Experimental Investigation of Low Global Warming Potential Refrigerant Blends in Domestic Vapor Compression Refrigeration System.

M.E. Uwadiae, M.Eng.; M.A. Akintunde, Ph.D.; and T.I. Ogedengbe, Ph.D.

Department of Mechanical Engineering, Federal University of Technology, Akure, Nigeria.

E-mail: tioged@yahoo.com

ABSTRACT

The refrigeration industry today needs refrigerants with global warming potential (GWP) ≤ 150 according to the European Union protocol, alongside other guidelines, which no single refrigerant has met as at today. This study focus on blending of existing refrigerants towards obtaining blends with GWP ≤ 150. This paper investigated the performance of blends of two existing refrigerant, R-134a and R-600a, blended together at ratios of 11%/89%, 7.5%/92.5% and 3.6%/96.4% to form blends K, L, and M, respectively. The blends were to have, according to the blending ratios, estimated GWPs ≤ 150 using Ali's model.

The blends flammability was tested and the blends were then charged into domestic vapor compression systems, where there operating temperatures and pressures were obtained every 5 minutes during the experimentation. The flammability test shows they are flammable while results obtained at ambient temperatures (37^{o}C, 32^{o}C) under same operating conditions indicated evaporator temperatures (7.7^{o}C, -3.1^{o}C, -3.7^{o}C, -4.7^{o}C, -5.3^{o}C); (6.2^{o}C, -3^{o}C, -4^{o}C, -4.8^{o}C, -6.5^{o}C) for R-134a, K, L, M, and R-600a, respectively. Also the analysis gave corresponding average Coefficient of Performance (COP) of (0.8389, 1.0708, 1.0898, 1.1181, and 1.1373) and (0.8283, 1.0923, 1.1254, 1.1579 and 1.2159) for the aforementioned respective refrigerants at an ambient temperature of 32^{o}C and 37^{o}C, respectively. Thus, the blends can replace R-134a without changing pipe, cooling method and lubricants and still obtain higher COP, though mildly flammable. That blend K offers significant improvement in flammability compared to R-600a alongside higher COP to R-134a, making it the best alternative of the blends.

(Keyword: coefficient of performance, COP, vapor compression refrigeration system, flammability, global warming potential, GWP, refrigerant, refrigerant blend)

INTRODUCTION

Refrigeration is the extraction of heat from a low temperature body to that of higher temperature [1]. This is possible due to the evaporation of a working fluid known as refrigerant flowing through sequentially arranged mechanical components forming a refrigeration system [2]. The refrigerant plays the vital role of heat circulation in a refrigeration system and it forms the bed rock of the industry [3].

Different refrigerants have been developed due to various developmental challenges untill the present threat of GWP, prompting the need of a new refrigerant of GWP≤150. Refrigerants having GWP>150 form a shield reflecting excess ultra-violet rays to the Earth, thus, increasing its temperature [4]. The difficulty of finding a single chemical refrigerant that can satisfy the required GWP has led to blend formation [5, 6]. The research objective is to develop a refrigerant blend of GWP≤150 and experimentally observe its performance in a domestic vapor compression refrigerating system if it is worthy of replacing R-134a whose shortcoming is its high GWP.

The Earth's temperature is controlled by the amount of solar energy received and reflected [4]. Smoke and other emissions resulting from carbon-based fuel have led to increases in health hazards and Earth's temperature among others issues. Researchers have made several efforts to improve the situation through renewable fuels and stoves [7, 8]. However, greenhouse gases, refrigerants inclusive, have been found to reflect rays to the Earth, thus, increasing its temperature.

To prevent this rise in temperature capable of making the Earth uninhabitable, the European Union has propose a ban of refrigerants having GWP>150 [9]. Though several refrigerants (non-synthetic and synthetic) have GWP<150, they are either flammable, toxic, ozone depletive, or have high operating pressures, hence, the need for a new refrigerant. The difficulty of finding a single chemical refrigerant devoid of these limitations, has led to blend consideration; as new refrigerants of desired properties can be developed by mixing two or more single refrigerants [10, 11]. This has since formed a pathway in the search of that ideal refrigerant for the replacement of R-134a, being the predominant refrigerant use in the domestic refrigeration industry even though R-22 is still been used [12].

Wongwise and Chimres [13] reported an experimental study on the application of a mixture of propane, butane, and isobutene to replace R-134a. The results showed that a 60%/40% propane/butane mixture was the most appropriate alternative refrigerant. Also, Wongwise et al. [14] presented an experimental study on the application of HC mixture, to replace R-134a and they found that propane/butane/isobutene at 50%/40%/10% was the best alternative refrigerant to replace it.

A trial was also made by Khorshid et al. [15] to replace R–134a by two different blends: one as R–134a (6.61%), R–32 (5.64%) and R–152a (87.75%); and the other as R–32 (15.34%), R–600a (8.79%) and R–152a (75.87%). The results of the test shows that COP improved by 11.93% and 2.07% using the former and latter respectively as compared with R–134a; with the new refrigerant blends having zero ozone depletion potential (ODP) and low GWP of the order of 242 and 200 respectively. Austin et al. [16] investigated a propane-butane mixture and found that the refrigerator worked efficiently when mixed refrigerant was used as refrigerant instead of R-134a.

Analysis of the above researches shows that though performance is enhanced, the resulted blends are either highly flammable or they have GWP exceeding the preferred optimum, thus, prohibiting their usage as define by the European Union. Therefore, the focus of this study is on developing a blend within the preferred GWP limit and considering its performance in the system. The Ali [17] model for estimating the GWP of blend when those of the individual refrigerants are known could be used to determine the ratio that will form a blend within the European Union's GWP limits. Since blends of HFC and HC has been reported to produce new refrigerant capable of overcoming their shortcomings of high GWP and flammability [11], R-134a and R-600a were selected for having better non-flammability and low GWP, respectively. Subsequently, three blends label K, L, and M with respective GWP of 150, 100, and 50 were formed, had their flammability tested and their performance investigated in a domestic vapor compression system.

METHODOLOGY

The steps adopted in developing and investigating the blend are given as follows:

(a) Selection of the Individual Refrigerant making the Blend

Blending HFC and HC usually produce new refrigerant overcoming their shortcoming of GWP and flammability respectively. The idea therefore, is to select an HFC refrigerant having good thermodynamic and thermo-physical properties, non-flammable, non-toxic and low GWP; and an HC refrigerant with low flammability to form the blend. With alkane, which is less flammable among the HC, and in its series and flammability reducing down the group, butane was selected among its first four members, which are refrigerant gases.

In the case of the HFC, Table 2 shows R-152a and R-32 have lower GWP but aside their mild flammability (being A2, as classify by ASHARE), their toxicity either in themselves or when combined with air during leakage makes them inconsiderable in this research since a domestic refrigeration system is to be used. Therefore, R-134a was considered, for its non-flammability; non-toxicity; and having the next lower GWP. The blend hence was a mixture of R-134a and R-600a. It is, assumed by this selection of R-134a and R-600a that the:

i. blend will have zero ozone depletion potential, since R-134a and R-600a are not ozone depleting substance couple with the non-presence of any ozone depleting atom; and

ii. blend will be non toxic as R-134a and R-600a are nontoxic.

(b) Determination of blends composition ratio, that ensures adherence to the preferred GWP limit:

Ali (2011), reported the model for the estimation of the GWP of refrigerant blend when those of its individual refrigerants are known as shown in Equation 1.

$$(GWP_1 \times M_1) + (GWP_2 \times M_2) = GWP_b \quad \textbf{(1)}$$

Where,

GWP_1 is the global warming potential of refrigerant 1,

GWP_2 is the global warming potential of refrigerant 2,

GWP_b is the global warming potential of refrigerant blend,

M_1 (%) is the mass percentage composition of refrigerant 1 in the blend, and

M_2 (%) is the mass percentage composition of refrigerant 2 in the blend.

Equation 1 was used to estimate the mass composition ratio. The GWP of the blend were chosen as 150, 100, and 50, with that of R-134a and R-600a as 1300 and 3, respectively, the composition ratio was estimated as follows:

Let (Q) be the mass composition of R-134a in the blend then, (1-Q) is the mass composition of R-600a

Therefore substituting the values into Eqn (1), we have:

For blend K: GWP = 150

$$(1300 \times Q) + \left(3 \times (1 - Q)\right) = 150$$

$$1300Q + 3 - 3Q = 150$$

$$1297Q = 147$$

$$Q = 0.11$$

Thus, the mass composition ratio is 11% R-134a and 89% R-600a;

For blend L: GWP = 100

$$(1300 \times Q) + \left(3 \times (1 - Q)\right) = 100$$

$$1300Q + 3 - 3Q = 100$$

$$1297Q = 97$$
$$Q = 0.075$$

Thus, the mass composition ratio is 7.5% R-134a and 92.5% R-600a;

and for blend M: GWP = 50

$$(1300 \times Q) + \left(3 \times (1 - Q)\right) = 50$$

$$1300Q + 3 - 3Q = 50$$

$$1297Q = 47$$

$$Q = 0.036$$

Thus, the mass composition ratio is 3.6% R-134a and 96.4% R-600a.

(c) Flammability test by ignition

Sample of the blends were allow to leak out of the cylinder into a flame and their flammability were observe.

(d) Determination of operating temperatures and pressure

The blends were charged into the compressor of the vapour compression refrigerating system and run, and the following parameters measured with the aid of thermometers and barometers:

i. evaporator temperature;
ii. condenser temperature; and
iii. compressor suction and discharge pressure which forms the operating pressure limit of the system.

(e) Evaluation of the coefficient of performance (COP)

The blend has no standard characteristic chart as at now, therefore, the values of the operating temperatures and pressure obtained earlier on were used to evaluate the coefficient of performance of the system, using the Carnot cycle efficiency formula given in Equation (2):

$$\text{Coefficient of Performance (COP)} = \frac{T_{condenser} - T_{evaporator}}{T_{condenser}} \quad (2)$$

Where,

$T_{condenser}$ is the temperature of the condenser, $T_{evaporator}$ is the temperature of the evaporator and (COP) is the coefficient of performance of the system.

Details of the Experimental Procedure

The required mass composition of blend K is 11% of R-134a and 89% of R-600a. In-order to achieve this, 1 kg of each of the refrigerant was purchased. The blend K was formed in an empty cylinder whose mass was measured as 2482 g, with the aid of a digital beam balance, by gradually injecting R-134a into the empty cylinder until 11% (110 g) of the 1 kg entered, making its mass read 2592 g (i.e. 2482 g of the empty cylinder + 110 g of R-134a). This was followed by further injecting 89% (i.e., 890 g) of R-600a into the cylinder until the mass now read 3482 g (i.e. 2592 g + 890 g), making a total of 1 kg of the blend in the cylinder. The same procedure was followed to formulate blends L and M.

After obtaining the blends, an attempt was made to ignite a sample, by allowing the blend to leak into a flame to determine their flammability. Thereafter, the blends were each charged into the compressor of vapor compression systems (Figure 1 shows a typical setup) having similar configuration.

For comparison, same mass of R-134a and R-600a were also charged separately into compressors of similar systems, and were all run simultaneously at controlled ambient temperatures. Since an open system was chosen which cannot be loaded, the experiment was performed at ambient temperatures of 37^{o}C, and 32^{o}C to observed the effect of the vary temperature on its characteristics.

Figure 1: A Typical Setup for Investigating the Coefficient of Performance of the Refrigerants.

To determine the operating temperatures and pressures, four thermometers were attached to each system's evaporator, condenser and compressor inlet and outlet to measure their respective temperatures while two barometers were attached to the inlet and outlet of the compressor to measure their operating pressures. The mass flow rates of the systems were set equal (0.05 kg/s) and readings from the thermometers and barometers were obtained every 5 minutes during operation.

RESULTS

Igniting of the samples showed that they were mildly flammable, as they all burned in flame. While the results obtained during the experimental investigation of the blends alongside R-600a and R-134a when run simultaneously under same conditions are as shown in Figures 2 to 7.

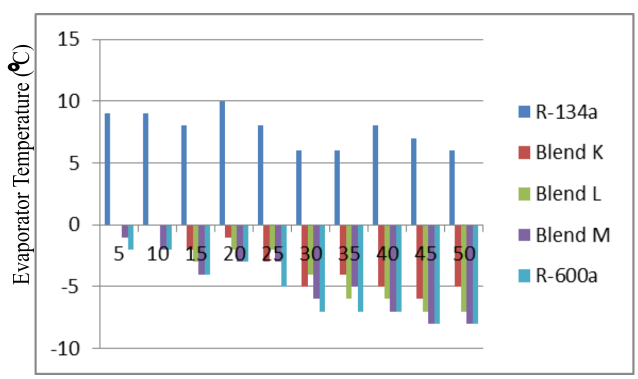

Figure 2: Variation of Evaporator Temperature with Time at an Ambient Temperature of 37^{o}C.

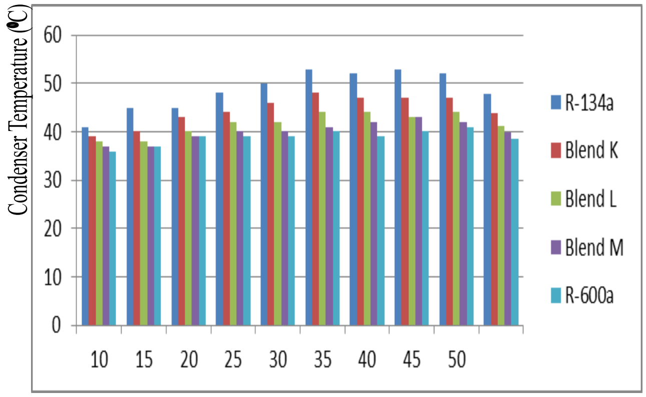

Figure 3: Variation of Condenser Temperature with Time at an Ambient Temperature of 37^{o}C.

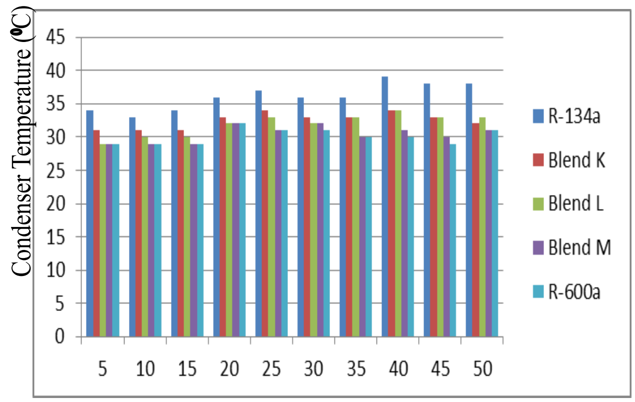

Figure 6: Variation of Condenser Temperature with Time at an Ambient Temperature of 32^{o}C.

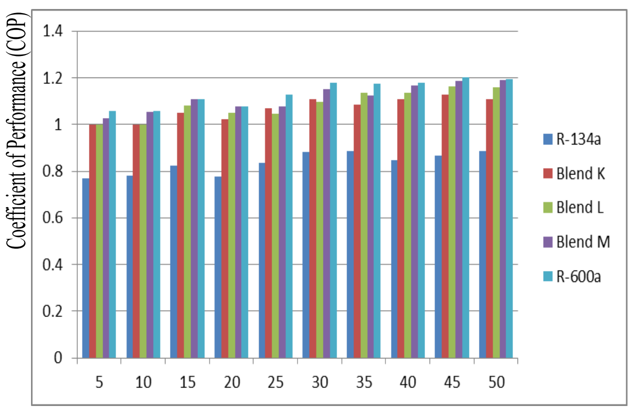

Figure 4: Variation of COP with Time at an Ambient Temperature of 37^{o}C.

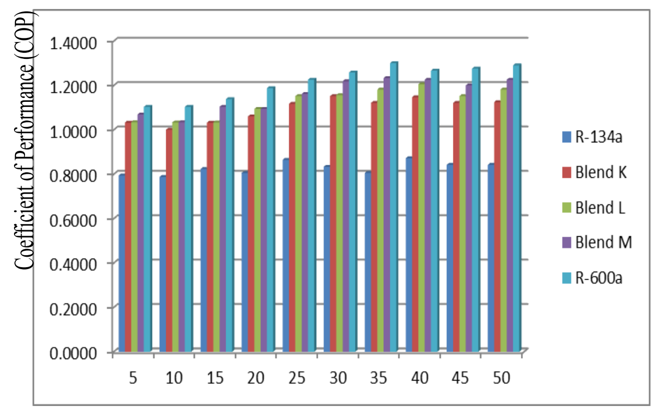

Figure 7: Variation at COP with Time at an Ambient Temperature of 32^{o}C.

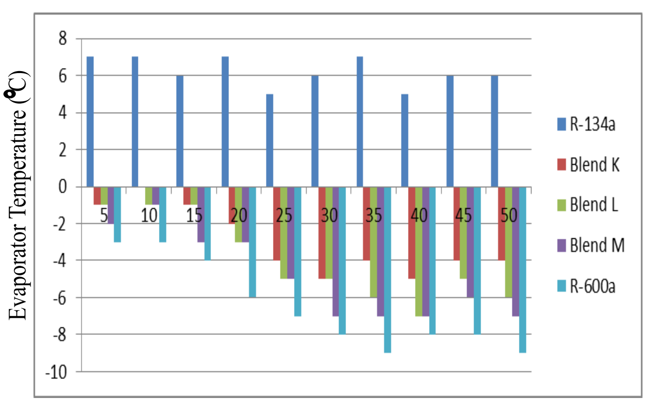

Figure 5: Variation of Evaporator Temperature with Time at an Ambient Temperature of 32^{o}C.

DISCUSSION

Observation of the blends' flammability when ignited showed that they are mildly flammable, though the rigour of their flammability (ease of ignition and rate of propagation) increases from blend K to R-600a. This is due to the reduction in the mass composition of R-134a which hinders the flammability of R-600a in the mixture. Analysis of the results obtained during the experimental investigation as presented in Figures 2 to 7, indicate the following:

i. the COP of the refrigerants increases as the ambient temperature reduces;

ii. the COP of the refrigerants increases from R-134a ,blends K, L, M, to R-600a irrespective of the ambient temperature;

iii. the difference in COP is due to the ability of the blends to attained different evaporator and condenser temperatures;

iv. the evaporator, condenser and compressor's suction and discharge temperatures as well as the compressor's suction and discharge pressure decreases from R-134a to R-600a irrespective of the ambient temperature– The lower discharge temperature increases the life of the compressor; and

v. the pressure ratios of the refrigerants are significantly close having (5.5, 5.3, 5.3, 5.3, 5.4) bars for R-134a to R-600a, respectively, thus allowing similar pipe thickness in the system.

Based on the above observations, it could be inferred that the COP of the formulated refrigerants blends is higher than that of R-134a indicating that each of the blend exhibit higher performance with respect to R-134a but lesser performance compared to R-600a. Therefore, the blends could be used in the place of R-134a without impacting the operation efficiency in a vapor compression refrigeration system.

It could also be observed from this study that blend K offers the best alternative when the COP and flammability are combined as performance metrics. This is because it has higher COP (1.0708; 1.0923) compared to R-134a (0.8389; 0.8283) at ambient temperatures of 37^{o}C and 32^{o}C, respectively with GWP of 150 to 1300 while its COP is close to those of blends L, M, and refrigerant R-600a (1.1373; 1.2159). Also it possesses improved flammability in comparison to blends L and M as well as refrigerant R-600a due to its higher mass composition of R-134a.

CONCLUSIONS

The aim of this research is to develop blends within the stipulated limit of GWP as defined by the European Union, and experimentally investigate their performance in a domestic vapor compression refrigeration system. Thus, the blends were formed as a mixture of R-134a and R-600a at ratios determine by Ali's model.

The results obtained revealed that the blends had better performance and can each successfully serve as replacement for R-134a without changing pipe thickness, compressors, cooling methods, and lubricants in the existing R-134a system, except that they are mildly flammable.

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ABOUT THE AUTHORS

M.E. Uwadiae, obtained his Masters of Engineering in Mechanical Engineering from The Federal University of Technology, Akure Nigeria in 2016

M.A. Akintunde, is a Professor in Mechanical Engineering Department of The Federal University of Technology, Akure, Nigeria. He received his Bachelors and Masters of Engineering in Mechanical Engineering from Obafemi Awolowo University and The Federal University of Technology, Akure (FUTA) Nigeria in 1992 and 1997, respectively. He obtained his Ph.D. in Mechanical Engineering at FUTA in 2004. He is Member of the Nigerian Society of Engineer.

T. I. Ogedengbe, is currently a Senior Lecturer in Mechanical Engineering Department of The Federal University of Technology, Akure, Nigeria. He received his Bachelors and Masters of Engineering in Mechanical Engineering from The Federal University of Technology, Akure, Nigeria in 1998 and 2003 respectively. He obtained his Ph.D. in Mechanical Engineering at The University of Manchester, United Kingdom, in 2010. He is Member of the Nigerian Society of Engineer and Member the Nigerian Institution of Engineering Management.

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