Comparative Analysis of Performance of R600a and R510a Refrigerants in a Retrofitted Refrigerating System

Francis Olusesi Borokinni [1], Babatunde Emmanuel Olatunbosun [2,*]

[1]Department of Mechanical Engineering, Yaba College of Technology, Yaba, Nigeria.

[2]Department of Agricultural Engineering, Akwa Ibom State University, Ikot Akpaden, Nigeria.

Received 26 July 2017; received in revised form 07 August 2017; accepted 17 August 2017

Abstract

Hydrocarbons, in the environmentally friendly group have drawn much attention of scientists and researchers for application as refrigerants. In this work, the performance of two eco-friendly hydrocarbon refrigerants (R510A and R600a) in a retrofitted vapour compression refrigeration system was investigated experimentally and compared with the baseline hydro fluorocarbon refrigerant (R134a). Thermocouples and pressure gauges were fitted at the inlet and outlet of the compressor, condenser, and evaporator to measure the temperature and pressure of the refrigerant at various stages of the refrigeration cycle. The results obtained showed that the coefficient of performance (COP) of the system using the two hydrocarbon refrigerants was higher than the coefficient of performance (COP) obtained using R134a as a working fluid. Generally, the two hydrocarbon refrigerants performed better than R134a, but R510A gave the best overall performance in that it exhibited the lowest discharge pressure of 0.656MN/m2and the highest refrigerating effect of 253.29kJ/kg.

Keywords: hydrocarbon, refrigerant, retrofitted, thermocouple

1. Introduction

Most of the refrigeration and air-conditioning system operate on vapour compression refrigeration cycle [1] in which the refrigerant change phases from liquid to gas and gas to liquid in a closed cycle to generate cooling in the evaporator. Refrigerants used in these systems are predominantly from a group of compounds called halocarbons (halogenated hydrocarbons)

In 1974, Sherwood Rowland and Mario Molina predicted that chlorofluorocarbon (CFC) refrigerant gases would reach the high stratosphere and there damage the protective mantle of the oxygen allotrope, ozone. In 1985, with the discovery of the "ozone hole" over the Antarctic, the prediction of Rowland and Molina's was proved correct.

CFCs are non-toxic, non-flammable are used extensively as refrigerants in refrigeration units, aerosol propellants, electronic cleaning solvents, and blowing agents [2]. Over time, these CFCs get released into the air and often, strong winds carry them into the stratosphere. When CFC molecules drift into the stratosphere, the UV-B and UV-C radiation from the sun releases their chlorine atoms. Complex chemical reactions in the atmosphere result in the formation of chlorine monoxide, which reacts with the ozone molecule to form oxygen and regenerates more chlorine atoms that carry on converting the ozone molecules. Each chlorine atom can destroy as many as 100,000 ozone molecules over 100 years. Thus, even a small amount of CFCs can cause tremendous damage to the ozone layer [3-4]. Therefore, they have been forbidden in developed countries since January, 1996. In 2010 production and usage of CFCs have been prohibited completely all over the world [5-6].

* Corresponding author. Email address: olat.tunde12@gmail.com

Many Studies have been carried out to find suitable replacement for CFCs [7-8] Transitional alternative compounds, such as hydro-chlorofluorocarbons (HCFCs), 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 [9].

2. Material and Method

2.1. Properties of selected refrigerants

Two Hydrocarbon (HCs) and one HFC refrigerants (R510A, R600a, and R134a) were selected and their performances in vapour compression refrigeration were investigated and analyzed. These are natural, chlorine free refrigerants; therefore they are not harmful to the ozone layer and global warming. Some of the properties and environment impact of the selected environmental friendly refrigerants are as tabulated below.

Table 1 Some properties and environmental impacts of selected alternative refrigerants

Physical and environmental characteristic of selected refrigerants			
Properties	R134a	R600a	R510A
Molecular weight (kg/kmol)	102.000	58.120	47.240
Critical temperature (^{o}C)	101.300	134.660	128.100
Critical pressure (Mpa)	4.0069	3.630	5.120
Density		225.500	268.560
Boiling point (^{o}C)	-26.07	-11.75	-34.40
ODP	0	0	0
GWP	1300	3	3

2.2. Experimental set-up

The system was incorporated with two pressure gauges with accuracy of ± 0.5kPa at the inlet and outlet of the compressor for measuring the suction and discharge pressures. The temperature of the refrigerant at four different points was measured with digital thermocouples with accuracy of ±0.1^{o}C. The energy consumption of the refrigeration system was measured with energy meter with accuracy of ±0.2kWh. Data were collected at different evaporator temperatures and the following performance parameters were obtained using equations 1 to 7: refrigerating effect (Q_{evap}), compressor work input (W_c), condenser heat load (Q_{cond}) Coefficient of Performance (COP), Volumetric Cooling Capacity (VCC) and pressure ratio (P_r). C.

2.3. Analysis of the heat transfer in the refrigeration system

2.3.1. Evaporator

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).

2.3.2. Compressor

The isentropic work input to compressor (Ks/S) is expressed as:

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

where h_2 is the enthalpy of refrigerant at the outlet of compressor (kJ/Kg)

The actual compressor work ($W_{e,}$ kJ/S) is given as

$$W_c = W_{cs} / ns \tag{3}$$

where *ns* is the isentropic efficiency

2.3.3. Condenser

The heat rejected by the condenser (Q_{cond}kJ/S) to the atmosphere is given as

$$Q_{cond} = M_r (h_2 - h_3) \tag{4}$$

where $h_3$is the enthalpy of refrigerant at the outlet of condenser (kJ/Kg)

2.3.4. Capillary Tube

In the capillary tube the enthalpy remains constant (isenthalpy process), therefore,

$$h_3 = h_4 \tag{5}$$

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 the refrigerating effect produced per unit of work required it is expressed as:

$$COP = Q_{evap} / W_c \tag{6}$$

The volumetric cooling capacity (Vcc , kJ/m^3) is the refrigerating effect per unit volume flow rate at the inlet to the compressor. It is expressed as

$$V_{cc} = Q_{evap} / m_r V_S \tag{7}$$

where V_s is the specific volume at inlet to the compressor (m^3/kg)

Compressor pressure ratio (P_r) is given as:

$$P_r = P_{dis} / P_{sue} \tag{8}$$

where, P_{dis} = refrigerant vapour pressure at the compressor discharge (kN/m^2) and P_{dis} = refrigerant vapour pressure at the compressor section (kN/m^2).

2.4. Retrofit procedures

The existing refrigerating system used was designed to work with R134a refrigerants need to be retrofitted to use Hydrocarbon refrigerants (R600a and R510A). The specific caution of the refrigerator is shown in Table 4. Retrofitting means the modification of an existing refrigeration system, which was designed to operate on R134a refrigerant so that it can safely and effectively operate on Hydrocarbon refrigerants. This is to ensure that existing equipment operates until the end of its economic life. R600a and R510A, which is widely accepted as a substitute for R134a in refrigeration systems, is not a "drop-in" replacement for R134a

2.5. Baseline test

The refrigerator was tested using R134a as the baseline and performance data prior to retrofit were obtained. The system was evacuated with the help of a Blue VAC vacuum pump to remove the non -condensable particle from the system. The system was charged with the help of manifold gauge. The pressure gauge and thermocouples were connected to the system. The system was instrumented with two pressure gauges with accuracy of + 0.5kPa at the inlet and outlet of the compressor for measuring the suction and discharge pressures.

2.6. Charging of refrigerant

Charging is the process of adding refrigerant to refrigeration system. The system may be charged with the refrigerant through the high or low sides. When charging is done on the high side, the refrigerant is introduced in liquid form but when charging in low side, the refrigerant is introduced in vapour form in order to prevent possible damage to the compressor. Normally it is more convenient to add refrigerant to system through the low side on small units or when small amounts are to be added to large systems. The low side method of charging refrigerant into the system was employed in this work.

WS - 150 Digital charging scale was used to charge the system. This is an automatic digital charging system that can charge the desired amount accurately. The charging system consists of platform, a processing LCD, an electronic controlled valve and charging line hose. The refrigerant cylinder is placed on the platform which measures the weight and also acts as a control panel. One charging hose is connected with the outlet of the cylinder and inlet of the electronic valve and another one is connected with the outlet of electronic valve and inlet of the service port. Using this charging system, R600a and R510A were charged and tested one after the other. The systems being charged with R600a and R510A require a smaller charge size than those using R134a. As recommended by [10], the charge of R600a and R510A was 90 percent by weight of the original R134a charge with the optimized capillary tube system.

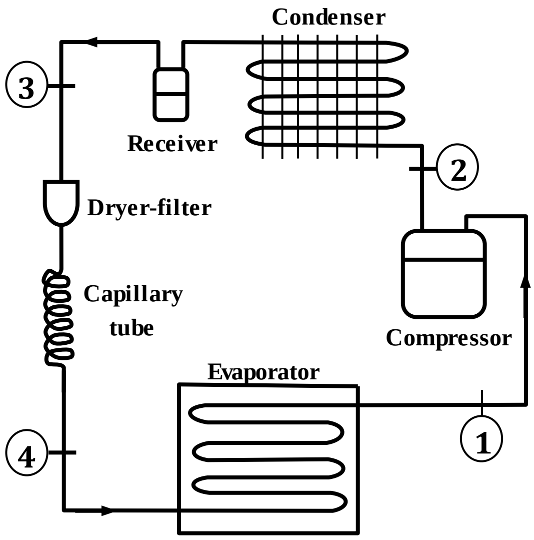

Fig. 1 Schematic diagram of the existing refrigerator

Table 2 The specification of the refrigerator

Specifications	**Value**
Freezer capacity (litres)	130
Fresh food compartment capacity (litres)	320
Power rating (W)	60
Current rating (A)	0.60
Voltage (V)	220
Frequency (Hz)	50
No of door	1
Refrigerant type	R 134a
Freezer dimension	Width : 43 mm, diameter :500 mm and height :830mm

3. Results

The performance comparison of the investigated refrigerants (R600a, R510A and R134a) in the retrofitted vapour compression refrigerating system was carried out and the enthalpies of the system at various evaporating temperatures and pressures were obtained using refrigerant database software known as REFPROP [11]. The performance parameters obtained using hydrocarbon refrigerants (R600a and R510a) in the system were analysed and compared with those obtained using the baseline refrigerant (R134a). The results of effects of the evaporating temperature on condenser heat load (Q_{cond}), volumetric cooling capacity (V_{cc}) Coefficient of performance (COP), Refrigerating effect (Q_{evap}) distance temperature (T_{dis}) and compressor work in put (Wc) are investigated.

Table 3 The system enthalpies at varying evaporating temperature for R600a

Evaporating temperature	Enthalpy	(KJ/kg)	
(^{o}C)	h_1	h_2	h_3
-28	519.92	582.21	223.15
-29	518.44	591.71	227.87
-30	516.96	599.93	234.94
-32	514.08	604.92	244.49
-33	512.62	609.96	258.98

Table 4 The system enthalpies at varying evaporating temperature for R510A

Evaporating temperature	Enthalpy	(KJ/kg)	
(^{o}C)	h_1	h_2	h_3
-26	476.36	528.12	89.46
-28	473.71	532.36	94.12
-30	471.08	535.22	106
-32	468.46	539.52	113.14
-34	465.84	546.76	122.76

Table 5 The system enthalpy at varying evaporating temperature for R134a

Evaporating temperature	Enthalpy	(KJ/kg)	
(^{o}C)	h_1	h_2	h_3
-25	386.9	422.08	227.47
-27	385.39	428.73	230.3
-29	383.88	430.39	234.55
-30	383.11	432.07	237.42
-32	381.61	433.75	241.72

4. Discussion

4.1. Effect of evaporating temperature on discharge pressure

The variations of the discharge pressure as a function of the evaporating temperature for the three refrigerants are shown in Fig. 2. As shown in the figure, the discharge pressure reduces as the evaporating temperature increases. R510A has the lowest pressure with average pressure of 13.40% lower than that of R134a. However, R134a exhibited significantly high pressure as compared to R510A and R600a. The pressure of R510A was very close to that of R600a. Refrigerant with low pressure is desirable in the system because the higher the pressure the weightier must be the equipment accessories and parts .

4.2. Effect of evaporating temperature on pressure ratio

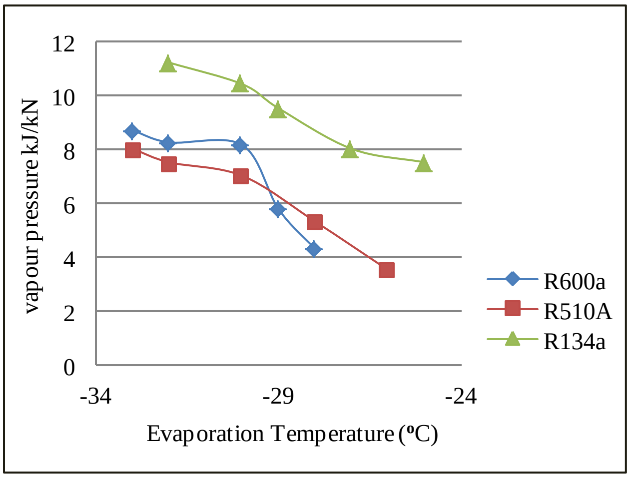

Fig. 2 Variation of vapour pressure varying evaporator temperatures for R134a, R600a and R510A

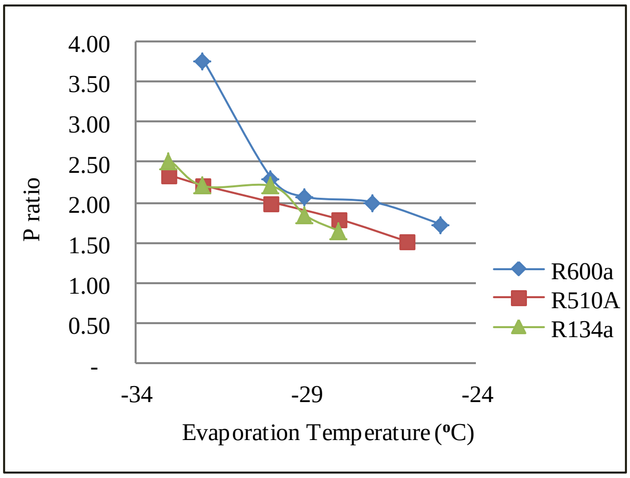

Fig. 3 Variation of pressure ratio with varying evaporator temperatures for R134a, R600a and R510A

Fig. 3 shows the variation of pressure ratio with varying evaporating temperature for R600a, R510A and R134a. The figure shows that the pressure ratio decreases with increase in evaporating temperature. The three refrigerants followed these similar trends. As reflected in the figure, the pressure ratios of R134a are higher than those of R510A and R600a. Average pressure ratios obtained using R510A and R600a in the system were 6.2 and 4.2% lower than that of R134a respectively. Therefore, same compressor is usable for both R510A and R600a, while a slightly heavy compressor for the same capacity will be needed for R134a.

4.3. *Effect of evaporating temperature on condenser heat load*

The function of the condenser is to remove heat of the vapour refrigerant discharged from the compressor. Heat is added to the refrigerant during evaporation in the evaporator by the compressor during the work of compression. The heat from the refrigerant is moved by transferring heat to the wall of the condenser tubes and then from the tubes to the condensing medium. The variations of the condenser heat load against evaporating temperature are presented in Figure 4 for the three refrigerants. The figure shows that the condenser heat load increases as the evaporating temperature increases. Also, in the figure, R134a has the highest mean heat load. The average heat loads of R510A and R600a were 23.3 and 16.90% lower than that of R134a respectively. If the temperature of the evaporator increases, the work of compression increases. As work of compressor increases the heat added to the refrigerant during compression increases so the condenser requires more heat to remove.

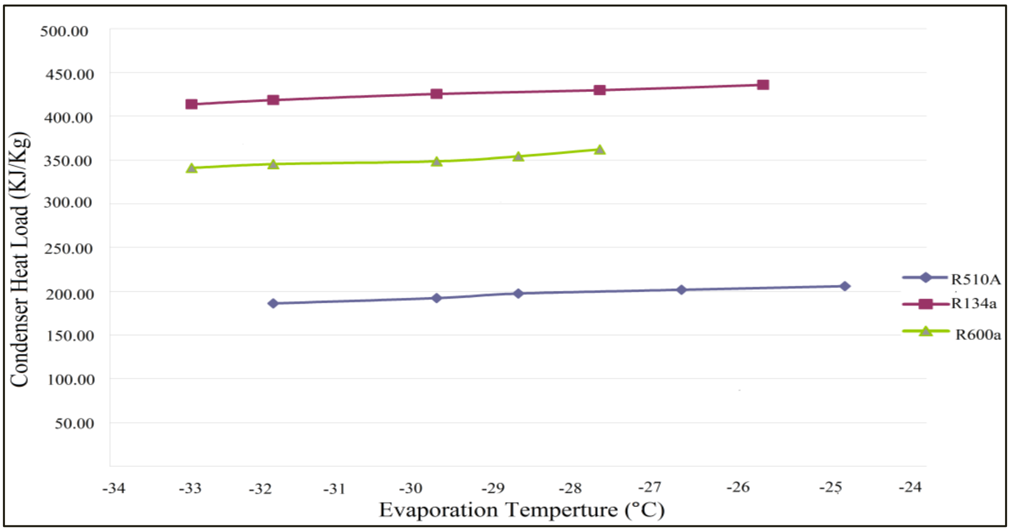

Fig. 4 Variation of condenser heat load with varying evaporator temperatures for R134a, R600a and R510A

4.4. *Effect of evaporating temperature on coefficient of Performance*

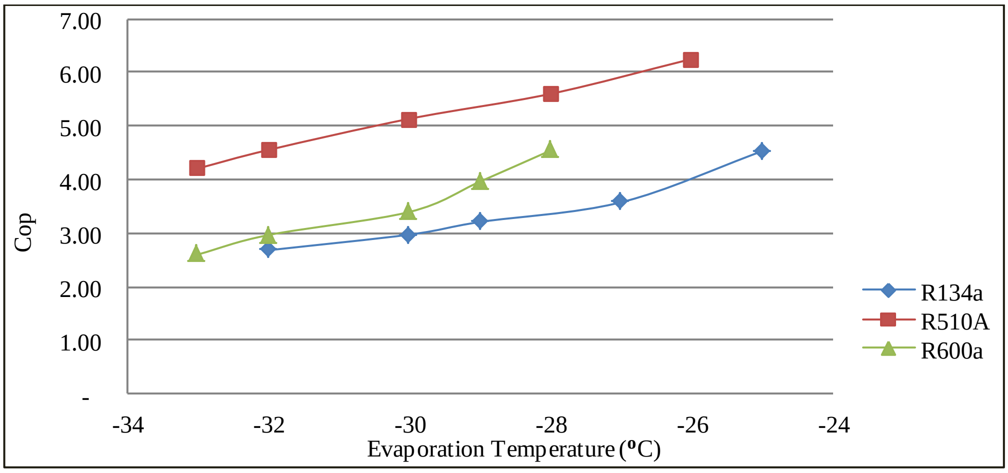

Fig. 5 Variation of coefficient of performance (COP) with varying evaporator temperatures for R134a, R600a and R510A

Fig. 5 shows the variation of coefficient of performance (COP) with varying evaporator temperature for the three refrigerants. As shown in this figure, the COP increases as evaporator temperature decreases. The COP is the ratio of the refrigerating effect to the compressor work. The increase in evaporating temperature increases the refrigerating effect and decreases the compressor work, therefore increases the COP of the refrigeration system. The COP of R510A is the highest with average values of 14.6 and 13.7% higher than those of R134a and R600a respectively.

4.5. Effect of evaporating temperature on refrigerating effect

The refrigerating effect is the main purposes of the refrigeration system. The liquid refrigerant at the low pressure side enters the evaporator. As the liquid refrigerant passes through the evaporator coil, it continually absorbs latent heat of vapourization at constant temperature through the coil walls, from the medium being cooled and turn to vapour refr igerant. The refrigerating effect is the difference between the enthalpies of the refrigerant in the inlet and the outlet of the evapo rator. The variation of refrigerating effect with the inlet evaporating temperature is shown in Fig. 6. From the figure it is evident that the refrigerating effect increases as the evaporating temperature increases. R134a has the lowest mean refrigerating effect. Average refrigerating effect obtained for R510A and R600a were 26.0 and 16.5% higher than that of R134a, respectively.

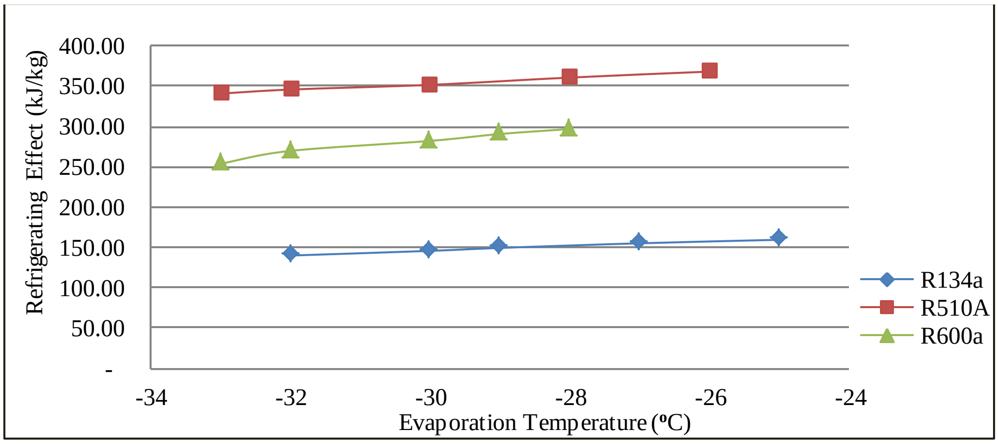

Fig. 6 Variation of refrigerating effect with varying evaporator temperatures for R134a, R600a and R510

5. Conclusion

Hydrocarbons are environmentally friendly. They have zero ozone Depletion Potential (ODP) and negligible Global Warming Potential (GWP). Hydrocarbon is cheaper than the R134a which is being used in the refrigerator at present. Hydrocarbon is also easily available. In this work the performances of three ozone friendly refrigerants, one hydro fluorocarbon (R134a) and two hydrocarbons (R510A and R600a) in a retrofitted existing vapour compression refrigeration system were investigated experimentally and compared. Based on the results obtained, the following conclusions are drawn:

(1) The coefficient of performance obtained for the two hydrocarbon refrigerants (R510a and R600a) were higher than that of baseline refrigerant (R134a)

(2) The average pressure of R510A and R600a are 13.4% and 10.2% lower than that of R134a respectively.

(3) The average compression work for R134a was 18.7% higher than that of R510A and R600a respectively.

(4) The average pressure ratio of R134a is higher than those of R510A and R600a by 4.2 and 6.2%, respectively.

(5) The condenser heat load increases as the evaporator temperature increases. R134a has the highest mean load. The mean heat load rates of R510A and R600a were 16.9 and 23.3% lower than that of R134a respectively

Generally, the two hydrocarbon refrigerants performed better than R134a and they can be used as retrofit substitutes for R134a in existing vapour compression refrigerating systems. The best performance was obtained from the use of R510A in the system.

References

[1] R. Kumar and R. Shekhar, "Performance analysis of vapour compression refrigeration system by using Azeotrops," International Journal for Scientific Research & Development, vol. 3, no. 4, pp. 255-267, 2015.

[2] F. Bill, and L. Duncan. "Chlorofluorocarbons (CFCs)," The Gale Encyclopedia of Science, http://link.galegroup.com/apps/doc/CV2644030480/SCIC?u=albertak12&xid=c35ecbf6, February 2018.

[3] B. O. Bolaji, A. O. Akintaro, O. J. Alamu, and T. M. A. Olayanju, "Design and performance evaluation of a cooler refrigerating system working with ozone friendly refrigerant," The Open Thermodynamics Journal, vol. 6, no. 1, pp. 25-32, 2012.

[4] A. B. Agrawal and V. Shrivastana, " Retrofitting of vapour compression refrigeration trainer by an eco-friendly refrigerant," Indian Journal of Science and Technology, vol. 3, no. 4, pp. 455-458, April 2010.

[5] Y. Kim, K. S. Chang, and H. Kim, "Thermodynamic performance analysis of vapour compression system using alternative refrigerants based on a cycle simulation program," Journal of Industrial Engineering Chemicals. vol. 13, no. 5, pp. 674-686, 2007.

[6] J. Fernandez-Seara, F. J. Uhia, R. Diz, and J. A. Dopazo, "Vapour condensation of R22 retrofit substitutes, R417A, R422A and R422D on CuNi turbo C tubes," International Journal of Refrigeration, vol. 33, no. 1, pp. 148-157, 2010.

[7] B. O. Bolaji, M. A. Akintunde, and T. O. Falade, "Comparative analysis of performance of Three-Ozone friends HFC refrigerants in a vapour compressor refrigerator," Journal of Sustainable Energy and Environment, vol. 2, pp. 61-64, 2011.

[8] D. Del Col, M. Azzolin, S. Bortolin, and C. Zilio, "Two phase pressure drop and condensation heat transfer of R32/R1234ze (E) non-azeotropic mixtures inside a single microchannel," Science and Technology for the Built Environment, vol. 21, no. 5, pp. 595-606, June 2015.

[9] B. O. Bolaji and Z. Huan, "Thermodynamic analysis of hydrocarbon refrigerants in a sub-cooling refrigeration system," Journal of Engineering Research, vol. 1, no. 1, pp. 317-3333, June 2013.

[10] Bitzer, Refrigerant Report, Bitzer International, www.bitzer.de, February 2018.

[11] E. W. Lemmon, M. O. Mclinden, and M. L. Huber, "NIST reference fluids thermodynamic and transport properties REFPROP 7.0," National Institute of Standards and Technology Standard Reference Database, vol. 7, 2002.