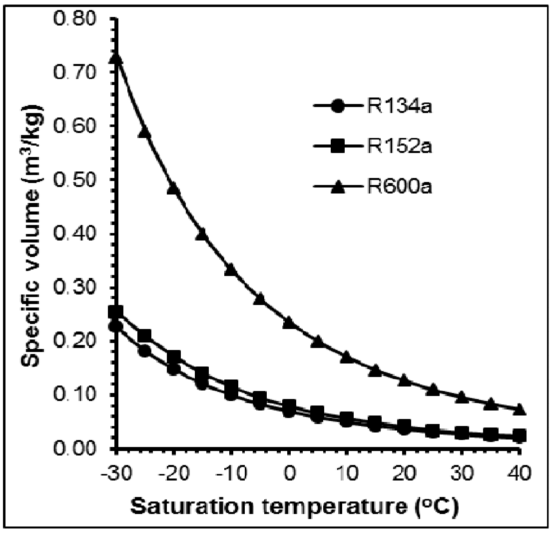


**Figure 3.** Specific volume of refrigerant vapour versus saturation temperature

Figure 4 shows the variation of thermal conductivity of liquid refrigerant with saturation temperature for R134a and its two potential alternative refrigerants. Thermal conductivity reduces as saturation temperature increases. Increase in saturation temperature will reduce the refrigerant viscosity and thereby reduce its thermal conductivity. The two alternative refrigerants (R152a and R600a) exhibited higher thermal conductivity than R134a. The highest thermal conductivity was obtained using R152a. The average values obtained using R152a and R600a were 17.7 and 6.3% higher than that of R134a, respectively.

The refrigerating effects of R134a and its two potential alternative refrigerants at varying evaporating temperature for condensing temperature of 40°C are shown in Figure 5. As shown in the figure, refrigerating effect increases as the evaporating 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 less. 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. It is clearly shown in Figure 5 that R152a and R600a exhibited higher refrigerating effect than R134a. Therefore, very low mass of refrigerant will be required for the same capacity and compressor size. The highest refrigerating effect (average value of 244.7 kJ/kg) was obtained using R152a compare with 136.1 kJ/kg of R134a at condensing temperature of 40°C. R600a has average value of 228.6 kJ/kg at the same condensing temperature.

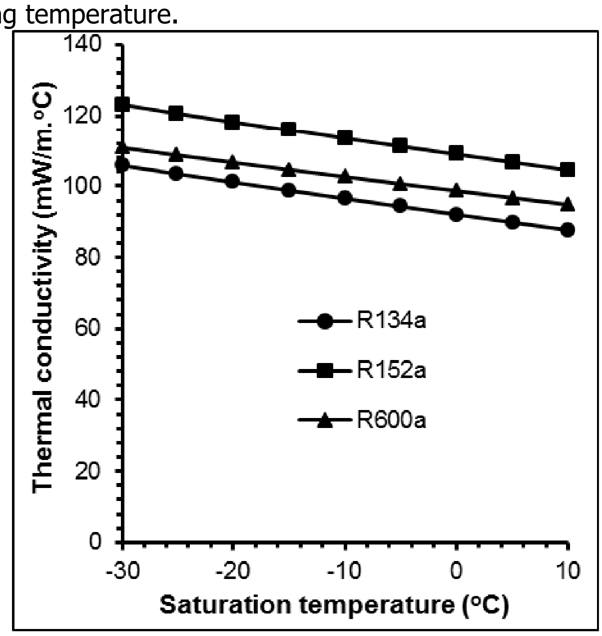


**Figure 4.** Variation of thermal conductivity with saturation temperature

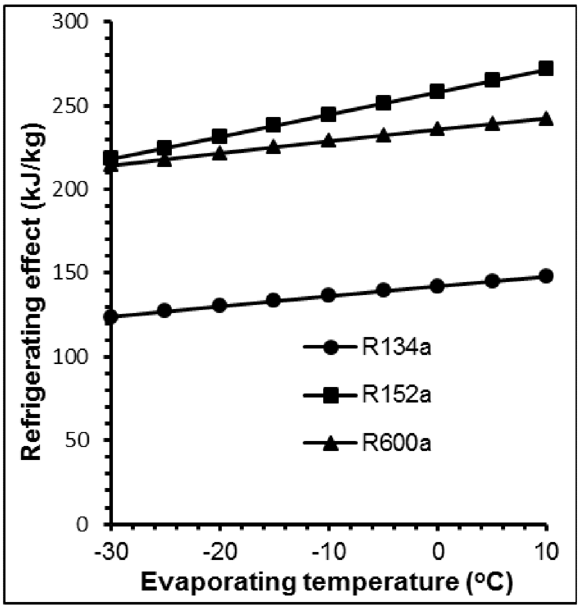


**Figure 5.** Variation of refrigerating effect with evaporating temperature at condensing temperature of 40°C.

Figure 6. shows the variation of the compressor energy input with evaporating temperature for R134a and its two alternative refrigerants at condensing temperature of 40°C. The figure shows that the compression energy input decreases as the evaporating temperature increases. This is due to the fact that when the temperature of the evaporator increases the suction temperature also increases. At high suction temperature, the vaporizing pressure is high and therefore the density of suction vapour entering the compressor is high. Hence the mass of refrigerant circulated through the compressor per unit time increases with the increases in suction temperature for a given piston displacement. The increase in the mass of refrigerant circulated decreases the work of compression. The two alternative refrigerants exhibited higher compressor energy input than R134a (Fig. 6), but they equally exhibited very high refrigerating effect (Fig. 5), which is a form of compensation for their high compressor work input. The compressor work input of R152a is lower than that of R600a.

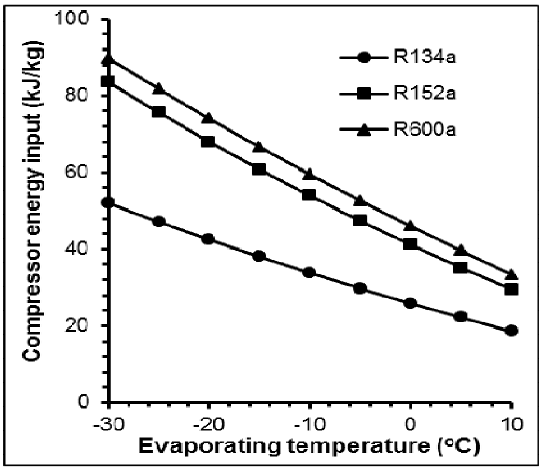


**Figure 6.** Variation of compressor energy input with evaporating temperature at condensing temperature of 40°C.

The coefficient of performance (COP) of a refrigeration cycle reflects the cycle performance and is the major criterion for selecting a new refrigerant as a substitute. The COPs for R134a, R152a and R600a refrigerants at varying evaporator temperature for condensing temperature of 40°C are shown in Figure 7. Similar trends were observed in the curve profiles for all the investigated refrigerants. COP increases with increase in evaporator temperature. As clearly shown in the figure, R600a has the lowest COP among investigated refrigerants, while R152a has the highest COP. The average COPs obtained for R152a and R600a were 13.4% higher and 5.4% lower than that of R134a, respectively.

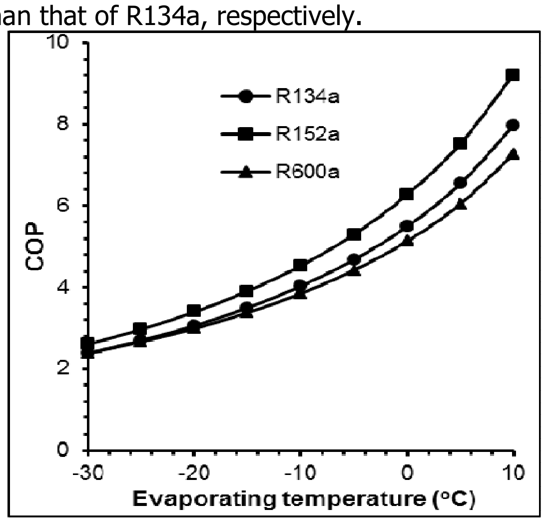


**Figure 7.** Coefficient of performance (COP) versus evaporating temperature at condensing temperature of 40°C.

The influence of evaporating temperature on the power consumption per ton of refrigeration at condensing temperature of 40°C for R134a and the two investigated alternative refrigerants is shown in Figure 8. As shown in the figure, the power per ton of refrigeration refrigerating reduces as the evaporating temperature increases for all the investigating refrigerants. In this result, R152a has emerged as the most energy efficient refrigerant among all the investigated refrigerants being the one that exhibited the lowest power consumption per ton of refrigeration with the average value of 10.6% less than that of R134a. The average value obtained for R600a is 3.5% higher than that of R134a, respectively.

Figure 9 shows the influence of evaporating temperature on the volumetric refrigerating capacity (VRC) at condensing temperature of 40°C for R134a and the two alternative refrigerants. 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 volume of refrigerant vapour at the exit of the evaporator. A high cooling capacity can be obtained from a high volumetric capacity refrigerant for given swept volume in the compressor. R152a exhibited high VRC with average value of 5.0% higher than that of R134a, while the average VRC obtained for R600a is significantly lower by 50.5%.

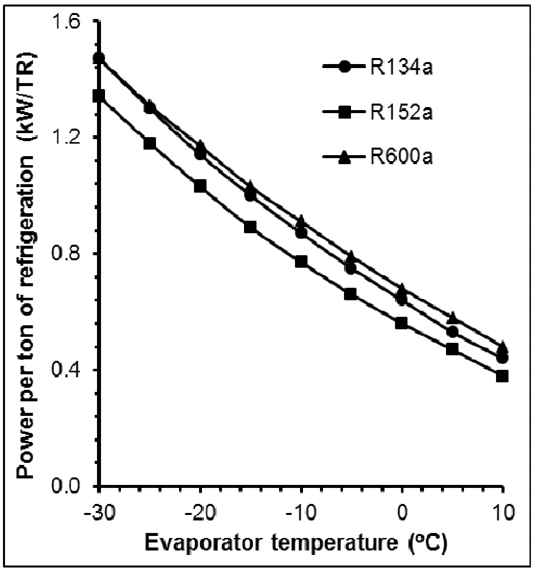


**Figure 8.** Influence of evaporating temperature on the power per ton of refrigeration at condensing temperature of 40°C

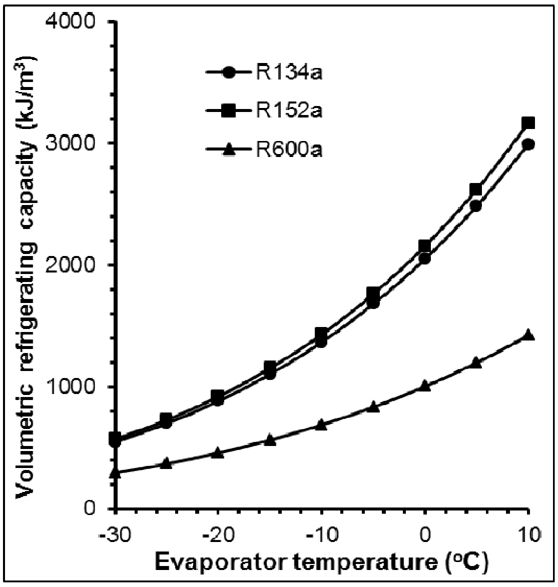


**Figure 9.** Influence of evaporator temperature on the volumetric refrigerating capacity at condensing temperature of 40°C

## 4. Conclusions

In this study, the thermal conductivity and energy performance of environmentally friendly refrigerants (R152a and R600a) were investigated theoretically as alternative to R134a in a vapour compression refrigeration system at varying evaporating temperature and condensing temperature of 40°C. The following conclusions can be drawn from the analysis and discussion of the results:

(i) The saturated vapour pressure and temperature characteristic profile of R152a is very close to the vapour pressure curve of R134a, therefore, R152a will work perfectly as R134a substitute. The saturated vapour pressure curve for R600a is significantly lower than that of R134a.

(ii) R152a refrigerant exhibited very close suction specific volume and temperature characteristic with R134a, which shows that both refrigerants can use the same compressor size. Again, the curve of R600a is significantly higher than that of R134a.

(iii) The thermal conductivity and refrigerating effect of the two alternative refrigerants are higher than those of R134a. The highest values of these two parameters were obtained using R152a. The average thermal conductivities of R152a and R600a were 17.7 and 6.3% higher than that of R134a, respectively.

(iv) R152a exhibited lower compressor energy input than R600a, but R134a has the lowest values. Both R152a and R600a exhibited significantly high refrigerating effect, which is a form of compensation for their high compressor energy input.

(v) R600a has the lowest COP among investigated refrigerants, while R152a has the highest COP. The average COPs obtained for R152a and R600a were 13.4% higher and 5.4% lower than that of R134a, respectively.

(vi) R152a emerged as the most energy efficient refrigerant among all the investigated refrigerants with average Power Per Ton of Refrigeration (PPTR) of 10.6% less than that of R134a.

(vii) The highest Volumetric Refrigerating Capacity (VRC) was obtained using R152a in the system with average value of 5.0% higher than that of R134a.

Generally, R152a performed better than R600a as R134a substitute in that it has approximately the same saturated pressure and specific volume with R134a, while higher deviations were obtained for R600a. Also, R152a has the lowest PPTR, highest thermal conductivity, refrigerating effect, VRC and COP.

## References


[1] Mcmullan J.T., *Refrigeration and the environment issues and strategies for the future*, International Journal of Refrigeration, Vol. 25, pp. 89-99, 2002.

[2] Bolaji B.O., *Investigating the performance of some environment-friendly refrigerants as alternative to R12 in vapour compression refrigeration system*, Ph.D. Thesis, Department of Mechanical Engineering, Federal University of Technology, Akure, Nigeria, 2008.

[3] Fernandez-Seara J., Uhia F.J., Diz R., Dopazo J.A., *Vapour condensation of R22 retrofit substitutes R417A, R422A and R422D on CuNi turbo C tubes*, International Journal of Refrigeration, Vol. 33, 148-157, 2010.

[4] Bolaji B.O., *Performance investigation of ozone-friendly R404A and R507 refrigerants as alternatives to R22 in a window air-conditioner*, Energy and Buildings, Vol. 43, 3139-3143, 2011.

[5] Aprea C., Renno C., *Experimental comparison of R22 with R417A performance in a vapour compression refrigeration plant subjected to a cold store*, Energy Conversion Management, Vol. 45, 1807-1819, 2004.

[6] Boumaza M., *Performances assessment of natural refrigerants as substitutes to CFC and HCFC in hot climate*, International Journal of Thermal and Environmental Engineering, 1, 125-130, 2010.

[7] Aprea C., Maiorino A., Mastrullo R., *Change in energy performance as a result of a R422D retrofit: An experimental analysis for a vapour compression refrigeration plant for a walk-in cooler*, Applied Energy, 88, 4742-4748, 2011.

[8] Del-Col D., Torresin D., Cavallini A., *Heat transfer and pressure drop during condensation of the low GWP refrigerant R1234yf*, International Journal of refrigeration, Vol. 33, 1307-1318, 2010.

[9] Wongwises S., Chimres N., *Experimental study of hydrocarbon mixtures to replace R134a in a domestic refrigerator*, Energy Conversion and Management, Vol. 46, 85-100, 2005.
[10] Wongwises S., Kamboon A., Orachon B., *Experimental investigation of hydrocarbon mixtures to replace R134a in an automotive air conditioning system*, Energy Conversion and Management, Vol. 47, 1644-1659, 2006.
[11] Calm J.M., Domanski P.A., *R22 replacement status*, ASHRAE Journal, Vol. 46, 29-39, 2004.
[12] Bitzer. Refrigerant Report. Bitzer International, 17th Edition, 71065 Sindelfingen, Germany, http://www.bitzer.de Accessed on April 28, 2014.
[13] Chen W. *A comparative study on the performance and environmental characteristics of R410A and R22 residential air conditioners*, Applied Thermal Engineering, Vol. 28, 1-7, 2008.
[14] Torrella E., Cabellob R., Sanchezb D., Larumbea J.A., Llopisb R*., On-site study of HCFC-22 substitution for HFC non-azeotropic blends (R417A, R422D) on a water chiller of a centralized HVAC system*, Energy and Building, Vol. 42, 1561-1566, 2010.
[15] Lee Y., Jung D., *A brief performance comparison of R1234yf and R134a in a bench tester for automobile applications*, Applied Thermal Engineering, Vol. 35, 240-242, 2012.
[16] Brown J.S., Zilio C., Cavallini A., *Critical review of the latest thermodynamic and transport property data and models, and equations of state for R1234yf*, International Refrigeration and Air Conditioning Conference, Purdue, July 12-15, 1130-1139, 2010.
[17] Bolaji B.O., *Experimental analysis of reciprocating compressor performance with eco-friendly refrigerants*, Proc. IMechE, Part A: Journal of Power and Energy, 224, 781-786, 2010.
[18] Lee M.Y., Lee D.Y., Kima Y., *Performance characteristics of a small-capacity directly cooled refrigerator using R290/R600a (55/45),* International Journal of Refrigeration, Vol. 31, 734-741, 2008.
[19] Palm B., *Hydrocarbons as refrigerants in small heat pump and refrigeration systems - a review*, International Journal of Refrigeration, Vol. 31, 552-563, 2008.
[20] Thonon B., *A review of hydrocarbon two-phase heat transfer in compact heat exchangers and enhanced geometries*, International Journal of Refrigeration, Vol. 31, 633-642, 2008.
[21] Fernando P., Palm B., Lundqvist P. Granryd E., *Propane heat pump with low refrigerant charge: design and laboratory tests*, International Journal of Refrigeration, Vol. 27, 761-773, 2004.
[22] Lemmon E.W., Mclinden M.O., Huber M.L., *NIST reference fluids thermodynamic and transport properties*, REFPROP 9.0., National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, 2002.

[23] Kumar K.S., Rajagopal K., *Computational and experimental investigation of low ODP and low GWP R123 and R290 refrigerant mixture alternate to R12*, Energy Conversion and Management, Vol. 48, 3053-3062, 2007.

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