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PERFORMANCE SIMULATION OF VAPOUR COMPRESSION REFRIGERATION SYSTEMS USING OZONE-FRIENDLY HYDRO-FLUOROCARBON REFRIGERANTS

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Abstract: This paper presents the performance of four hydro-fluorocarbon (HFC) refrigerants (R125, R134a, R143a and R152a) selected to replace ozone depleting refrigerant in the existing vapour compression refrigeration systems using thermodynamic simulator. The performance in term of refrigeration capacities (RC), compressor work (W_c) and coefficient of performance (COP) were evaluated for the investigated refrigerants at various evaporating and condensing temperatures. The system performance increases as the evaporating temperature increases, but reduces as the condensing temperature increases. The results showed that R134a and R152a have thermodynamic performances similar to R12, while deviations of performances of R125 and R143a from that of R12 were very large. The overall assessment of the results for the R134a and R152a refrigerants, and the consideration of their global warming potentials (GWPs) showed that R152a will be a better alternative refrigerant than R134a in refrigeration system.
Keywords: hydro-fluorocarbon (HFC) refrigerants, refrigeration systems, thermodynamic simulator

1. INTRODUCTION

The chlorofluorocarbon (CFC) refrigerants have been used extensively over the last eight decades in refrigeration systems due to their favourable characteristics such as non-flammable, non-toxicity, non-explosiveness and chemical stability behaviour with other materials. However, the results of many researchers have shown that stratospheric ozone layer which absorbs the sun high energy ultraviolet radiations and protects both humans and other living organisms from exposure to the harmful radiation is being depleted. This is mainly caused by the increased upper stratospheric loading of the chlorine released by CFCs. The general consensus for the cause of the event is that free chlorine radicals remove ozone from atmosphere and later, chlorine atoms continue to convert more ozone to oxygen. A further consequence of the discharge of CFCs into atmosphere is their contribution to the greenhouse effect or global warming of the earth's atmosphere (Bolaji, 2008).

The discovery of the depletion of the earth's ozone layer, which shields the earth's surface from UV radiation, has resulted in a series of international treaties demanding a gradual phase out of halogenated fluids. The CFCs have been phased out in developed countries since 1996, and 2010 in developing countries. 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 (Radermacher and Kim, 1996; UNEP, 2003; Bolaji, 2011).

The technology for replacing R12 in the refrigeration systems has been fully developed, but is still undergoing rapid changes where it concerns the selection of the appropriate refrigerant.

Originally, a large number of refrigerant candidates were compared and the results of tests narrowed down the list of possible candidates to only one refrigerant (R134a) The thermo-physical properties of R134a are very similar to those of R12 and the refrigerant is also non-toxic ozone-friendly refrigerant (Bolaji, 2010b).

Many research works have been done on R134a. It has been reported that the power consumption of a R134a system would be 10 - 15% more than R12 system (Muir, 1995). The performance study on single evaporator domestic refrigerator indicated that the COP of R134a is 3% less than that of R12 (Jung and Radermacher, 1991). Due to the reactive nature of the residual mineral oil with the lubricant polyol ester (POE) oil and R134a, a stringent flushing procedure should be adopted so that the mineral oil residue comes below 1% while retrofitting R12 systems with R134a (Akintunde, 2006). Experimental studies on the retrofitted R134a system indicated 5 - 8% lesser COP than that of conventional R12 system (Camporese, 1997).

However, while the ozone depletion potential (ODP) of R134a is zero, global warming potential (GWP) is high (GWP = 1430). Due to this reason, some restrictions have already been placed on their use in Europe. Therefore, the production and use of R134a will be terminated in the near future (Tashtoush et al., 2002; Fatouh and El Kafafy, 2006). According to Bitzer (2007) the refrigerants R32, R152a, R143a and R134a are regarded as direct substitutes in domestic refrigeration system from the line of hydro-fluorocarbon (HFC) refrigerants. These refrigerants belong to the chlorine free (ODP = 0) alternatives, the first two have been used for many years as components in blends but not as a single substance refrigerant till now. Especially advantageous is their very low GWP (650 and 124 for R32 and R152a, respectively).

Simulation and modelling of refrigeration system are used to predict the system performance and to optimize the combination of system components during the design process and also to provide insights into control strategies that may improve the system performance. The refrigerator performance is usually assessed by one of the following approaches: simplified calculations based on curves of the component characteristics, numerical analysis via CFD packages, and standardized experiments. A faster and less costly alternative is the use of first-principles thermodynamic models to simulate the thermo-hydrodynamic behaviour of refrigeration systems (Hermes and Melo, 2009).

Many studies have been reported on simulation and mathematical modelling of refrigeration systems. Jian et al. (2004) developed a general steady state mathematical model for fin and tube heat exchanger based on the graph theory. With help of the directed graph and graph-based traversal methods (Breadth-first search and Depth-first search), this model is capable to describe any flexible refrigerant circuit arrangement and quality of the refrigerant distribution in the refrigerant circuit and heat conduction through fins. An alternative iteration method was also developed to solve the conservation equations which can shorten the simulating time effectively. Gupta (2006) presented modelling of a domestic frost free refrigerator using a comprehensive thermo-fluidic model. The governing equations couple with pertinent boundary conditions are solved by employing control volume formation, in the environment of a three-dimensional unstructured mesh.

Cristian et al. (2009) presented the development and validation of a condenser three zones model using deterministic model of a refrigeration condenser. The model assumes that the condenser can be divided into three distinct zones on the refrigerant side: the vapour de-superheating zone, the two-phase zone and the sub-cooled liquid zone. The pressures and temperatures in each zone and the corresponding heat flows were identified. The model also gives the geometrical repartition among the zones and the pressure drop on air-side.

Most of the studies reviewed above worked on modelling and simulation of refrigeration systems and their components, not on their working fluids (refrigerants). The development of dynamic models for household refrigerators was stimulated by the R12 phase-out in the late 1980s (Hermes and Melo, 2009). Gopalnarayanan (1998), and Han and Zheng (1999) reported that hydro-fluorocarbons (HFCs) and their mixtures are refrigerants for definite substitution of both CFCs and HCFCS because they do not contain chlorine and hence they have zero ozone depletion. In this study, thermodynamic simulation model was used to investigate the performance of vapour compression refrigeration system using some eco-friendly hydro-fluorocarbon refrigerants. The performance characteristics of the system with alternative refrigerants were evaluated and compared with those of baseline refrigerant (R12).

2. SIMULATION OF REFRIGERATION CYCLE

Four hydro-fluorocarbon (HFC) refrigerants (R134a, R152a, R125 and R143a) and the baseline CFC refrigerant (R12) were selected for investigation. Some of the properties and environmental impact of selected refrigerants are shown in Table 1 and Table 2, respectively.

Table 1: Physical Properties of Investigated Alternative Refrigerants

Refrigerant	Chemical Formula	Molecular Weight (g)	Boiling Point (°C)
R12	CF_2Cl_2	121	-29.8
R32	CH_2F_2	52	-51.7
R152a	$C_2H_4F_2$	66	-24.0
R143a	$C_2H_3F_3$	84	-47.2
R134a	$C_2H_2F_4$	102	-26.1

Sources: ASHRAE, 2001

Table 2: Environmental Impact of Investigated Alternative Refrigerants

Refrigerant	Ozone depletion potential (ODP)	Global warming potential (GWP)
R12	1	8100
R32	0	650
R152a	0	124
R143a	0	3800
R134a	0	1430

Sources: Bitzer, 2012.

The simulation model was developed to investigate the effect of the evaporating and condensing temperatures on the following performance parameters of the vapour compression refrigeration system: the refrigeration capacity (RC), the compressor power (W_c) and the coefficient of performance (COP). The required data for the model are: the physical and thermodynamic properties obtained from ASHRAE (2001), the evaporating and condensing temperatures, and the refrigerant mass flow rate. The experimental analysis is based on the following relevant assumptions:

(i) pressure losses due to friction and pipelines are considered to be negligible,
(ii) heat losses to the surrounding through the system components are negligible, and
(iii) the compression process is assumed to be isentropic.

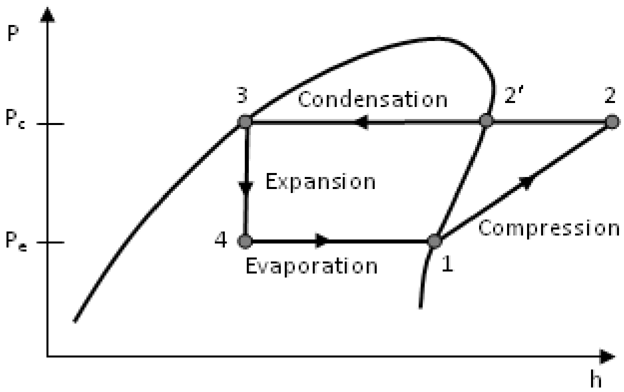

Figure 1: Conventional Refrigeration Cycle on p-h Diagram

The conventional refrigeration cycle as shown on p-h diagram in Figure 1, is made up of four major components: Compressor, condenser, expansion device and evaporator. Assuming isentropic compression (process 1-2), the compressor discharge temperature (T_2) is given as (Eastop and McConkey, 1996):

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{1}$$

where, T_1 = suction temperature (K); P_1 = compressor suction pressure (kN/m²); P_2 = compressor discharge pressure (kN/m²); and γ = isentropic index. Isentropic index is the ratio of specific capacity of the refrigerant at constant pressure (C_p) to the specific capacity of the refrigerant at constant volume (C_p), and it is expressed as:

$$\gamma = \frac{C_p}{C_v} \tag{2}$$

The heat absorbed by the refrigerant in the evaporator or refrigeration (RC, kW) is expressed as:

$$RC = m_R\,(h_1 - h_4) \tag{3}$$

where, m_R = refrigerant mass flow rate (kg/s); 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 power (W_c, kW) is expressed as:

$$W_c = m_R\,(h_2 - h_1) \tag{4}$$

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

From the first law of thermodynamic point of view the measure of performance of the refrigeration cycle is the coefficient of performance (COP) and is defined as the refrigeration capacity per unit of power required (Dossat and Horan, 2002). It is expressed as:

$$COP = \frac{RC}{W_c} \text{ or } COP = \frac{h_1 - h_4}{h_2 - h_1} \tag{5}$$

The model Equations (1) to (5) were implemented using RefSimulation platform developed by Olonila (2010) and connected to REFPROP 7.0 software (Lemmon et al., 2002). The solution algorithm is represented schematically in form of the information flow diagram of Figure 2. The input parameters are basically the compressor suction temperature (T_1), suction pressure (P_1), discharge pressure (P_2) and isentropic index.

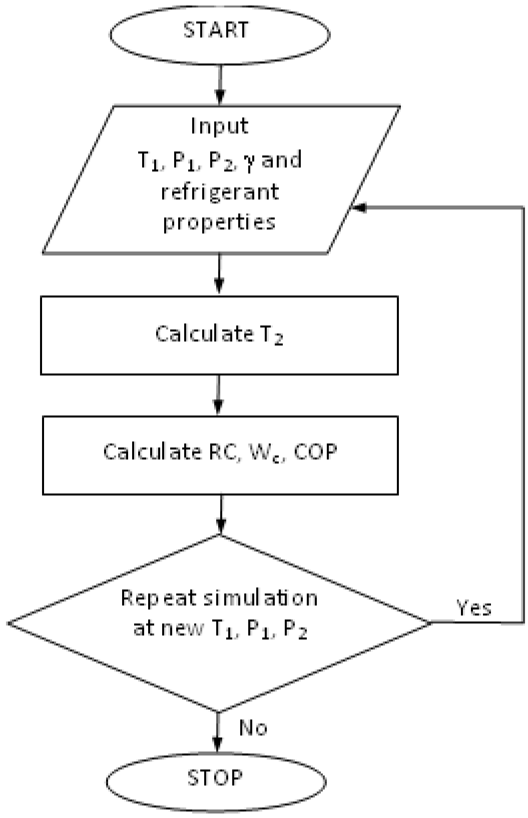

Figure 2: Flow Chart for the Thermodynamic Cycle Simulation

3. RESULTS AND DISCUSSION

Figures 3 and 4 show the effect of condensing temperatures on the compressor power input for evaporating temperatures of -20°C and -10°C, respectively. Comparison between the two figures showed that the increase in evaporating temperature from -20°C (Figure 3) to -10°C (Figure 4) reduces the compressor power input. The reduction in compressor power is due to the reduction in the temperature between the two heat exchangers (evaporator and condenser) of the system. As shown in the two figures, compressor work increases as the condensing temperature increases for all the investigated refrigerants. The compressor power for R134a and R152a are very close to that of R12 than those of R125 and R143a. The average compressor power input of R143a was found to be the highest with 25.2% higher than that of R12, while that of R152a was found to be the lowest with 6.7% lower than that of R12 at -10°C evaporating temperature.

The variation of the refrigeration capacity with condensing temperature at evaporating temperatures of -20°C and -10°C are shown in Figures 5 and 6, respectively. It was observed that for all the investigated refrigerants, the refrigeration capacity reduced with increase in condensing temperature. Comparison between the two figures showed that the increase in evaporating temperature from -20°C (Figure 5) to -10°C (Figure 6) increases the refrigeration capacity. R152a has the highest refrigeration capacity which is very close to those of R12 and R134a. Average refrigeration capacities of R134a and R152a are 5.1% lower and 7.8% higher, respectively, than that of R12, while average capacities of R125 and R143a are 23.0% and 29.6% lower than that of R12, respectively, at evaporating temperature of -10°C.

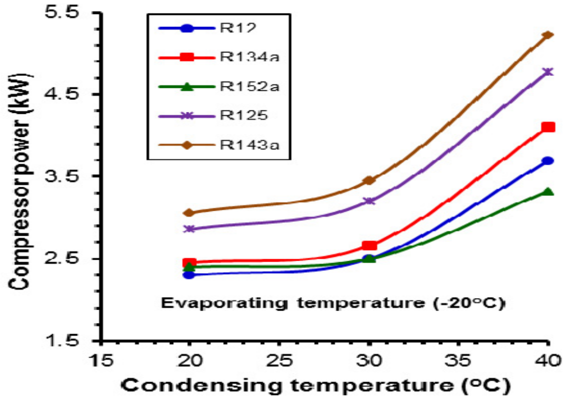

Figure 3: Variation of Compressor Power with Varying Condensing Temperature for Evaporating Temperature of -20°C.

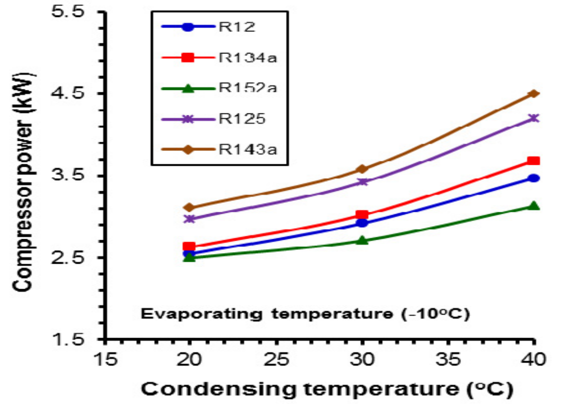

Figure 4: Variation of Compressor Power with Varying Condensing Temperature for Evaporating Temperature of -10°C.

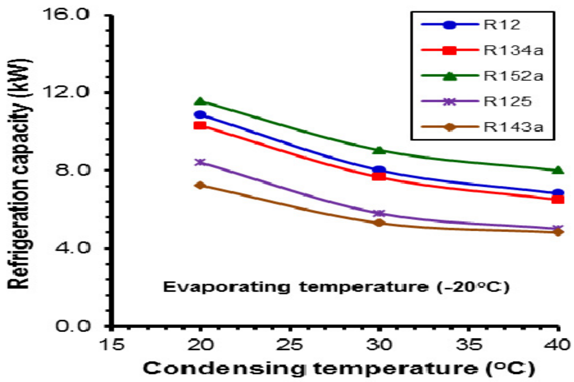

Figure 5: Variation of Refrigeration Capacity with Varying Condensing Temperature for Evaporating Temperature of -20°C.

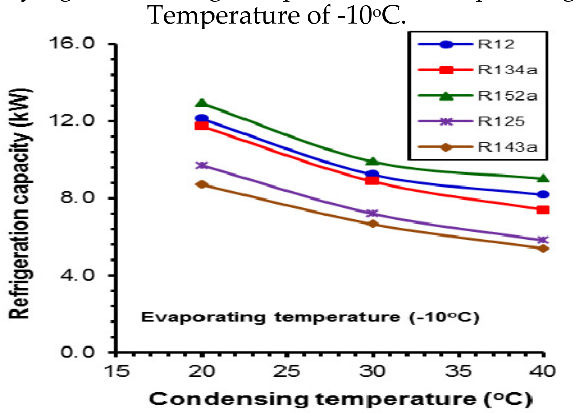

Figure 6: Variation of Refrigeration Capacity with Varying Condensing Temperature for Evaporating Temperature of -10°C

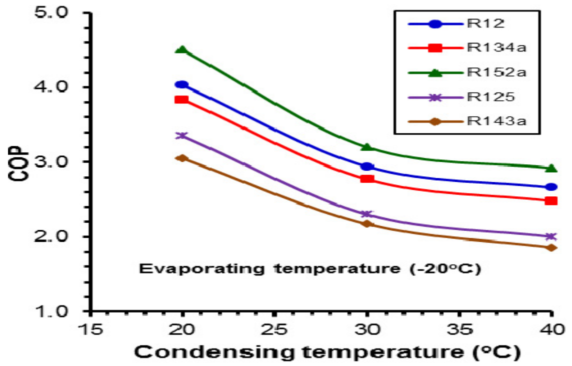

Figure 7: Variation of Coefficient of Performance (COP) with Varying Condensing Temperature for Evaporating Temperature of -20°C

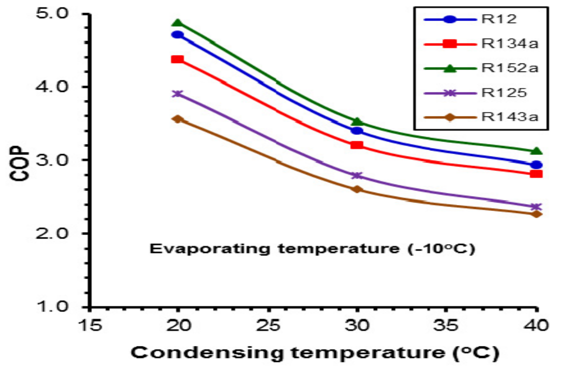

Figure 8: Variation of Coefficient of Performance (COP) with Varying Condensing Temperature for Evaporating Temperature of -10°C

The effect of condensing temperature on the coefficient of performance (COP) for R12 and the selected alternative refrigerants for evaporating temperatures of -20°C and -10°C are shown in Figures 7 and 8, respectively. As shown in the two figures, for all investigated refrigerants, as the condensing temperature increases the COP reduces and as the evaporating temperature increased from -20°C (Figure 7) to -10°C (Figure 8) the COP also increased. The figures show that R152a has the highest COP. The COPs of R152a and R134a are very close to that of R12 over the considered range of operating conditions. The average COPs of R134a and R152a at -10°C evaporating temperature are 6.0% lower and 4.3% higher, respectively, than that of R12, while the average COPs of R125 and R143a are 17.9% and 23.6% lower respectively, than that of R12.

4. CONCLUSION

In this study, the performance of four HFC refrigerants (R134a, R152a, R125 and R143a) regarded as R12 alternatives in vapour compression refrigeration system were investigated using simulation model. The thermodynamic model was developed to predict the performance of the selected refrigerants based on their compressor power input (W_c), refrigeration capacity (RC) and coefficient of performance (COP) at various operating conditions.

The results obtained showed that as condensing temperature increases the compressor power input increases, while refrigeration capacity and COP reduce. Also, as evaporating temperature increases the compressor power reduces, while refrigeration capacity and COP increase. The overall assessment of the results showed that R152a and R134a refrigerants have the most similar performance characteristics to R12, while the performances of R125 and R143a were significantly lower than that of R12. R152a has higher refrigeration capacity, higher COP and lowest compressor power input than R134a, and the consideration of the global warming potentials (GWPs) of these two refrigerants showed that R152a will be a better alternative than R134a in vapour compression refrigeration system.

REFERENCES

[1.] Akintunde, M.A.: Experimental investigation and modelling of moisture solubility in R12 and R134a, AU Journal of Technology, 9(4), 261-266, 2006.

[2.] ASHRAE: Thermophysical Properties of Refrigerants, Chapter 20, ASHRAE Fundamental, Inc. Atlanta (GA), 20.1 - 20.67, 2001.

[3.] Bitzer: Refrigerant Report. Bitzer International, 13th Edition, 71065 Sindelfingen, Germany, http://www.bitzer.de Accessed on March 8, 2012.

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

[5.] Bolaji, B.O.: Experimental analysis of reciprocating compressor performance with eco-friendly refrigerants, Proc. IMechE, Part A: Journal of Power and Energy, 224(6), 781-786, 2010.

[6.] Bolaji, B.O.: Performance investigation of ozone-friendly R404A and R507 refrigerants as alternatives to R22 in a window air-conditioner, Energy and Buildings, 43(11), 3139-3143, 2011.

[7.] Camporese, R.; Bigolaro, G. and Bobbo, S.: Experimental evaluation of refrigerant mixtures as substitutes for R12 and R502, International Journal of Refrigeration, 20, 22-31, 1997.

[8.] Cristian, C.; Jean, L.; Vincent, L. and Philippe, N. (). Development and validation of a condenser three zones model, Applied Thermal Engineering, 22, 3542-3551, 2009.

[9.] Dossat, R.J. and Horan, T.J.: Principles of refrigeration, Prentice-Hall International Inc. New Jersey, USA, 2002.

[10.] Eastop, T.D. and McConkey, A.: Applied thermodynamics for engineering technology, Longman Publishers, Singapore, 1996.

[11.] Fatouh, M. and El Kafafy, M.: Assessment of propane/ commercial butane mixtures as possible alternatives to R134a in domestic refrigerators, Energy Conversion and Management, 47, 2644-2658, 2006.

[12.] Gopalnarayanan, S.: Choosing the right refrigerant, Mechanical Engineering, the American Society of Mechanical Engineers (ASME), 120(10), 92-95, 1998.

[13.] Gupta, A.: Modelling of a domestic frost-free refrigerator using a comprehensive thermo-fluidic model, International Journal of Refrigeration, 27, 2511-2524, 2006.

[14.] Han, H.D. and Zheng, Q.R.: Research on the replacement for R12 in refrigerating units for coming 21st century, Proceedings of the 20th International Congress of Refrigeration, Sydney, 1-7, 1999.

[15.] Hermes, C.J.L. and Melo, C.: Assessment of the energy performance of household refrigerators via dynamic simulation, Applied Thermal Engineering, 22, 1153-1165, 2009.

[16.] Jian, L.; Wen, J.W.; Gou, L.D.; Chunlu, Z.; Masaharu, F.; Kaijian, W. and Takefumi, I.: A general study state mathematical model for fin-and-tube heat exchanger based on graph theory, International Journal of Refrigeration, 27, 965-973, 2004.

[17.] Jung, D.S. and Radermacher, R.: Performance simulation of single evaporator domestic refrigeration charged with pure and mixed refrigerants, International Journal of Refrigeration, 14, 223-232, 1991.

[18.] Lemmon EW, McLinden MO, Huber ML.: NIST reference fluids thermodynamic and transport properties REFPROP 7.0. National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, 2002.

[19.] Muir, E.B.: Commercial Refrigeration and CFCs, International Journal of Refrigeration, 13, 106-112, 1995.

[20.] Olonila, J.R.: Performance simulation of vapour compression refrigeration systems using eco-friendly refrigerants, B.Eng. Thesis, Department of Mechanical Engineering, University of Agriculture, Abeokuta, Nigeria, 2010.

[21.] Radermacher, R. and Kim, K.: Domestic refrigeration: recent development, International Journal of Refrigeration, 19, 61-69, 1996.

[22.] Tashtoush, B.; Tahat, M. and Shudeifat, M.A.: Experimental study of new refrigerant mixtures to replace R12 in domestic refrigerator, Applied Thermal Engineering, 22, 495-506, 2002.