Journal of Engg. Research **Vol. 1 - (1) June 2013** pp. 317-333, 2013

Thermodynamic analysis of hydrocarbon refrigerants in a sub-cooling refrigeration system

BUKOLA O. BOLAJI* AND ZHONGJIE HUAN**

**Department of Mechanical Engineering, College of Engineering, Federal University of Agriculture, PMB. 2240, Abeokuta, Nigeria*
***Department of Mechanical Engineering, Faculty of Engineering and Built Environment, Tshwane University of Technology, Pretoria, South Africa*
*E-mails: *bolajibo@funaab.edu.ng , bobbolaji2007@yahoo.com*

ABSTRACT

In this study, the performance simulation of some hydrocarbon refrigerants (R290, R600 and R600a) as alternatives to R134a in refrigeration system with sub-cooling is conducted by thermodynamic calculation of performance parameters using the REFPROP software. The results obtained showed that the saturated vapour pressure and temperature characteristic profiles for R600 and R600a are very close to that of R134a. The three hydrocarbon refrigerants exhibited very high refrigerating effect and condenser duty than R134a. The best of these parameters was obtained using R600. The discharge temperatures obtained using R600 and R600a were low, while that of R290 was very much higher. The highest coefficient of performance (COP) and relative capacity index were obtained using R600. Average COPs of R600 and R600a are 4.6 and 2.2% higher than that of R134a, respectively. The performances of R600 and R600a in system were better than those of R134a and R290. The best performance was obtained using R600 in the system.

Keywords: Alternative refrigerants; hydrocarbons; performance; sub-cooling; thermodynamic analysis.

INTRODUCTION

Chlorofluorocarbons (CFCs) have been used extensively over the last eight decades in refrigeration due to their favourable characteristics such as non-flammability, non-toxicity, non-explosiveness, and chemically stable behaviour with other materials (Calm *et al.*, 1999; Bolaji, 2011). These characteristics are the primary requirements of the ideal refrigerant. However, in recent years it has been recognised that the chlorine released from CFCs migrates to the stratosphere and destroys the earth's stratospheric ozone layer causing health hazards (Kim & Park, 2000; UNEP, 2003).

International concern regarding the potential destruction of the earth's protection layer led to twenty-four nations and the European Community signing the Montreal Protocol in 1987, which regulates the production and trade of ozone depleting substances. Therefore, CFCs have been banned in developed countries since January of 1996. In 2010 production and usage of CFCs have been prohibited completely all over the world (Kim *et al.*, 2007; Fernandez-Seara *et al.*, 2010). Also, the partially halogenated HCFCs (hydro-chlorofluorocarbons), which are less harmful to the ozone layer, including R22, R123 and R124 will be phased out internationally by 2020 and 2030 in developed and developing countries respectively, because they still contain ozone depleting chlorine though their ozone depletion potentials (ODPs) are very small and less than those of CFCs (Kim *et al.*, 2002; Akash & Said, 2003; Sattar *et al.*, 2007).

Until the time of the awareness of the stratospheric ozone layer damage, virtually all of the working fluids in refrigeration and air-conditioning systems contained chlorine (Calm & Didion, 1998). The elimination of this important element has caused considerable changes in the refrigeration and air-conditioning technology. It has also caused new interest in the fundamentals of working fluid performance so that the "fluid design" and the "machine system design" are being considered in parallel (Bolaji, 2008).

These days, greenhouse warming has become one of the most important global issues and Kyoto protocol was proposed to resolve this issue, which classified Hydro-fluorocarbons (HFCs) as part of the greenhouse warming gases (Park & Jung, 2009; Del-Col *et al.*, 2010). HFC refrigerants are the leading replacement for CFC and HCFC refrigerants, in refrigeration and air-conditioning systems. Although the ODP of HFC refrigerants is zero, their global warming potentials (GWPs) are relatively high (Table 1). Therefore, application of HFC refrigerants as ultimate refrigerants in refrigeration air-conditioning systems may not be adequate any more. International concerns over their relatively high GWPs have caused some European countries to remove R134a (HFC refrigerant) from refrigerator and freezers and abandon it as a replacement refrigerant in domestic refrigerators (Wongwises & Chimres, 2005).

Table 1: Environmental effects of some common refrigerants

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	140
Natural Refrigerants	R290	0	3
	R600a	0	3
	R1270	0	3
	R717	0	0
	R718	0	0
	R744	0	1

(Sources: Hwang *et al.*, 1998; Calm & Domanski, 2004; Bitzer, 2012)

In addition to zero ODP, the working fluids in refrigeration systems must also have very low GWP (Bolaji *et al.*, 2011). Due to this new requirement, once again, industry will be forced to change refrigerants. This time from the newly introduced chlorine-free alternative refrigerants to those that does not absorb the infrared re-radiation from the earth's surface. Also, additional stringent criteria relating to system efficiency will be necessary so that the new refrigerants do not cause additional CO_2 generation at the power source.

Some studies have been carried out on the performance of R134a in vapour compression refrigeration systems. Linton *et al.* (1990) compared the performance of R134a with that of R12 in residential heat pump. Their results showed that approximately the same heating output was achieved with R134a, but the coefficient of performance (COP) of the system was approximately 15% less with R134a than with R12.

Akintunde (2006) also investigated the moisture solubility in R12 and R134a at various temperatures in order to evaluate the performance of R134a as a substitute for R12 in relation to moisture retention. The results obtained showed that the R134a absorbed more moisture than R12 at all temperatures. Therefore, R134a systems will be more prone to rusting and copper plating due to large moisture content in the refrigerant. For this reason, a more efficient and environment benign alternative refrigerant is needed in the refrigeration system.

The natural refrigerants are the naturally occurring substances such as ammonia, hydrocarbons, carbon dioxide, water and air. In this group, the hydrocarbons are most closely related to the HFCs. Their thermodynamic and transport properties are very similar to most HFCs currently used in refrigeration and air-conditioning systems, which make them suitable as substitute refrigerants in the existing HCFC and HFC systems without any major changes in the design (Castro *et al.*, 2005; Park & Jung, 2007; Palm, 2007).

In addition to their zero ODP and very low GWP (Table 1), hydrocarbon refrigerants are compatible with common materials found in refrigerating systems and are soluble in conventional mineral oils. Since they contain no chlorine or fluorine atoms, they cannot undergo reaction with water and hence, do not form the corresponding strong acids that can lead to premature system failure (Palm, 2007).

The most important concern regarding the adoption of hydrocarbons as a refrigerant 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 for safety. The same approach is also been followed by the refrigeration industry. Various 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 (Palm, 2008; Thonon, 2008).

Sub-cooling heat exchangers are commonly installed in refrigeration systems with the intent of ensuring proper system operation and increasing system performance. Specifically, sub-cooling heat exchangers are effective in (Bolaji, 2010): (i) increasing the system performance; (ii) sub-cooling liquid refrigerant to prevent flash gas formation at inlets to expansion devices; and (iii) fully evaporating any residual liquid that may remain in the compressor suction line. Therefore, sub-cooling heat exchanger is a tool that can be used to evaluate the impact of refrigerants on refrigeration system's capacity and performance.

This tool has been used by some researchers (Fernando *et al.*, 2004; Domanski *et al.*, 1994; Klein *et al.*, 2000; Bolaji, 2010) to evaluate alternative refrigerants to R22 and R12. Therefore, in this study, the performance simulation of some hydrocarbon refrigerants (R290, R600 and R600a) as alternatives to R134a in refrigeration system with sub-cooling was conducted by thermodynamic calculation and analysis of performance parameters. The effects of sub-cooling on performance of the investigated refrigerants were quantified in terms of relative capacity index.

MATERIALS AND METHODS

Refrigeration system with sub-cooling

Sub-cooling in refrigeration implies cooling the refrigerant in liquid state, at uniform pressure, to a temperature that is less than the saturation temperature, which corresponds to condenser pressure. Schematic diagram of vapour compression refrigeration system with a sub-cooling heat exchanger is shown in Figure 1.

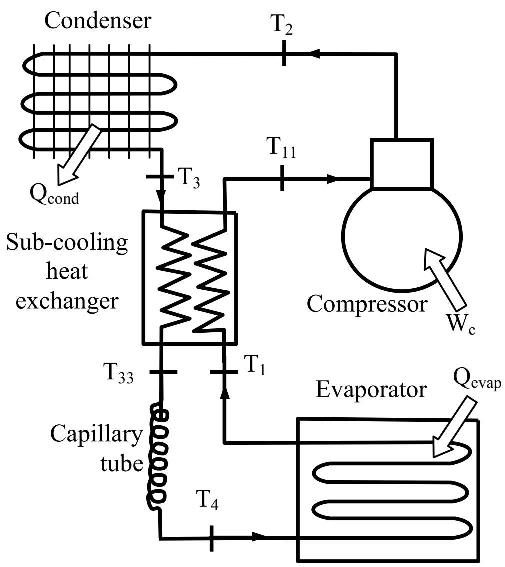

Fig. 1. Refrigeration system with a sub-cooling heat exchanger

In this system, high temperature liquid from the condenser is sub-cooled in the heat exchanger before entering the expansion device where it is being throttled to the evaporator pressure. The sub-cooling heat exchanger is an indirect liquid-to-vapour heat transfer device where high temperature and pressure liquid refrigerant transfers heat to the low temperature refrigerant vapour leaving the evaporator. The heat exchanger also prevents the carrying-over of liquid refrigerant from the evaporator to the compressor.

The sub-cooling heat exchanger affects the performance of a refrigeration system by influencing both the high and low pressure sides of a system. Figure 2 shows the key state points for a vapour compression cycle utilizing an idealized sub-cooling heat exchanger on a pressure-enthalpy diagram. Degree of sub-cooling is the difference between the saturation temperature of the liquid refrigerant corresponding to condenser pressure and the temperature of the liquid refrigerant before entering to the expansion device. The following are the energy changes in each component of the refrigeration system as shown in Figure 1:

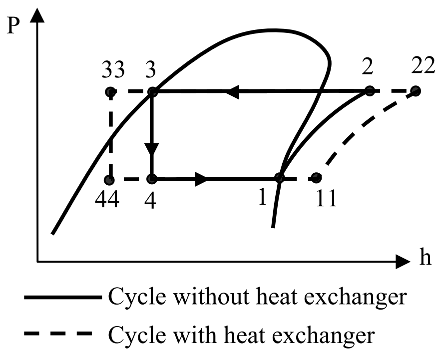

Fig. 2. Pressure-enthalpy diagram showing effect of an idealized sub-cooling

The heat absorbed by the refrigerant in the evaporator or refrigerating effect (Q_{evap}, kJ/kg) is expressed 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 isentropic work input to compressor (W_c, kJ/kg) is expressed as:

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

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

The coefficient of performance (COP) is the refrigeration effect produced per unit of work required. It is expressed as:

$$COP = \frac{Q_{evap}}{W_c} \tag{3}$$

Relative Capacity Index (*RCI*)

Without a sub-cooling heat exchanger, the refrigerating effect per unit mass flow rate of circulating refrigerant is the difference in enthalpy between states 1 and 4 in Figure 2. When the heat exchanger is installed, the refrigeration effect per unit mass flow rate increases to the difference in enthalpy between states 11 and 44. If there were no other effects, the addition of a sub-cooling heat exchanger would always lead to an increase in the refrigeration capacity of a system. The extent of the capacity increase is a function of the specific heat of refrigerant, the degree of sub-cooling and the system operating conditions. According to Klein and Reindl (1998), the effect of a sub-cooling heat exchanger on refrigeration capacity can be quantified in terms of a relative capacity index (*RCI*) as defined in Eq. (4):

$$RCI = \left(\frac{RC_{hx} - RC_{nohx}}{RC_{nohx}}\right) \times 100\% \tag{4}$$

where, RC_{hx} = the refrigeration capacity with a sub-cooling heat exchanger; and RC_{nohx} = the refrigeration capacity for a system operating at the same condensing and evaporating temperatures without a sub-cooling heat exchanger.

Refrigeration cycle performance calculations were carried-out with assumption that refrigerant exits the evaporator as a saturated vapour at the evaporator pressure (state 1) and exits the condenser as a saturated liquid at the condenser pressure (state 3). When a sub-cooling heat exchanger is employed, the refrigerant entering the compressor (state 11) has been superheated by heat exchange with the liquid exiting the condenser which causes the liquid to enter the expansion device in a sub-cooled state (state 33).

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 (Didion, 1999; Lemmon *et al.*, 2002). 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 (Kumar & Rajagopal, 2007). This software was used to compute the properties of investigated refrigerants.

RESULTS AND DISCUSSION

Figure 3 shows the variation of saturated vapour pressure and temperature for R134a R290, R600 and R600a. The figure revealed that the saturated vapour pressure curves for R600 and R600a are very close to the vapour pressure curve of R134a. This indicates that R600 and R600a can exhibit similar properties and could be used as substitute for R134a. The saturated vapour pressure curve for R290 is significantly higher than that of R134a.

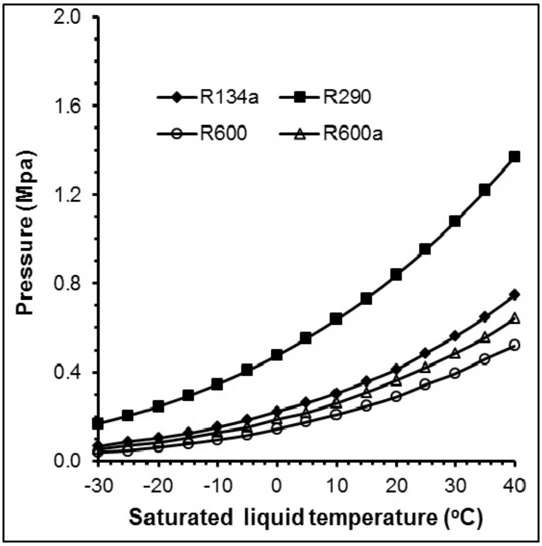

Fig. 3. Variation of pressure with saturated liquid temperature

Figure 4 shows the effect of degree of sub-cooling on the refrigerating effect at 40°C condensing and -20°C evaporating temperatures for R134a and the three hydrocarbon refrigerants. As shown in the figure, refrigerating effect increases with increase in degree of sub-cooling. 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. It is clearly shown in Figure 4 that R290, R600 and R600a exhibited higher refrigerating effect than R134a. Therefore, very low mass of refrigerant will be required for the same capacity. The highest average refrigerating effect was obtained using R600 with value of 280.5 kJ/kg compare with 141.6 kJ/kg of R134a. R290 and R600a have average refrigerating effect of 267.2 and 251.4 kJ/kg, respectively.

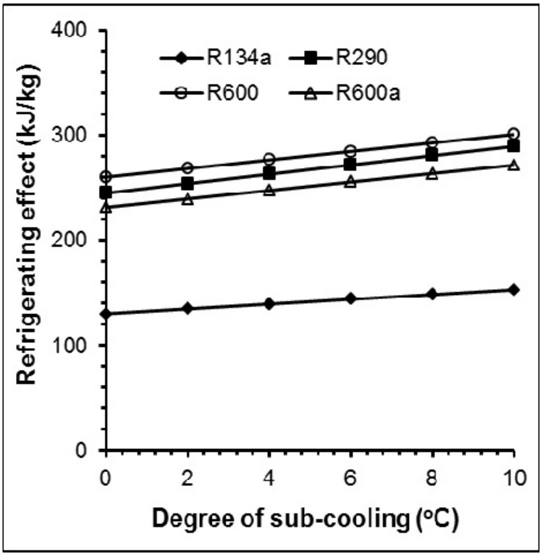

Fig. 4.: Variation of refrigerating effect with degree of sub-cooling

Figure 5 shows the compressor work input for the investigated refrigerants at varying degree of sub-cooling for 40°C condensing and -20°C evaporating temperatures. This figure revealed that compressor work input increases slightly with increase in degree of sub-cooling for R134a and the three hydrocarbon alternatives. All the three hydrocarbon refrigerants exhibited higher compressor work input than R134a, but they equally exhibited very high refrigerating effect (Figure 4), which is a form of compensation for their high compressor work input.

The effect of the degree of sub-cooling on the discharge temperature at 40°C condensing and -20°C evaporating temperatures for R134a and its three hydrocarbon alternatives is shown in Figure 6. This figure revealed that R600 and R600a exhibit lower discharge temperature than R134a and R290. 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 average discharge temperature obtained for R600 and R600a were 18.0, and 19.7% lower than that of R134a, respectively, while the value of R290 was 1.4% higher than that of R134a.

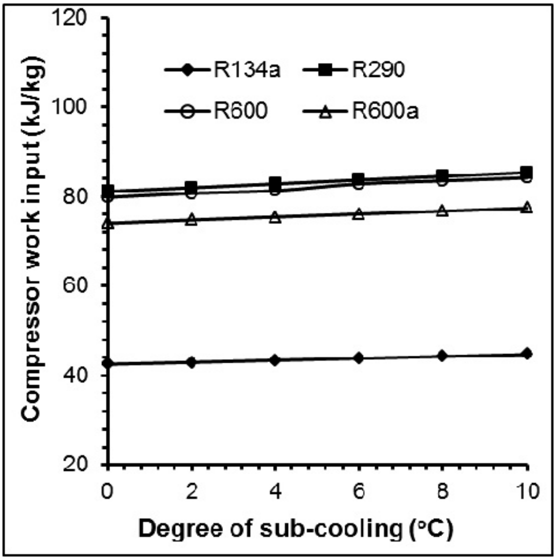

Fig. 5. Variation of compressor work input with degree of sub-cooling

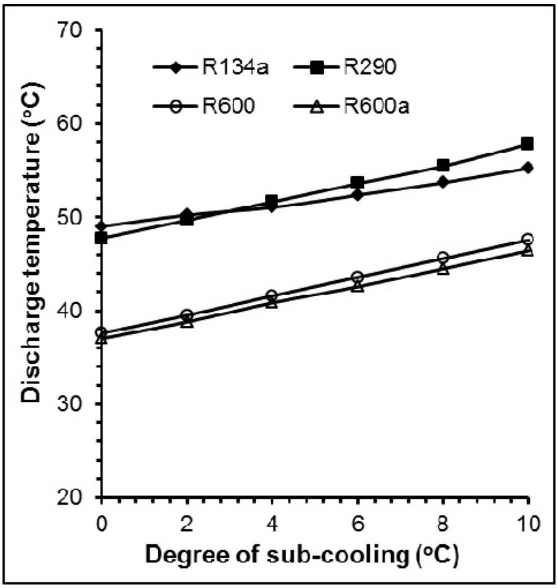

Fig. 6. Variation of discharge temperature with degree of sub-cooling

The effect of degree of sub-cooling on the condenser duty at 40°C condensing and -20°C evaporating temperatures for R134a and three hydrocarbon refrigerants is shown in Figure 7. The figure shows that the condenser duty increases as degree of sub-cooling increases. The increase in the degree of sub-cooling reduces the temperature of the liquid refrigerant at the exit of the condenser and therefore increases the quantity of heat to be removed by the condenser. The three hydrocarbon refrigerants exhibited higher condenser duty than R134a. The highest condenser duty was obtained using R600.

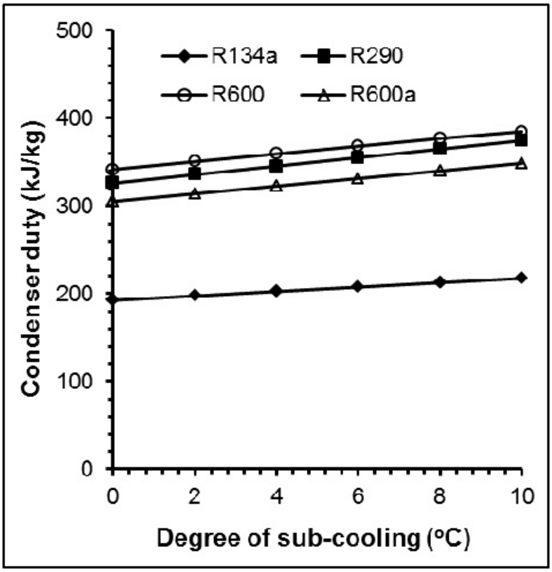

Fig. 7. Variation of condenser duty with degree of sub-cooling

Figure 8 shows the effect of degree of sub-cooling on the coefficient of performance (COP) at 40°C condensing and -20°C evaporating temperatures for the investigating refrigerants. The COP of the refrigeration cycle reflects the cycle performance and is the major criterion for selecting a new refrigerant as a substitute. COP is directly proportional to refrigerating capacity and is inversely proportional to energy consumption through the compressor (Eq. 3), therefore, higher rate of increase in refrigerating effect (Fig. 4) than the rate of increase in the compressor work input (Fig. 5) with respect to increase in the degree of sub-cooling, greatly increased the COP of the system. The COPs obtained using R600 and R600a were higher than the COP of R134a. The highest COP was obtained using R600 with average value of 4.6% higher than the value of R134a, while those of R00a and R290 are 2.2% higher and 1.2% lower than that of R134a, respectively.

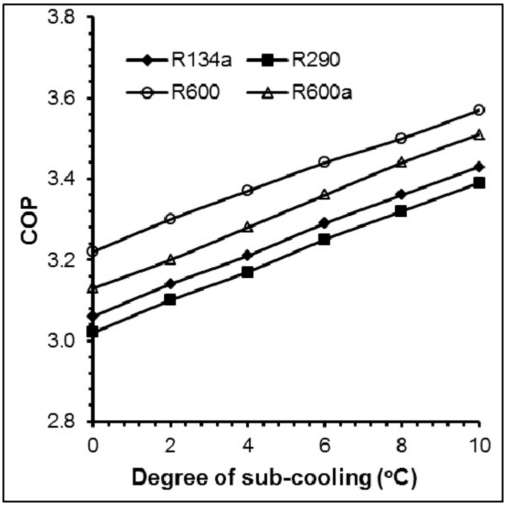

Fig. 8. Variation of coefficient of performance (COP) with degree of sub-cooling

The effect of degree of sub-cooling on the compressor discharge pressure is shown in Figure 9. The discharge pressure of R600 and R600a are lower than that of R134a, while R290 exhibited higher discharge pressure than that of R134a. 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. Therefore, refrigerants with lower discharge pressure are more suitable than those with high discharge pressure. The lowest discharge pressure was obtained using R600.

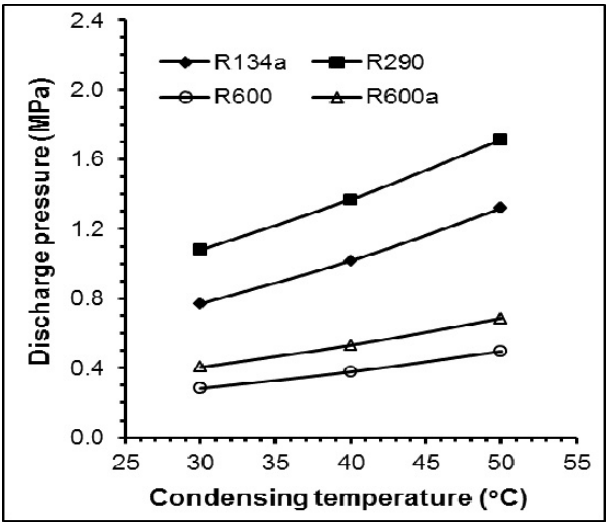

Fig. 9. Variation of with degree of sub-cooling with condensing temperature

Figure 10 shows the variation of relative capacity index (RCI) with degree of sub-cooling at condensing temperature of 40°C and evaporating temperature of -20°C. Increase in capacity due to sub-cooling is observed for all refrigerants, although there is considerable variation in the magnitude of the effect of sub-cooling on each refrigerant. The RCI obtained for R600a was close to that of R134a with 4.9% lower deviation. The highest RCI was obtained using R600 with 14.6% higher deviation from that of R134a, while R290 produced the lowest RCI with 17.4% lower deviation from that of R134a.

R134a is the most popularly used refrigerant by the refrigeration industry presently. However, while the ODP of R134a is approximately zero, its GWP of 1300 is relatively high (Table 1). R600 is a hydrocarbon refrigerant; it has neither an ozone depletion effect nor a global warming effect. The use of R600 has the direct environmental advantage of a greatly reduced GWP when compared to R134a. It is non-toxic and compatible with both mineral and synthetic oils. It has been reported that the amount of charge associated with R600 was roughly half that of R134a in a refrigerator. Also, the tests conducted indicated that hydrocarbons are quite safe in domestic refrigerators due to the very small amounts involved (Fatouh, M. and El-Kafafy, 2006).

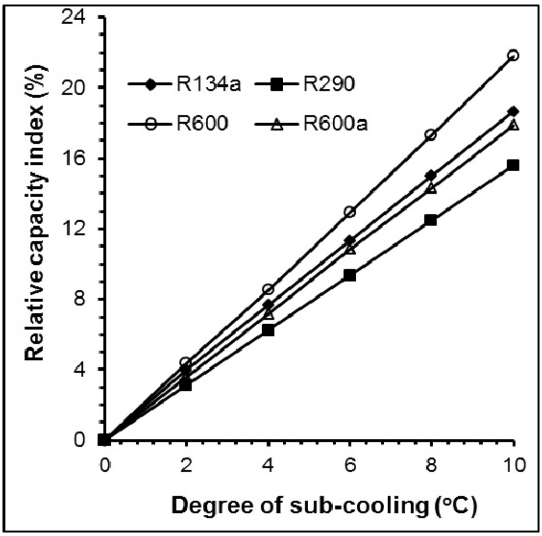

Fig. 10. Variation of relative capacity index (RCI) with degree of sub-cooling

CONCLUSION

In this study, the performance simulation of some hydrocarbon refrigerants (R290, R600 and R600a) as alternatives to R134a in a refrigeration system with sub-cooling at condensing temperature of 40°C and evaporator temperature of -20°C was conducted by thermodynamic calculation and analysis of performance parameters. The effects of sub-cooling on performance of the investigated refrigerants were quantified in terms of relative capacity index. The following conclusions can be drawn from the analysis and discussion of the results:

(i) The saturated vapour pressure and temperature characteristic profiles for R600 and R600a are very close to that of R134a. This indicates similar properties and they could be used as substitutes for R134a. The saturated vapour pressure for R290 is significantly very high as compared to that of R134a.

(ii) All the three investigated hydrocarbon refrigerants exhibited very high refrigerating effect and condenser duty than R134a. Therefore, very low mass of refrigerant will be required for the same capacity. The highest values in terms of these two parameters were obtained using R600.

(iii) The three alternative refrigerants exhibited higher compressor work input than R134a, but their high refrigerating effect will compensate for this.

(iv) The average discharge temperatures obtained for R600 and R600a were 18.0% and 19.7% lower than that of R134a, respectively, while the value of R290 was 1.4% higher than that of R134a.

(v) R600 and R600a refrigerants exhibited lower values of discharge pressure than R134a, while the discharge pressure obtained for R290 was higher than that of R134a.

(vi) The highest COP was obtained using R600 with average value of 4.6% higher than the value of R134a, while those of R00a and R290 are 2.2% higher and 1.2% lower than that of R134a, respectively.

(vii) The RCI obtained for R600a was close to that of R134a with 4.9% lower deviation. The highest RCI was obtained using R600 with 14.6% higher deviation from that of R134a, while R290 produced the lowest RCI with 17.4% lower deviation from that of R134a.

(viii) The performances of R600 and R600a in refrigeration system with sub-cooling were better than those of R134a and R290. Also, R600 performed better than R600a in terms of producing the highest refrigerating effect, condenser duty, COP, RCI and the lowest discharge pressure.

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Submitted : *27/3/2012*
Revised : *22/1/13*
Accepted : *7/2/2013*

تحليل ديناميكي حراري لمبردات هايدروكربونية في أنظمة ثلاجات فائقة التبريد

بوكولا بولاجي و زونجي هوان

*قسم الهندسة الميكانيكية – كلية الهندسة – الجامعة الفدرالية– أبيكوتا نيجيريا

**قسم الهندسة الميكانيكية– كلية الهندسة والبيئة – جامعة تشوين للتكنولوجيا – بركوريا جمهورية جنوب أفريقيا

خلاصة

في هذه الدراسة تم مماثلة أداء بعض المبردات تم مماثلة أداء بعض المبردات (R290, R600, R600a) كبدائل للمبرد (R134) في ثلاجات بالغة التبريد وذلك لقياس الخواص الميكانيكية الحرارية باستخدام برنامج (REFPROP) أظهرت النتائج أن تغيير ضغط البخار المشبع والخصائص الحرارية للمبردات (R600) و(R600a) قريبة جدا للمبرد (R134a). الهيدروكرويونات الثلاث أظهرت فعالية في التبريد والتكثق أكبر من (R134a) وأفضلها كان (R600). أفضل درجة حرارة التفريغ تم الحصول عليها باستخدام (R600) درجة حرارة التفريغ ل (R600) و(R600a) كانت منخفضة بينما ل (R290) كانت أعلى بكثير. أعلى معامل فعالية ومؤشر الكفاءة النسبية تم الحصول عليها باستخدام (R600). متوسط معامل الفعالية لـ (R600) و(R600a) كان (4.6%) و(2.2%) على التوالي وكان أعلى من (R134a).

أداء (R600) و(R600a) في نظام التبريد كان أعلى من (R134a) و (R290). أفضل أداء كان ل (R600).

المجلة التربوية

مجلة فصلية، تخصصية، محكّمة

تصدر عن مجلس النشر العلمي - جامعة الكويت

رئيس التحرير: أ. د. عبدالله محمد الشيخ

تنشر:

- البحوث التربوية المحكمة
- مراجعات الكتب التربوية الحديثة
- محاضر الحوار التربوي
- التقارير عن المؤتمرات التربوية وملخصات الرسائل الجامعية

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- تنشر لأساتذة التربية والمختصين بها من مختلف الأقطار العربية والدول الأجنبية.

الاشتراكات:

في الكويت: ثلاثة دنانير للأفراد، وخمسة عشر ديناراً للمؤسسات.

في الدول العربية: أربعة دنانير للأفراد، وخمسة عشر ديناراً للمؤسسات.

في الدول الأجنبية: خمسة عشر دولاراً للأفراد، وستون دولاراً للمؤسسات.

توجه جميع المراسلات إلى:

رئيس تحرير المجلة التربوية - مجلس النشر العلمي ص.ب. ١٣٤١١ كيفان - الرمز البريدي 71955

الكويت هاتف: ٢٤٨٤٦٨٤٣ (داخلي ٤٤٠٣ - ٤٤٠٩) - مباشر: ٢٤٨٤٧٩٦١ - فاكس: ٢٤٨٣٧٧٩٤

E-mail: joe@ku.edu.kw