Exergetic Performance of Household Refrigerator using R600a and LPG

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Abstract. This paper presents a case study of coefficient of performance (COP), exergetic performance and irreversibility of four major components (compressor, condenser, capillary tube and evaporator) of a household refrigerator using R600a and LPG. The results showed that the COP and exergetic efficiency of LPG were 9.5% and 7.1% higher than that of R600a respectively. Also, the total irreversibility of LPG was lower than that of R600a with 22.4%. In general, LPG performed better than R600a in terms of COP, power consumption, exergetic efficiency and irreversibility in the system.

Keywords: Exergetic efficiency, COP, R600a, LPG

1. Introduction

Majority of the household refrigerators used today are working on vapour compression principle and halogenated refrigerants such as Chlorofluorocarbons (CFCs) and Hydrofluorocarbon (HFCs) are mostly used as the working fluids in household refrigerator due to their characteristics such non-flammability, non-toxicity and stability with materials vapour compression refrigerator are made up of. However, the use of CFC’s in household refrigerator has been banned worldwide and also the use of CFC’s refrigerant has been banned in Europe due to their high ozone depleting potential (ODP) and global warming potential (GWP). In line with the Montreal and Kyoto protocols, HFC’s refrigerants such as R134a will be phase out fully in the future [1-2]. As these refrigerants are being prohibited and phased out in Europe, they are gradually gaining access into Sub Saharan region as fairly used products. Recently, the use of Hydrocarbon refrigerants such as R600a has been embraced as working fluid in household refrigerator in Europe and other hydrocarbons mixture are rapidly gaining attention due to their good characteristics and better environmental features and such as miscibility with mineral oils, compatibility with materials used in vapour compression refrigeration system. Hydrocarbon refrigerant is less expensive and available in abundance in major oil producing nation of the world. Hydrocarbons have good thermodynamic properties; therefore, they are energy efficient [3-4]. The disadvantage of hydrocarbons is it high flammability. However, a maximum mass charge of 150 g has been recommended in household refrigerator [5].

Some researchers have carried out researches on replacement of R134a with an eco-friendly refrigerant in a domestic refrigerator. Mahmood et al [6] investigated the use of R600a as a drop-in replacement for R134a in vapour compression system the result revealed that R134a has higher exergy destruction in the system than R600a with the destruction more pronounced more in the compressor, condenser, evaporators and expansion valve decreasingly. In a similar way, Rasti et al [7] also performed experimental analysis on energy efficiency improvement of a household refrigerator using R436A and R600a as a substitute for R134a refrigerant in a domestic refrigerator originally designed to work with R134a as the working fluid. The results obtained showed that with R134a compressor the energy consumption of R600a and R436A were reduced. Babarinde et al [8] conducted an experimental study on the use of liquefied petroleum gas (LPG) as a drop in replacement for R134a in a domestic refrigerator system. The results obtained indicated that the coefficient of performance (COP) of the system was better and the power consumption reduced...
when compared with R134a. Bolaji [9] carried out a research on the exergetic and performance of a domestic vapour compression refrigerator using R134a and R152a to replace R12, the performance was compared with the performance of R12 in the refrigerator. The results indicated that the COP of R152a was almost the same in comparison with that of R12 and the highest exergetic efficiency was also obtained for R152a refrigerant in the system. The total efficiency defect of R152a in the refrigerator was the lowest compared to that of R12 and R134a. Babarinde at [10] investigated the coefficient of performance (COP) exergetic destruction and exergetic performance of a household refrigerator R134a and R600a the result outcome showed that the coefficient of performance and exergetic efficiency is higher than that of R134a and the total exergetic defect of R600a is lower than that R134a in the system.

The goals of this research are to investigate the more economical refrigerant between the two hydrocarbons (R600a and LPG) in terms of evaporator temperature energy efficiency in a household refrigerator.

2. Experimental procedure

The experiments were carried out using refrigerator designed to work with R134a. The capillary tube was extended by 30% in order to enhance the performance of the hydrocarbon refrigerants. The experiment was tested using 60 g charge of R600a and 40g charge of LPG; this is because the latent heat of hydrocarbon is much higher than that of R134a and also, the density of LPG is lower than R600a. Type K thermocouples were connected to measure the inlet and outlet temperature of the four components (compressor, evaporator, condenser and capillary tube) of the refrigerator. Two pressure gauges were also connected to the suction and discharge of the compressor, see Figure 1. The measurements of uncertainties of the measuring instrument used are in Table 2. Table 3 shows the experimental condition and ranges for continuous and cycling experiment. The experiment was repeated four times. The thermodynamic properties of the results obtained were analyzed using Refprop, version 9 [11]. The experiment was conducted at an average an environmental temperature of 27°C at no load conditions.

| Refrigerants | NPB(°C) | T(°C) | GWP | Safety group | Molar mass (kg/kmol) |
|--------------|---------|-------|-----|--------------|---------------------|
| R134a        | -26     | 101   | 1300| A1           | 102.03              |
| R600a        | -12     | 135   | 20  | A3           | 58.12               |
| R600         | -0.49   | 151.98| 20  | A3           | 58.12               |
| R290         | -42     | 97    | 20  | A3           | 44.09               |
| LPG          | -25.4   | 101   | 20  | A3           | 48.8                |
Table 2: Characteristics of the measuring instruments

| S/N | Measured Data          | Manufacturers Specification       | Range                  | Uncertainty |
|-----|------------------------|-----------------------------------|------------------------|-------------|
| 1   | Temperature            | Digital Thermocouple K            | -50°C - 750°C          | ±3°C        |
| 2   | Pressure               | Digital pressure gauge            | 5 - 5000 Pa            | ±1%         |
| 3   | Power                  | Digital Watt/Watt-h-meter         | 1-3000W                | ±1          |

Table 3: Range and conditions of experiment

| S/N | Parameters            | Range of Experiment |
|-----|-----------------------|---------------------|
| 1   | R600a refrigerant charge | 60g                |
| 2   | LPG Refrigerant       | 40g                 |
| 3   | Compressor lubricant  | Mineral oil         |
| 6   | Test environment temperature | 27°C     |
| 7   | Capillary tube length | 1.5m                |
| 8   | Condenser type        | Air cooled          |
| 9   | Evaporator size       | 72litres            |

The exergy efficiency of the cycle is calculated as follows:

Exergy is a degree of how a system deviates from its given and reference state. The total Exergy that is obtainable at the system output (X_out) is less than total Exergy at the system inlet (X_in). This amount of Exergy used up in the system is as a result of irreversibility. The summation of irreversibility in each component of the system is called total irreversibly of the system. The following assumptions below were made to calculate the performance of the refrigerator system.

1. Steady-state operation is assumed in all the system components.
2. Pressure losses along each component are neglected.
3. There is no heat gain and heat loss from or to the system.
4. Potential and Kinetic energy are neglected.
5. There is no pressure drop along the condenser and evaporator of the system.

The exergy efficiency of the cycle is evaluated as follows:

\[ I = X_{in} - X_{out} \]  (1)

When equation (1) is applied to each (evaporator, compressor, condenser and expansion valve) of the system

**Exergy of the evaporator**

Where \( \dot{m} \) is the refrigerant mass flow rate (in kg/s), \( h_4 \) represents the specific enthalpy (in kJ/kg) of the refrigerant at the evaporator inlet and, \( h_1 \) is the specific enthalpy (in kJ/kg) of the refrigerant at the evaporator outlet, \( S_1 \) is the specific entropy (kJ/kg.K) of the refrigerant at the outlet of the evaporator, \( S_4 \) is the specific entropy (kJ/kg.K) of the refrigerant at the evaporator inlet, \( Q_e \) (kW) is heat transfer rate through the boundary at \( T_{evap} \). Thus Exergy efficiency of the evaporator can be written as

\[ I_{evap} = \dot{m}(h_4 - T_0 S_4) + Q_{evap} \left(1 - \frac{T_0}{T_r}\right) - \dot{m}(h_1 - T_0 S_1) \]  (2)

**Exergy of the compressor**
Where $S_2$ is the specific entropy (kJ/kg.K) of the refrigerant at the compressor outlet. $W_{comp}$ is compressor power input (kW).

### Exergy of the condenser

Exergy at the condenser are calculated from equation (9) and (10)

$$I_{cond} = \dot{m}(h_2 - T_O S_2) - \dot{m}(h_3 - T_O S_3) - Q_{cond} \left(1 - \frac{T_0}{T_{cond}}\right)$$

Where $S_3$ is the specific entropy (kJ/kg.K) of the refrigerant at the condenser outlet. $Q_{cond}$ is heat transfer rate at the condenser (kW).

### Exergy of the expansion valve

Where $S_4$ is the specific entropy (kJ/kg.K) of the refrigerant at the expansion valve outlet.

### Total irreversibility of the refrigerator

The total exergy of the refrigerator system is the summation of the components.

$$I_{total} = I_{evap} + I_{comp} + I_{cond} + I_{exp}$$

### Exergetic efficiency

The second law efficiency of vapour compression system is written as follows:

**The total exergy efficiency** ($n_X$) is the ratio of exergy output ($X_{out}$) to exergy input

$$n_X = \left(\frac{X_{out}}{X_{in}}\right) \times 100\%$$

$$X_{out} = X_{in} - X_{total}$$

$$n_X = \left(1 + \frac{X_{total}}{W_{comp}}\right)$$

$$COP = \frac{m(h_1-h_4)}{m(h_2-h_1)}$$

### 3. Results and discussion

The exergetic performance analysis of household refrigerator system is discussed below:

According to ISO (1991), the pull-down can be defined as the required time for the evaporator air chamber to attain the steady state condition from ambient temperature.

Figures 2 show the pull-down time of R600a and LPG in the refrigerator. The operating temperatures of $-12$ and $-14^\circ C$ were obtained in the refrigerator at a pull-down time of 240 and 210 min for R600a and LPG respectively.
Figure 2 shows the cooling capacity and power consumption by the compressor of the system. The power 236 and 111 W were recorded for cooling capacity and power consumption power respectively for R600a while the power 205 and 90 W were recorded for cooling capacity and power consumption respectively for LPG. The cooling capacity and power consumption of LPG is 13.4% and 18.9% lower than R600a refrigerant respectively in the system.

Figure 4 shows the comparison of coefficient of performance (COP). The results showed that the COP of R600a and LPG are 2.1 and 2.3 respectively. The COP for LPG is 9.5% higher when compared to R600a. This was due to decrease in compressor work of LPG. With lower COP of R600a it implies it requires more electric power to produce the same refrigerating effect, which is not cost effective.
Figure 4 and 6 shows variation of irreversibility in compressor, condenser, capillary tube and evaporator and total irreversibility of R600a and LPG refrigerants. The figure shows that irreversibility in the compressor, condenser, capillary and evaporator are 0.265, 0.258, 0.09 and 0.031W respectively for R600a refrigerant, while irreversibility in the compressor, condenser, capillary and evaporator are 0.224, 0.054, 0.071 and 0.149W respectively for LPG refrigerant. The irreversibility reduces for LPG compared to R600a. The irreversibility in evaporator for LPG is higher than R600a refrigerant. However the total irreversibility of LPG is 21.9% lower than that R600a in the system.

Figure 5 comparison of irreversibility of the refrigerator components
Figure 3 shows exergetic efficiency for R600a compared with LPG. The average exergetic efficiency for LPG is 7.1% higher compared to that of R600a. Exergetic efficiency of 45 and 42% were attained at evaporator temperature of -14 °C and -12°C for LPG and R600a, respectively. This is as a result of the irreversibility of the components and evaporator temperature increase.

4. Conclusion

The performance of refrigeration system is studied using R600a and LPG, environment-friendly refrigerant after the analysis on the exergetic performance of R600a and LPG in the system, the following conclusions are made:

- The COP of the household refrigeration system using R600a as a refrigerant was considered as baseline. The COP obtained using LPG higher than that of R600a.
- Lower power consumption was obtained for LPG in the refrigerator.
The highest exergetic efficiency was obtained using LPG in the system. The total irreversibility of LPG is lower than R600a, which indicates improving energy management. Generally, the refrigeration system performance improved with LPG than R600a in the system. Hence household refrigerator is more economical to run with LPG working fluid than R600a.

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