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Experimental analysis of the performance characteristic of an eco-friendly HC600a as a retrofitting refrigerant in a thermal system

***[1]S.O. Banjo, [2]B.O. Bolaji, [3]I. Osagie, [1]O.S.I. Fayomi, [4]O.B. Fakehinde, [4]P.S. Olayiwola, [1]S.O. Oyedepo, [1]N. E. Udoye**

[1]Mechanical Engineering Department, Covenant University, P.M.B. 1023, Ota, Nigeria
[2]Mechanical Engineering Department, Federal University, Oye-Ekiti, Nigeria
[3]Nigerian Building and Road Research Institute (NBRRI), Km 10 Idiroko Road, Ota, Ogun State, Nigeria
[4]Mechanical and Biomedical Department, Bells University of Technology, Ota, Ogun State, Nigeria.
Corresponding Author: Solomon.banjo@covenantuniversity.edu.ng

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Abstract
The negative influence of refrigerants on the climate and the immediate environment in terms of their higher global warming potential (GWP) and ozone depletion potential (ODP) has prompted this study. Currently, natural refrigerants are the preferred alternative refrigerants and hydrocarbon is numbered among these natural refrigerants with zero ODP and negligible GWP. In order to improve and enhance the performance of the refrigeration system, the performance characteristics of the system were investigated experimentally using eco-friendly refrigerant HC600a as alternative to HFC134a. In addition, comparisons were made using refrigerant mass charge of 46 g of isobutane (HC600a) and 70 g of conventional refrigerant (HFC134a). Thermodynamic parametric analysis was conducted using electric power consumption, coefficient of performance (COP), cooling load and pull-down time (PDT) for the used mass charges. REFPROP software was applied to capture the thermodynamic properties of the vapour compression system (VCS). The results showed that the COP increased by 32.2 % when using 46g charge of hydrocarbon refrigerant with energy reduction of 4.5 %. Furthermore, the vapour compression system while using 46 g of isobutane (HC600a) attained an evaporating temperature of -21 ^{o}C in 60 minutes while 70 g of HFC134a attained the same temperature in 2 hours 15 minutes, which makes HC600a alternative refrigerant to run in the traditional refrigerator.

1. Introduction
In the early eighteenth century, natural ice was harnessed, circulated and employed for domestic and commercial purposes, such as food preservation. There was also, a discovery in the 1800s that the same volatile liquids could be condensed by application of compression and cooling [1]. The combination of these two innovations that result in the development of the traditional refrigeration system (TRS), which has turned to a renowned application worldwide. Since, nineteen centuries when the vapour compression refrigeration system have been invented, its practical application has cut across many field which include, preservation of food and vaccine, industrial processing, heat ventilation and air-conditioning (HVAC) for the purpose of human comfort and preservation of other farm produce. Preservation became necessary to extend the shelf life of product which enhances the quality in terms of property that include flavour, colour, and texture. In addition,

among other techniques of food preservation, refrigeration process has been the most effective, desirable, dependable and applicable at all level in the developing and developed countries [2-5]. However, due to the presence of impending energy, there is need to develop thermal and environmental friendly systems, which will suit the 21st century technology in terms of energy efficiency and coefficient of performance enhancement. Over two decades, thermal systems have found increase application in the tropical region and they consumed enormous amount of electric power [6]. Different from the issue of excessive energy consumption, the effect of refrigerants on the domestic refrigeration system cannot be overemphasized, the Kyoto Protocol and Montreal protocol have placed a ban on pure fluids that have high global warming potential (GWP) and ozone depletion potential (ODP). Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) possess excellent thermodynamic properties, non-flammability, material compatibility and non-toxic which have enables them to be widely used both at the domestic and commercial purpose across the continents. Although, CFC has been phased out since 1996 in most of the developed nations while HCFCs is meant to be phased out in the developed and developing countries between the year 2020 and 2030 respectively [7-8]. The result from various researches show the depletion of ozone layer due to the presence of fluorine in some classes of chemicals, which isolate the ozone from the atmosphere [9-11].

Since the discovery of the damage that CFCs and HCFCs refrigerant causes on the environment and climate, the American Household Manufacturers have recommended HFC134a as a potential alternative refrigerant for CFCs refrigerant in traditional refrigerators but over period of time, HFC134a refrigerant was found to have high global warming potential (GWP) of 1430 due to the presence of fluorine content in the compound [12-14].

The organic refrigerant has been in use since mid-1800s all through to 1930s, due to its eco-friendly behaviour on the immediate environment, miscibility with mineral oil and high energy efficient. Natural refrigerants are currently the preferred alternative refrigerants and hydrocarbon refrigerant is numbered among those refrigerants with zero ozone depletion potential and negligible global warming potential (GWP). The major success of hydrocarbon refrigerant is to use them in fully closed systems of relatively low mass charge. Isobutane (HC600a) began to attain high level of recognition in 1990s and now being taken as the alternative refrigerant to halocarbon refrigerants in different engineering applications such as venting machine, traditional refrigerator, deep freezer, industrial refrigeration system, mining, cold storage and water dispenser [15-16]. They perform excellently in practice due to its thermodynamic properties resulting in high energy efficiency, good compatibility with the elastomer materials found in refrigeration system [17-18], relatively high critical temperature, which tend to make them efficient in operation [19]

This study is focused on improving the refrigerating effect, reduce the global warming potential and energy consumption of the system using hydrocarbon refrigerant (isobutane) as replacement to halogenated refrigerant (hydrofluorocarbon) in a domestic refrigeration system.

2. Methodology

The system has some essential components through which the thermodynamic properties of the refrigerant were measured using various mechanical devices. This includes single hermetic compressor, evaporator, standard parallel tube condenser and capillary tube for the refrigeration cycle as shown in Figure 1. Furthermore, temperature sensors were connected to each of the cardinal points of the refrigeration system to measure their temperatures at an interval of 15 minutes for a period of 5 hours. The experiment was conducted by charging the system with 70 g of R134a refrigerant and it was allowed to run for a period of 5 hours. The corresponding values for each of the segment was taken after 15 minutes by the mechanical measuring devices (Type-K digital thermocouple) attached to the system. After series of experiments, the average values of the accumulated data were used to process the performance characteristics of the refrigerator. The same system was used to carry out similar test but the compressor was now charged with 46 g of isobutane (R600a) after retrofitting. The mass charge of isobutane (HC600a) was smaller compared with HF134a due its high volumetric capacity or higher value of latent heat. In order to improve the performance and increase the refrigerating effect of the system, different refrigerant mass charge of HC134a and HC600a refrigerants were examined. Performance analysis was carried out on the system to establish the coefficient of performance (COP), refrigerating effect (R.E) and power consumption under the same ambient temperature of 28 ºC. The refrigerant charge into the system was made possible using digital weighing balance. Two valves were connected to the pressure lines in order to measure the suction and discharge pressures. Furthermore, the vapour compression system was retrofitted and some components of the system were altered such as the compressor, mineral oil, capillary tube and dryer so as accommodate the new configuration. In the process, vacuum pump was introduced intermittently to trap the gas and moisture content within the system to prevent clogging. The system was thoroughly checked for leakage using digital halogen leakage detector and commissioned, in the refrigeration and air conditioning laboratory.

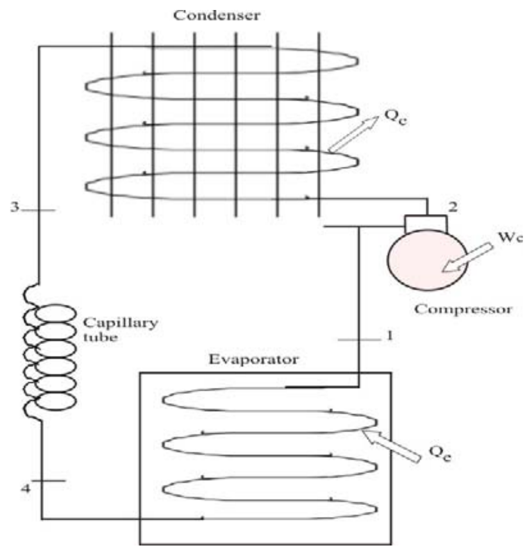

Fig. 1: Refrigeration cycle

The following expression explain the relationship between the input and output of a refrigeration system. The available of the pure substance can be defined by equation (1) to (6).

Heat absorbed in the evaporator
$Q_e = \dot{m}(he_1 - he_4)$ in kW (1)
Where, Q_e = heat of evaporator, he_1 = enthalpy of vapor existing evaporator in kJ/kg and he_4 = enthalpy of a cooled refrigerant entering evaporator in kJ/kg.

Compressor Work

$$W_c = \dot{m}(hc_2 - hc_1) \quad (2)$$

Where, W_c = Compression Work input, hc_2 = enthalpy of vapour exiting compressor in kJ/kg and hc_1= enthalpy of vapour entering compressor in kJ/kg.

Coefficient of Performance

$$COP = \frac{\dot{m}(he_1 - he_4)}{\dot{m}(hc_2 - hc_1)} \quad (3)$$

Where, COP = coefficient of performance, Q_e= heat of evaporator in kJ/kg and W_c = Compressor work done in kJ/kg, in = mass flow rate of the refrigerant in kg/s.

Refrigerating Effect

$$R.E = COP \cdot W_c \quad (4)$$

Where, $R.E$ = Refrigerating Effect, COP = coefficient of performance, W_c = compressor work done on the working fluid.

Heat rejected by condenser

$$hcond = \dot{m}(hc_2 - hc_3) \quad (5)$$

Where, h_{cond} = heat of condenser, hc_2 = enthalpy of vapour entering condenser in kJ/kg and hc_3 = enthalpy of subcooled refrigerant exiting condenser in kJ/kg.

Refrigerant mass flow rate

The refrigeration system mass flow rate is defined as the ratio of the refrigerating effect to the enthalpy change in the evaporator.

$$\textit{Mass flow rate } (\dot{m}) = \frac{cooling\ load}{he_1 - he_4} \quad \text{in kg/s} \quad (6)$$

3. Result and Discussions

Figure 2: shows the variation of coefficient of performance (COP) with time of a vapour compression system (VCS). The system COPs when working with 46 g of HC600a was 32.2 % higher than the system when working with 70 g of HFC134a refrigerant. The system had its lowest COP to be 5.4 when working with refrigerant charge of 70 g and the domestic refrigerator was at its best performance when working with 46 g of HC600a.

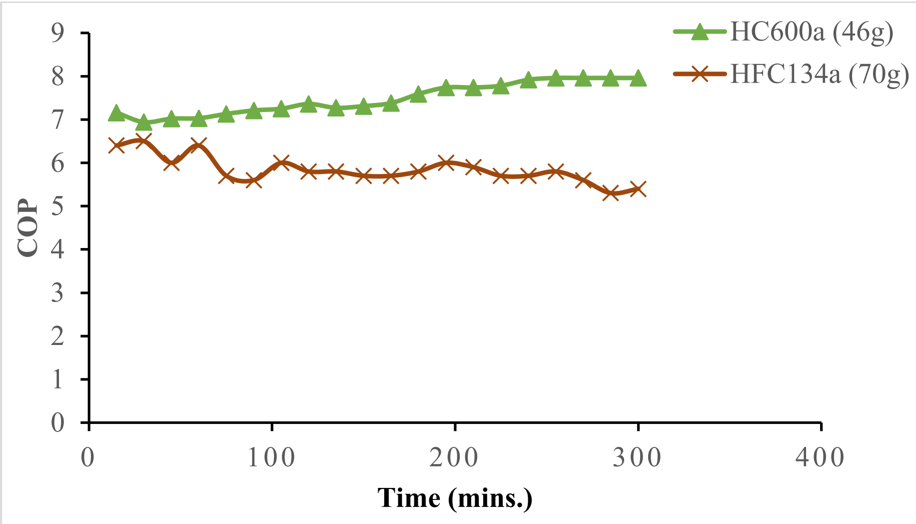

Fig. 2: Variation of coefficient of performance with time

Figure 3 shows the comparison of energy consumption by the traditional refrigeration system when working with 46 and 70 g refrigerant mass charge of HC600a and HFC134a respectively. The energy consumption was reduced by 4.5 % when the system worked with HC600a refrigerant. And this made 46 g refrigerant charge to be cost efficient than when the system worked with 70 g charge of HFC134a refrigerant.

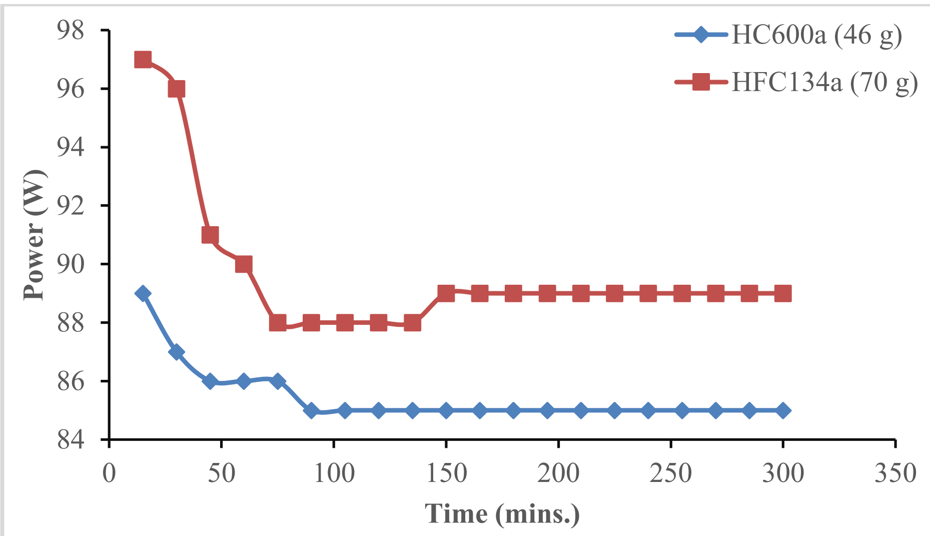

Fig.3: Variation of electric power consumption with time

Figure 4 displays heat transfer within the condenser when the system worked with refrigerant mass charge of 46 g HC600a and 70 g HFC134a. The refrigeration system when running with 46 g of HC600a refrigerant had increase of 12.8 % over the same system working with 70 g of HFC134a refrigerant. The rate of heat rejection at the condenser enhances the sub cooled state of the system which in turn improve the performance of the refrigerator [20].

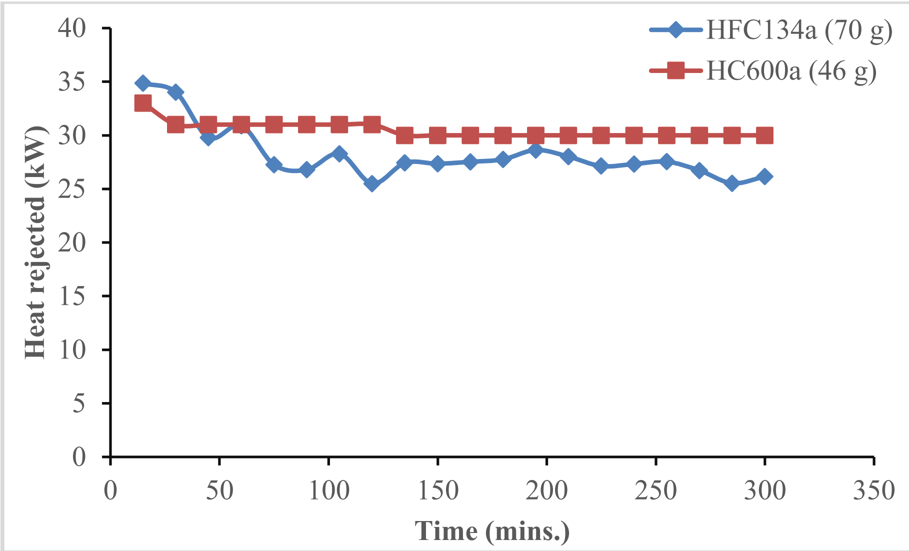

Fig.4: Variation of heat rejected by condenser with time

Figure 5 shows the pull-down time (PDT) of the system when working with 46 and 70 g refrigerant charges of HC600a and HFC134a accordingly and it was deduced that the domestic refrigeration system attained its PDT of -21 °C in 1 hour (60 minutes) while working with 46 g of HC600a refrigerant charge against 70 g of HFC134a which was -21 °C in 2 hours 15 minutes. This had made the refrigerator with the PDT of -21 °C in 1 hour to performance better and conserved energy than when the system had -21 °C in 2 hours 15 minutes using 70 g refrigerant charge.

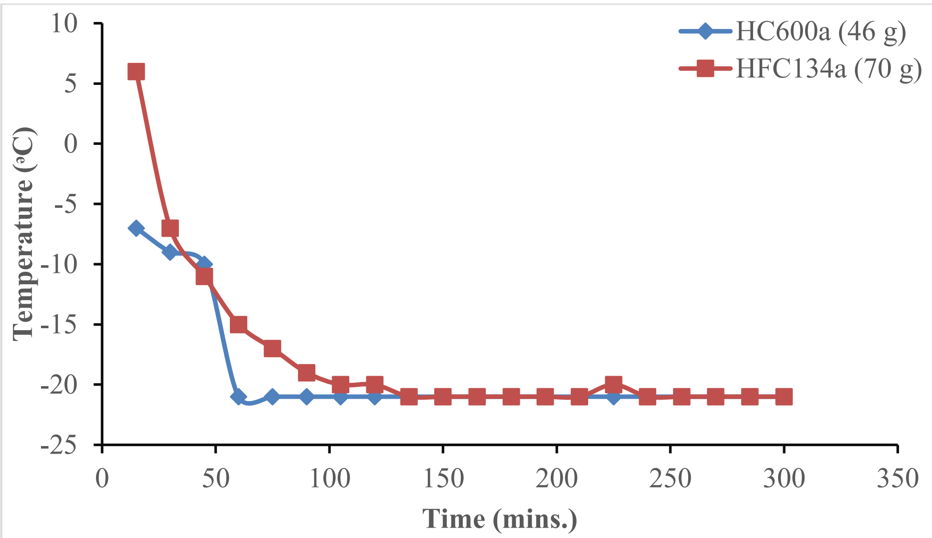

Fig. 5: Variation of pull-down time of HC600a (46 g) and HFC134a (70 g)

4. Conclusion

In this study, the comparison of performance characteristics of chosen refrigerants and their global impact on the climate, energy efficient and heat transfer was analyzed. Primarily, this evaluation involved the critical examination of the effect of different refrigerants on the vapour compression refrigeration system (VCRS) under the same local ambient temperature. Experimental test was conducted using hydro-chlorofluorocarbon and hydrocarbon refrigerants. The following results were obtained during the processes in the refrigeration cycle.

The energy conservation rate was improved with isobutane refrigerant (HC600a) and this serves as one of the parameters to justify isobutane as the best alternative refrigerant to convectional refrigerant (HFC134a). The pull-down time is the time required for a refrigeration system to attain its minimum evaporating temperature. Furthermore, pull-down time (PDT) of HC600a refrigerant was better than HFC134a refrigerant. More so, the average COP over the entire period of the 46 g HC600a refrigerant mass charge was higher compared to the convectional refrigerant (HFC134a).

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