PERFORMANCE INVESTIGATION OF DOMESTIC REFRIGERATOR USING R600 AND LIQUEFIED PETROLEUM GAS

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ABSTRACT

This paper compares the performance of hydrocarbon refrigerant R600 with liquefied petroleum gas (LPG) in a one horse power vapour compression refrigerator. The refrigerator was equipped with type-T thermocouples and pressure gauges for the measurement of temperatures and pressures in the cycle of the refrigerator. The thermocouples were attached at the compressor suction, discharge, condenser outlet and at the evaporator inlet. The pressure gauges were installed at the discharge line and at the condenser exit for the measurement of high side pressures while another ones were installed at the suction line and the evaporator inlet for the measuring the low side pressures. The refrigerator was first charged to optimum capacity with the R600 and temperature and pressure readings were taken for 3 hours at 10 minutes interval. The same was done for the LPG after the refrigerator was allowed to sufficiently cool and purged of the R600 for the same time frame. The results showed that the refrigerator was charged to optimum capacity with 100g R600 while it was 50g for the LPG. The evaporator temperature for R600 was lower than that of LPG resulting in a higher compression discharge temperature than LPG. Higher refrigerating effect was obtained for R600 alongside an average coefficient of performance higher than LPG. Generally, the performance of R600 and LPG are quite similar but the overall best performance is obtained using R600. It is therefore concluded that R600 recorded a better performance because of its high latent heat as a single refrigerant. But the LPG being a mixture of hydrocarbon refrigerants with each component with its own latent made it register relatively a lower performance in the refrigerator.

Keywords: Performance, evaporator, domestic refrigerator, R600, Liquefied petroleum gas.

INTRODUCTION

The dual phenomena of ozone depletion and global warming are of global concern now. While the ozone depletion is caused by hydrocarbons containing some halogens especially chlorine and iodine, the global warming is a product of accumulation of products of the gases resulting from the activities of mankind of which the halogenated hydrocarbons are one. Refrigerants used in refrigeration and air conditioning sector have been proven to be partly and heavily responsible. As a result refrigerants belonging to chlorofluorocarbons (CFCs) class have been banned from use since 1996 through the clean air act (Najak, *et al*., 2017) as they have ozone depleting potential (ODP) as well as high global warming potential (GWP). A replacement for these refrigerants was the class of hydrofluorocarbons (HCFs). Of course, these new refrigerants do not deplete the ozone layer but have very high GWP and a result they were equally banned from use in this sector. There is therefore the need to search for globally recommended refrigerants with zero ODP and with GWP of not more than 150 as replacement to these refrigerants especially to replace R134a in mobile air conditioners and refrigerators since 2011 (Al-Sayyab, 2014). Hydrocarbon (HC) refrigerants are therefore found to meet up with these requirements especially in the vapour compression refrigeration system.

Refrigeration may be defined as lowering the temperature of an enclosed space by removing heat from the space transferring it elsewhere (Adeyemo, 2000). The vapour compression refrigeration system is an improved type of air refrigeration system in which a suitable working substance, the refrigerant is used. The refrigerant is a medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat elsewhere. The refrigerants used generally does not leave the system, but is circulated throughout the system alternately condensing and evaporating. In evaporating, the refrigerants absorbs its latent heat from the heat load and while condensing it gives out the latent heat to condensing medium, air or water. The vapour compression refrigeration system is nowadays used for most purpose refrigeration, especially in small domestic refrigerators (Ajeet and Salem, 2015).

A number of works have been reported in the area of hydrocarbon being used as a refrigerant in domestic refrigerators. Ajeet and Salem, (2015) conducted a study on performance evaluation of domestic refrigerator using a mixture of 24.4% propane, 56.4% butane and 17.2% isobutene as refrigerant. The result showed that 25g of the blend charged into the compressor performed better under no load condition when compared with 90g of R134a under same condition. Suresh *et al.,* (2016) compared the performance of a domestic refrigerator using R134a and R600a.The condenser of the refrigerator was replaced with a helical coiled condenser. They reported that the COP of R600a was higher when the coiled condenser was used than when the normal condenser was used. However the reverse was the case for R134a. Kharat *et al.,* (2018) conducted an experimental study of alternative refrigerants to replace R134a in a domestic refrigerator. The possibility of using hydrocarbon mixtures as working fluid to replace R134a was evaluated using simulation analysis because R134a was found to have significant increase in the world's greenhouse warming problem with high global warming potential (GWP). The simulation result showed that hydrocarbon refrigerants offer desirable environmental requirements such as zero ozone depletion potential (ODP) and approximately zero GWP. Oyedepo *et al.* (2017) carried out a comparative study on the performance of domestic refrigerator using R600a and liquefied petroleum gas (LPG) with varying refrigerant charge and capillary tube length. The enthalpy of the refrigerants R600a and LPG for each data set for the experimental conditions were obtained using REFPROP software (version 9.0). The result showed that the design temperature and pull down time set by ISO for a small refrigerator was achieved using refrigerant charge 60g of LPG with 1.5m capillary tube length. The highest coefficient of performance (COP) of 4.8 was obtained using 60g charge of LPG and 1.5m capillary tube length with average COP of 1.14% higher than that of R600a. Shrikant and Manish, (2016) carried out an experimental study of hydrocarbon blend of isobutane (R600a) and propane (R290) as an environment friendly refrigerant to replace convectional refrigerants (R134a) in a domestic refrigerator. With same system being used, the performance obtained was compared for both refrigerants and the result obtained showed that due to the high latent heat of hydrocarbons, the amount of refrigerant charge required reduced as compared with R134a. Also, the comparative performance study showed that the refrigerating effect improved when using hydrocarbon blend as there was a reduction of 35-40% in the refrigerant charge and 5-10% reduction in energy consumption per day. Sanjeev and Jagdev (2015) experimentally investigated the performance of coiled adiabatic capillary tube with LPG as refrigerant and concluded that an increase in the inner diameter resulted in an increase in the mass flow rate. A decrease in the coil diameter of the capillary tube also resulted in a decrease in the mass flow rate, whereas the mass flow rate decreased with an increase in length of the tube. He also observed that the COP of system increased with similar change in geometry of capillary tube.

Ashish and Amitesh, (2014) carried out performance analysis on vapour compression refrigeration system utilizing different refrigerants such as R134a and blend of 50% each of R290 (propane) and R600a (Isobutane). Performance measures like compressor discharge temperature, pressure ratio, mass flow-rate and volumetric efficiency were analyzed. The performance in terms of COP, refrigerating capacity and compressor work were evaluated for the different refrigerants at various evaporating and condensing temperatures. Their results showed that the system performance increased as the evaporating temperature increased and the COP for R134a was lower than the blend of R290 and R600a. Mohammed *et al.,* (2014) investigated the experimental study of isobutane (R600a) to replace R134a in a domestic refrigerator. A refrigerator designed to work with R134a was tested and its performance using R600a was evaluated and compared with that of R134a. The average COP using R600a was 27% higher than that of R134a respectively and the power consumption by compressor reduced by 3.7% with R600a refrigerant. The compressor on time ratio was lowered by 6.98% with R600a compared with R134a. The experimental result showed that R600a can be used as replacement for R134a in domestic refrigerator. Mohanraj *et al*. (2008) studied experimentally the drop-in substitute for R134a with the environment friendly energy efficient hydrocarbon (HC) mixture of 45% R290 and 55% R600a at various mass charges of 50g, 70g and 90g in a domestic refrigerator. The HC mixture, because of its high energy efficiency also reduced the indirect global warming. He concluded that HC mixture of 70g was found to be an effective alternative to R134a in 165 liters domestic refrigerator. Baskaran and Koshy, (2012) carried out performance evaluation on vapour compression refrigeration system using eco-friendly refrigerants of low global warming potential with the new R290/R600a refrigerant mixture as a substitute refrigerant for R12 and R134a. They discovered that R600a had a slightly higher coefficient of performance (COP) than R134a for the condensation temperature of 50 ^{o}C and evaporating temperatures ranging between -30 ^{o}C and 10 ^{o}C.

Fatouh and El Kafafy (2006) investigated a substitute for R134a in a single evaporator domestic refrigerator with a total volume of 0.283 m^3 with LPG comprising 60% propane and 40% commercial butane. The performance of the refrigerator test was conducted with different capillary lengths and different charges of R134a and LPG. Experimental results of the refrigerator using LPG of 60g and capillary tube length were compared with those using R134a of 100g and capillary tube length of 4m. They reported that the COP of LPG refrigerator was 7.6% higher than that of R134a. Wongwises and Chimmres, (2005) also investigated a substitute for R134a in a domestic refrigerator with hydrocarbon mixtures of propane (R290), butane (R600) and Isobutene (R600a). The experiments were conducted with the refrigerants under the same no load condition at a surrounding temperature of 25 ^{o}C. The results showed that 60% R290 with 40% R600 was the most suitable alternative refrigerant to R134a.

Therefore, the objective of this paper is to compare the performance of a refrigerator using R600 and LPG refrigerant mixture.

Theory of operation of a vapour compression refrigeration system (VCRS)

This is explained through thermodynamic analysis of VCRS using the P-h and T-s diagrams as shown in Figures 1a and 1b respectively.

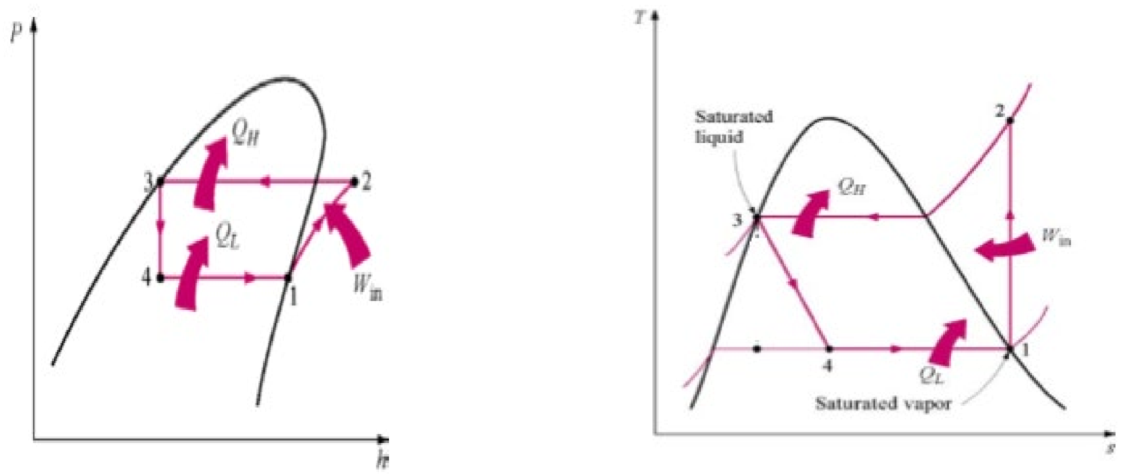

Figure 1: P-h and T-s diagram of a vapour compression refrigeration system

From the P-h and T-S diagrams for a simple vapour compression refrigeration cycle shown in Figure 1, (Cengel and Boles, 1998), refrigerant (in vapour form) entering the compressor is in dry saturation condition. The dry and saturated vapour entering the compressor at point 1 compresses isentropically from point 1 to 2 which increases the pressure from the evaporator pressure to condenser pressure. At point 2 the superheated vapour enters the condenser where heat is rejected at constant pressure, due to heat rejection, firstly there is de-superheating and then change of phase takes place as latent heat is removed. The high pressure liquid refrigerant from the condenser then flows through the expansion valve where it is throttled keeping the enthalpy constant and reducing the pressure and temperature.

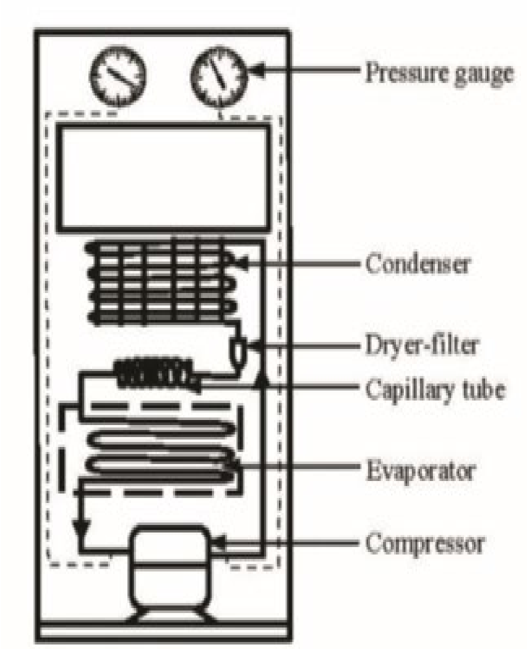

Figure 2: A schematic diagram of the domestic refrigerator

The composition and properties of R600 and that of a typical LPG is as shown in Table 1 (Eric, 2019)

Table 1:Refrigerant Property (Eric, 2019)

Properties	R600	LPG
Chemical formula	C_4H_{10}	C_3H_8 or C_4H_{10}
Chemical name	Butane	Propane and/or Butane
Molecular mass	58.12 g.mol^{-1}	44.097 or 58.12 g.mol^{-1}
Appearance	Colourless gas	Colourless gas
Density	2.48 kg/m^3 (at 15 ^{O}C)	1.89 kg/m^3 (at 15 ^{O}C)
Melting point	-140 to -134 ^{o}C	-188 ^{o}C
Boiling point	-1 to 1 ^{o}C	-42 ^{o}C to -0.4 ^{o}C
Ozone depletion potential	0	0
Global warming potential	4.0	4.0

MATERIALS AND METHODS

The materials used for the experiment are a vapour compression refrigerator which was designed and constructed incorporating all the components parts of compressor, condenser, expansion device (capillary tube) and the evaporator, four pressure gauges for measuring pressures at the high and low sides respectively, type- t thermocouples and a data logger. Other materials include LPG as a refrigerant mixture and R600.

The constructed vapour compression refrigerator with dimensions 440*510*640 mm^3 is shown in Plate 1. Its external structure is made of mild steel, inner structure of aluminum and polystyrene as the insulation material. It also has a reciprocating compressor, air-cooled condenser, plate evaporator and capillary tube as the expansion valve. The refrigerator was instrumented with four pressure gauges with two at the hot side (at compressor discharge and at condenser exit) and the other two at the cold side of the refrigerator (at evaporator inlet and at compressor suction) measuring the discharge and condenser pressures, and the capillary and evaporator pressures respectively. The test rig was thoroughly checked and commissioned before it was used for the experiment.

Plate 1: The Vapour Compression Refrigerator

The refrigerants were charged into the system manually. The refrigerator was first charged with R600 until it attained optimum charging capacity with 100g of R600. Type-T thermocouples were installed to measure the temperature at inlet and outlet of the evaporator and outlet of the compressor and condenser. Readings were taken three times for each value of pressure and temperature using a data logger with an accuracy of ± 0.02 for three hours at ten minute interval. Thereafter, the system was purged and cooled before being charged with liquefied petroleum gas (LPG). The system was charged optimally with 50g LPG. The experiment was carried out at an average ambient temperature of 31 ^{o}C for the same period of time as it was done when R600 was used.

The data obtained were used to calculate work done (W) by the compressor, the refrigerating effect (R_E) and COP of the refrigerator using equations (1), (2) and (3) respectively.

$$\text{Compressor Work done, } W = (h_2 - h_1) \text{ kJ/kg} \quad (1)$$

$$\text{Refrigerating effect Per kg, } R_E = (h_1 - h_4) \text{ kJ/kg} \quad (2)$$

where,
h_1 is Specific Enthalpy at the inlet of compressor (kJ/kg)
h_2 is Specific Enthalpy at the outlet of compressor (kJ/kg)
h_3 is Specific Enthalpy at the outlet of condenser (kJ/kg)
h_4 is Specific Enthalpy at the inlet of evaporator (kJ/kg)

$$COP = \frac{\text{Refrigerating effect}}{\text{Compressor work done}} \quad (3)$$

The pressure ratio was determined using equation (4) (Bolaji *et al.,* 2017)

$$\text{Pressure ratio} = \frac{\text{Discharge pressure}}{\text{Suction pressure}} \quad (4)$$

RESULTS AND DISCUSSION

The optimum charging of the refrigerator was achieved with 100g charge for R600 and 50g with LPG.

The effect of time on the evaporator temperature for R600 and LPG is as shown in Figure 3. From the graph, evaporator temperature decreased with time for both refrigerants but R600 had a lower evaporator temperature than LPG. This may be as a result of R600 being a single gas, refined and easily compressed giving it a reason to absorb more latent heat during expansion but LPG been a mixture of gases in which some may not be easily compressed and so absorbed less latent heat during exapansion.

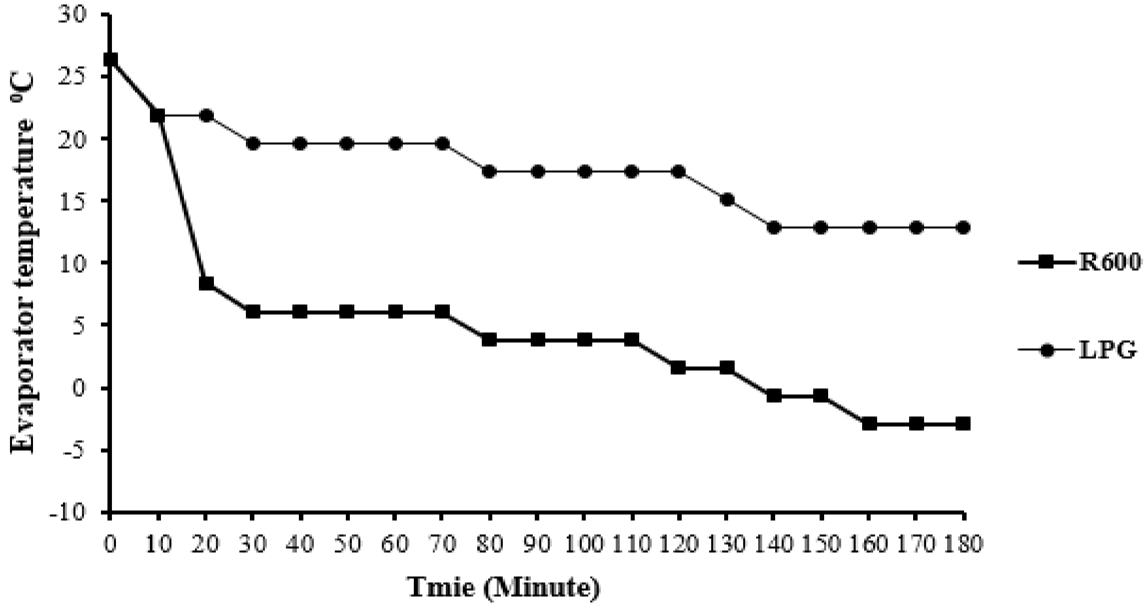

Figure 3: Effect of time on evaporator temperature for R600 and LPG

Figure 4 shows the behaviour of the compressor discharge temperatures with time. The graphs indicate that the compressor discharge temperatures for both refrigerants increased with time at the initial start of the refrigerator, and then later attained a constant value. R600 has a higher compressor discharge temperature than LPG because its evaporator temperature was lower. When the evaporator is low, the compressor must compress the refrigerant from this low evaporator pressure to the condensing temperature. This added work of compression would make the heat of compression higher, thus the compressor discharge temperature will be higher.This result agrees with Ijabiken, (2017) in the development of a refrigerator system for the storage of perishable food items that the compressor discharge temperature increases over time which also results in an increase in compression work.

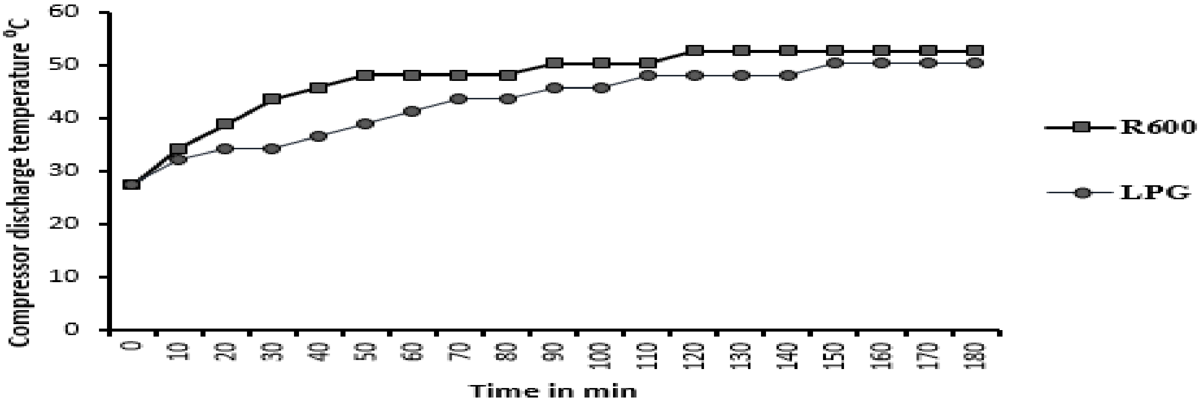

Figure 4: Effect of time on the compressor discharge temperature for R600 and LPG

Figure 5, shows the effect of evaporator temperature on the compressor work on the system for both R600 and LPG. The graph depicts that the compressor work reduced as evaporator temperature increased and this is as a result of less work done on the refrigerant thereby increasing the latent heat vaporization. This result agrees with Baskaran and Koshy, (2012) in a performance comparison of vapour compression refrigeration system using eco-friendly refrigerants of low global warming potential and Shoyab, (2015) in improvement of COP in vapour compression cycle with change in evaporator and condenser pressure that the compressor work decreased as the evaporating temperature increased.

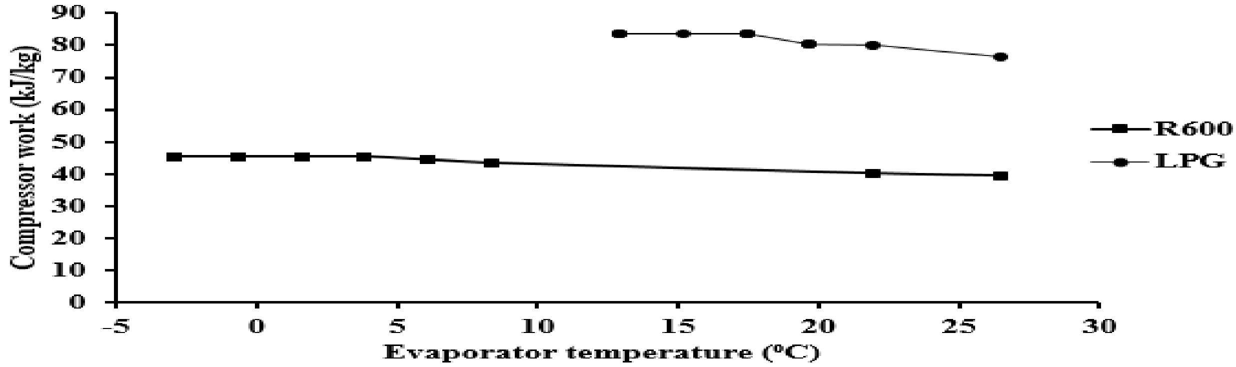

Figure 5: Effect of evaporator temperature on the compressor work for R600 and LPG

Figure 6, shows the effect of evaporator temperature on pressure ratio for R600 and LPG. From the graph, pressure ratio reduces as evaporator temperature increases. This is because an increase in the evaporator temperature increases the temperature of the refrigerant vapour before entering the compressor as a result reducing its compressor work while simutaneously reducing its pressure ratio. This agrees with Bolaji, (2014) in performance study of the eco-friendly hydrofluorolefins and dimethyl-ether refrigerants in refrigeration systems that the pressure ratio for the refrigerants investigated reduced with increase in evaporating temperature. Also, Sarthak, (2017) in performance analysis of a domestic refrigerator using various alternative refrigerants that the compression ratio increase with decrease the evaporator temperature. It equally greed with the work of Bolaji, *et al.* (2017).

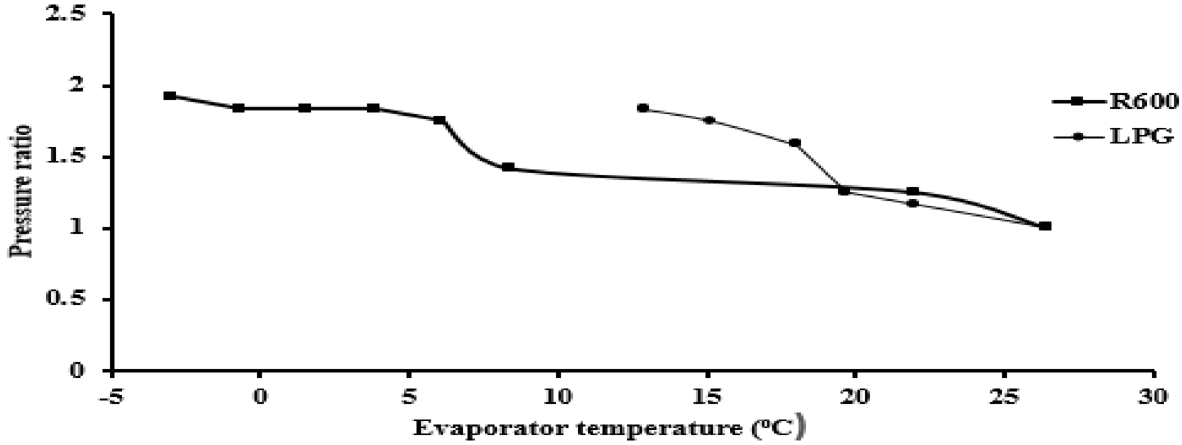

Figure 6: Effect of evaporator temperature on pressure ratio for R600 and LPG

Figure 7, shows the influence of evaporator temperature on the refrigerating effect for both R600 and LPG. From the graphs, the refrigerating effect increases as the evaporating temperature increases for both R600 and LPG. This is in agreement with the work of Raiyan *et al.,* (2017). The latent heat of refrigerant increases as its evaporating temperature increases; hence, the refrigerating effect increases. This results agrees with Bolaji. (2014) in performance study of the eco-friendly hydrofluorolefins and dimethyl-ether refrigerants in refrigeration systems and Sarthak, (2017) in performance analysis of a domestic refrigerator using various alternative refrigerants that refrigerating effect increases as the evaporator temperature increases.

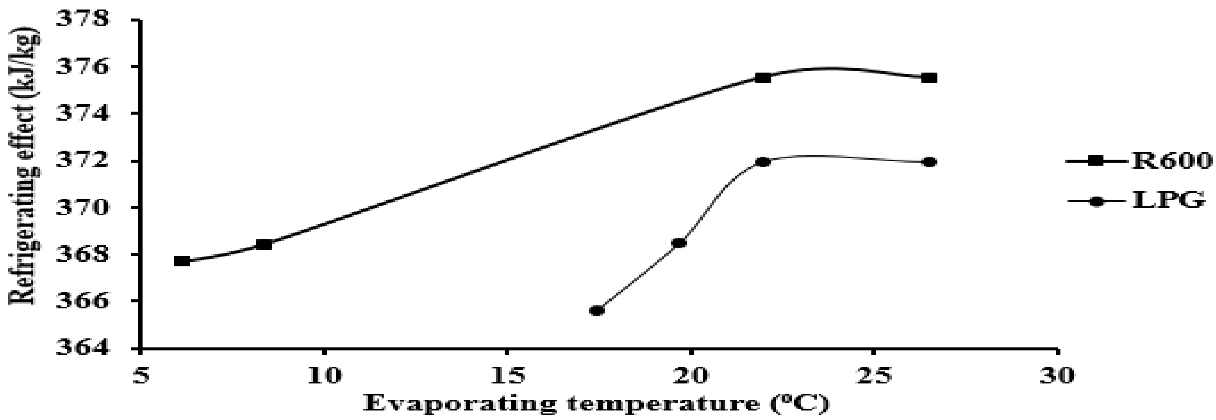

Figure 7: Influence of evaporator temperature on the refrigerating effect for R600 and LPG

Figure 8, shows the variation of coefficient of performance (COP) with evaporator temperature for R600 and LPG. From the graph, COP increased as evaporating temperature increases and an increase in the evaporator temperature of the system increases the COP by reducing the compression ratio. This is because the required compression power to ascertain cooiling capacity reduces as the evaporator temperature increases hence leading to an increase in COP. This agrees with Kharagpur, (2008) in refrigeration and air-conditioing and Bolaji, (2014) in performance study of the eco-friendly hydrofluorolefins and dimethyl-ether refrigerants in refrigeration systems that COP of the system increases with increase in evaporating temperature. Also Sarthak, (2017) in performance analysis of a domestic refrigerator using various alternative refrigerants confirms that COP decrease as the evaporator temperature is decreased. This is in agreement with the first law effeiciency that COP will increase as the evaporating temperature increases (Mishra, 2019).

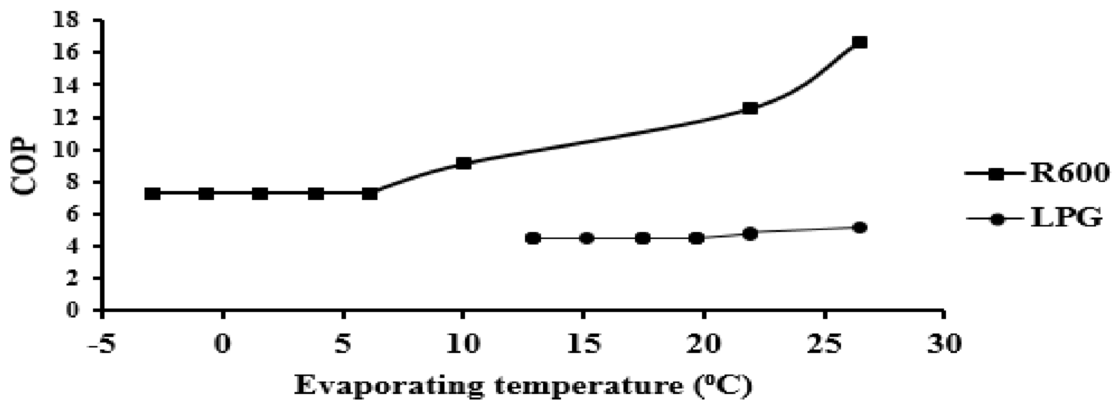

Figure 8: Variation of coefficient of performance with evaporator temperature for LPG and R600 at no load condition.

CONCLUSION

Based on the investigation carried out on the performance analysis of R600 and LPG, the results show that the evaporator temperature for R600 was lower than that of LPG resulting in a higher compression discharge temperature than LPG. A higher refrigerating effect was obtained for R600 and alongside a higher coefficient of performance than LPG. Generally, the performance of the refrigerator with R600 and LPG are quite similar but its overall best performance is obtained using R600.

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