Experimental Investigation of the Performance of Liquefied Petroleum Gas (LPG) Refrigerant in A Vapour Compression Refrigeration System

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Abstract: In this work, the performance of Liquefied Petroleum Gas (LPG), which has zero ozone depleting potential and very low global warming potential, was investigated as working fluid in the vapour compression refrigerating system as a possible alternative. The LPG used for the study consist the mixture of propane and butane in the ratio 60/40% by mass. An experimental refrigerator was developed as test rig and the rig was charged with 50g of LPG. Tests were carried out at various ambient temperatures, producing average ambient temperatures ranging from 27.5 to 33.5℃. A steady-state process design and operational analysis simulation software, SIMSCI/PROII, was used to determine the enthalpy values for LPG refrigerant. The values obtained were then used to calculate important performance parameters. The results showed that as the ambient temperature increases, the coefficient of performance (COP), and the refrigeration capacity decreases, but the compressor power input increases. The average compressor power consumption of LPG was 12.5% lower than that of R134a, while the average refrigeration capacity and COP of LPG were 4.2% and 11.16% higher, respectively, than those of R134a. Finally, the results showed that, the system performed better with LPG than R134a. Therefore, LPG refrigerant can be successfully adopted.

Keywords: Refrigerant, Chlorofluorocarbons (CFC), Global Warming Potential (GWP)

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Introduction

Refrigeration is defined as the process of achieving and maintaining a temperature below that of the surroundings, the aim being to cool an item or space to the required temperature. Refrigeration has many applications including but not limited to: household refrigerators, industrial freezers, cryogenics, air conditioning, and heat pumps. In satisfying the Second Law of Thermodynamics, some form of work must be performed to accomplish this. In vapour compression refrigerating system, the work is supplied by the compressor.

In vapour compression refrigerating systems, a fluid is the medium that transfers the heat; the fluid is referred to as the refrigerant. Over the years different refrigerants have been employed in the system, but recently there is growing need for efficient and environmental friendly refrigerants. The rate of depletion of the ozone layer, which absorbs the sun's high energy ultraviolet rays and thus protect all living things including human, is at the high level according to literatures. According to research reports, chlorine particles causes the removal of ozone from the atmosphere. Different sector have been called for the elimination of chlorofluorocarbons (CFC) (David, 2010; Wikipedia, 2010).

The 1992 meeting of the United Nations Environment Program called for the phase-out of CFCs by 1996 (Hammed and Alsaad, 1999). Alternative refrigerants should be found to replace the existing CFCs. The American Household Appliances Manufacturers (AHAM) has identified some hydro fluorocarbon (HFC) refrigerants such as R134a and R152a as better replacement for R12 in domestic refrigerators. These refrigerants were commonly used due to their superior stability and safety properties: they are non-flammable and non-toxic as the fluids they replaced. However, these chlorine-bearing refrigerants (CFCs) reach the upper atmosphere when they escape and in the stratosphere, CFCs break up due to UV-radiation, releasing their chlorine atoms. These chlorine atoms act as catalysts in the breakdown of ozone, thus causing severe damage to the ozone layer that shields the Earth's surface from the Sun's strong UV radiation (Doohlinger, 1993; MacKenzie, 1994).

The chlorine will remain active as a catalyst until and unless it binds with another particle, forming a stable molecule. Newer refrigerants that have reduced ozone depletion effect include HCFCs (e.g. R22, used in most homes today and R23 used in

industrial chillers). HCFCs in turn are being phased out under the Montreal Protocol and replaced by hydro-fluorocarbons (HFCs), such as R134a, R407C and R410A which lack chlorine. However, CFCs, HCFCs, and HFCs all have higher global warming potentials.

Natural refrigerants are currently the subject of research, such as supercritical carbon dioxide, known as R744 and hydrocarbon refrigerants. These have similar efficiencies compared to existing CFC and HFC based compounds, and have many orders of magnitude lower global warming potential (MacKenzie, 1994). The adoption of R152a which is a non toxic and environmentally friendly substitute, has a low value of global warming potential (GWP) in comparison to CFCs except for the challenge of being an HFC refrigerant, which has problem of oil miscibility with mineral oil, therefore, it is necessary to use synthetic oil instead of mineral oil. This type of oil is highly hygroscopic, expensive and it is harmful to health. Richardson and Butterworth have used propane and propane/isobutene mixture in R12 systems and came out with a better COP than R12 under same operating conditions (Hammed and Alsaad, 1999). Hydrocarbons generally have their ozone depletion potential to be zero and their green house effect considered insignificant compared with R12. They have very good physical, chemical and thermodynamic properties.

The Montreal Protocol is saddled with the responsibility of regulating the production and trade of ozone-depleting substances (UNEP, 1987). The present working fluids in the existing vapour compression refrigerating systems are CFC, HCFC and HFC refrigerants. Different sectors are challenged to find suitable alternatives. Appliance energy standards, designed to contain the global warming effects, is another major challenge facing the refrigeration industry. Thus the need for a suitable, efficient and more environmentally friendly working fluid to replace the existing working fluid in vapour compression refrigerating systems. In searching for a suitable refrigerant, the performance of Liquefied Petroleum Gas (LPG) was investigated experimentally in a vapour compression refrigeration system and compared with current alternative refrigerant (Kiran, 2009; Kuijpers, 1988).

Liquefied Petroleum Gas (LPG) is a flammable mixture of hydrocarbon gases used as a fuel in heating appliances and vehicles. It is increasingly used as an aerosol propellant and a refrigerant, replacing chlorofluorocarbons in an effort to reduce damage to the ozone layer. Varieties of LPG available include mixtures that are primarily propane C_3H_8 and butane C_4H_{10}, depending on the season — in winter more propane, in summer more butane. Propylene and butylenes are usually also present in small concentration. A powerful odorant, ethanethiol, is added so that leaks can be detected easily. In the United States, thiophene or amyl mercaptan is also approved odorants. LPG is a low-carbon-emitting hydrocarbon fuel available locally, emitting 81% of the CO_2 per kWh produced by oil, 70% of that of coal, and less than 50% of that emitted by coal-generated electricity distributed via the grid. Being a mix of propane and butane, LPG emits less carbon per joule than butane but more carbon per joule than propane (ACRIB, 2001; Alsaad, et al; Akash and Said, 2003).

Experimental Procedure

In investigating the performance of Liquefied Petroleum Gas (LPG) refrigerant in a vapour compression refrigerating system, a test rig is designed having its joints properly welded, to avoid leakages and also having other modifications. The following assumptions were made in the design of the experimental vapour compression refrigerator: (a) steady state operation; (b) no pressure loss through pipelines, that is, pressure changes only through the compressor and the capillary tube; (c) heat losses or heat gains from or to the system are neglected and of 75% isentropic efficiency. Some important performance characteristics like

operating pressure, refrigeration capacity, coefficient of performance (COP) and compressor discharge temperature were considered in using LPG as refrigerant in the system.

A vapour compression refrigerator constructed as test rig was tested using LPG refrigerant and important performance parameters, such as refrigeration capacity (Q_{evap}), compressor power ($\dot{W}_c$), coefficient of performance (COP) and pressure ratio (Pr) were evaluated using the following equations:

- Refrigeration capacity, Q_{evap} $= \dot{m}$ (h_1 – h_4)   (kW)   (1)

  Where: $\dot{m}$ = mass flow rate (kg/s); h_1 – h_4 = refrigerating effect of refrigerant (kJ/kg)

- Power requirement of compressor:

  The compressor power consumption, $\dot{W}_c = \dot{m}\left(h_2 - h_1\right)$ (W)   (2)

  Compressor pressure ratio, (P_R) is given as: $P_R = \dfrac{P_{dis}}{P_{suc}}$ (3)

  Where: P_{dis} = compressor discharge pressure (bar)

  P_{suc} = compressor suction pressure (bar)

- Coefficient of Performance, $COP = \dfrac{Q_{evap}}{W_c}$ (4)

- Heat ejected by Condenser, $Q_{cond} = \dot{m}$ (h_2 – h_3)   (kW)   (5)

For LPG system, obtaining thermodynamic properties (like the enthalpy and entropy) of LPG at steady state needs the use of special computer software for simulation, because LPG has different compositions.

0.05kg of LPG with composition 40% of butane and 60% of propane was charged into the system with the help of charging system. The mercury thermometer, thermocouples and a pressure measuring device, also a special temperature gauge called Athermeter, with a wide range of - 40 to + 40, and accuracy value of ±0.05 dedicated for taking the evaporator readings, with the probe protruding to the refrigerating space through a drill on the cooler. The output of these sensors was recorded. The temperature and pressure readings were taken at an interval of 45 minutes at the inlet and outlet of various units, three times daily for five days, random selection at different ambient temperature of all this was used for this experimental investigation. The values obtained from the readings were feed and ran in SIMSCI/PROII software to determine the enthalpy of the refrigerant. SIMSCI/PROII software developed by Invensys System in 2004, is a steady-state simulator enabling improved process design and operational analysis. It is designed to perform rigorous mass and energy balance calculations for a wide range of chemical processes. SIMSCI/PROII offers the most comprehensive process simulation solution available today to the following industries: chemical, petroleum, natural gas, solids processing and polymer industries. Therefore SIMSCI/PROII simulator was used to obtain thermodynamic properties of LPG. The readings were then used obtaining parameters such as the refrigeration capacity (Q_e), compressor power ($\dot{W}_c$), coefficient of performance (COP) and pressure ratio (Pr). All equipment and test unit was placed under different environmental conditions, (ambient temperature) at the same time. The ambient temperatures range from 27.5 to 33.5℃. When the temperature and humidity under each condition was at steady state, the experiments started. The experiment was conducted on the fabricated experimental refrigerator at closed door conditions.

Results and Discussion

The results of performance parameters obtained at various ambient temperatures, evaporator and condenser temperatures are shown in Figures (1 - 3), (4 – 8) and (9 – 11), respectively.

Figure 1 shows the variation of the refrigeration capacity with ambient temperature for LPG and the current alternative refrigerant (R134a) in vapour compression refrigeration system. It was observed that for the two investigated refrigerants, refrigeration capacity decreases with increase in ambient temperature. At the same ambient temperature, the refrigeration capacity obtained from LPG is higher than that obtained from R134a by 4.2%. Average refrigeration capacities of 23.236 kW and 22.295 kW were obtained during the tests using LPG and R134a, respectively.

Figure 2 shows the variation of the compressor power with ambient temperature for LPG and R134a. It was observed that the compressor power input increases with increase in ambient temperature and compressor power inputs for both LPG and R134a were almost the same within the range of ambient temperature considered. At the same ambient temperature, the compressor power input of LPG is lower than that obtained for R134a by 12.5%. Average compressor power input of 5.390kW and 6.065kW were obtained using LPG and R134a, respectively.
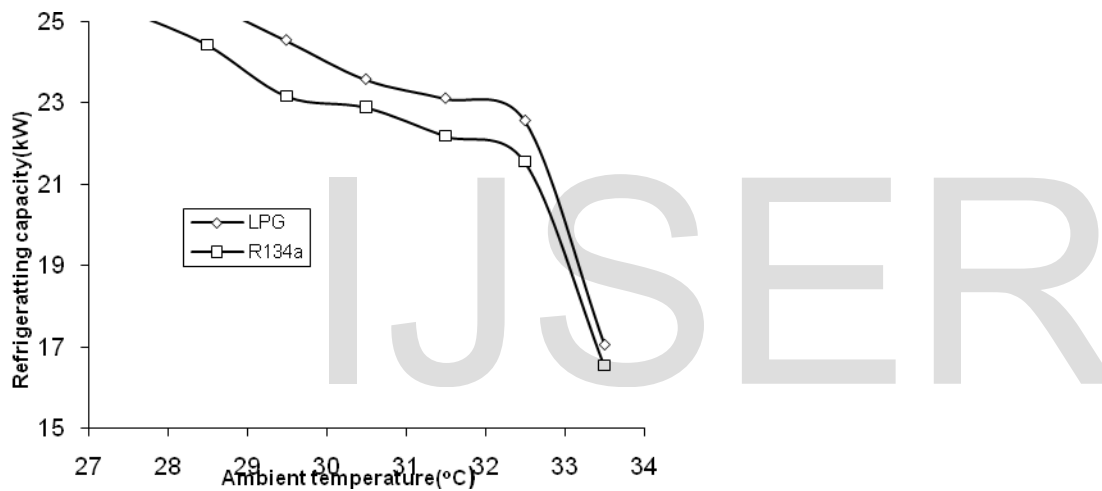

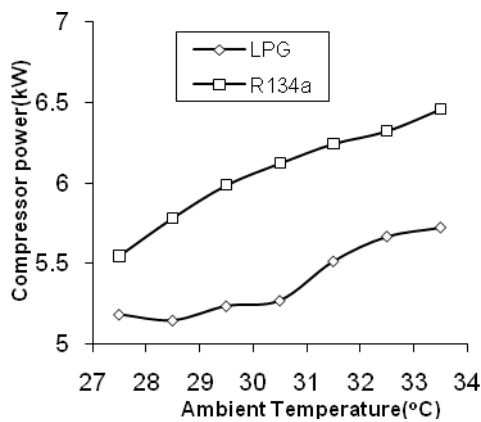Figure 1: Variation of refrigeration capacity (Q_{evap}) with ambient temperature

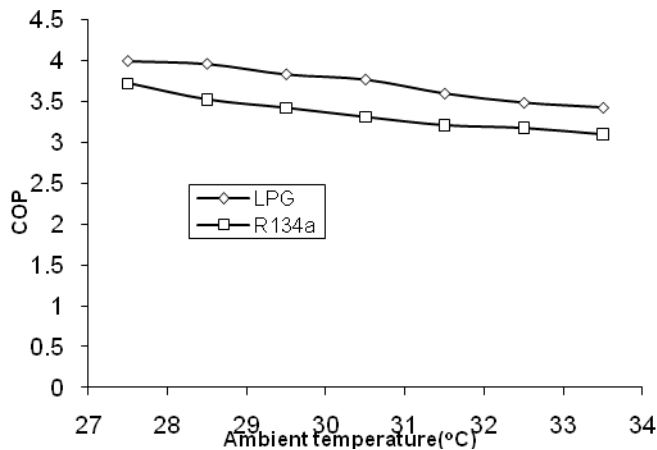Figure 2: Variation of compressor power (W_c) with ambient temperature

Figure 3: Variation of coefficient of performance (COP) with ambient temperature

The variation of the coefficient of performance (COP) with ambient temperature for LPG and R134a is shown in Figure 3. It was observed that the coefficient of performance decreases with increase in ambient temperature. At the same ambient temperature, The COP of LPG is higher than that obtained for R134a by 11.16%. Average COP of 3.725 and 3.351 were obtained during the tests using LPG and R134a, respectively.

The variation of the refrigeration capacity with evaporator temperature for LPG and R134a is shown in Figure 4. Refrigeration capacity increase with the increase in evaporator temperature. This is due to high enthalpy values of saturated vapour leaving the evaporator as evaporator temperature increases. At the same evaporator temperature, the refrigeration capacity obtained from LPG is higher than that obtained from R134a by 4.2%.

Figure 5 shows the variation of the compressor power with evaporator temperature for LPG and R134a. It was observed from the figure that for the two investigated refrigerants, the compressor power input for the two refrigerants, increase with the increase in evaporator, this is due to high enthalpy values of saturated vapour leaving the evaporator as evaporator temperature increases. At the same evaporator temperature, the compressor power obtained for LPG is lower than that obtained for R134a .

Figure 6 shows the variation of the coefficient of performance with evaporator temperature for the two investigated refrigerants (LPG and R134a). It was observed that for the two refrigerants, the coefficient of performance decreases with increase in evaporator temperature, since the coefficient of performance is the ratio of refrigeration capacity to compressor work input. At the same evaporator temperature (-3℃), the COP obtained for LPG is higher than that obtained for R134a by 10.6%. Average COP of 3.429 and 3.098 were obtained during the tests using LPG and R134a, respectively.
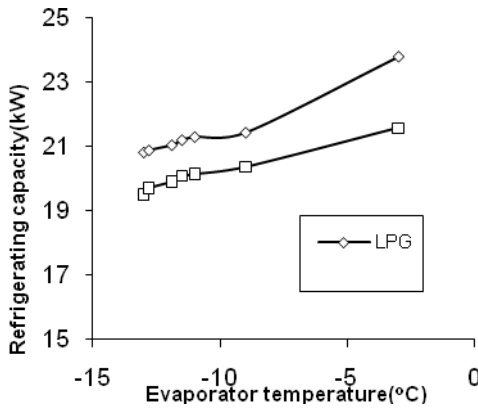
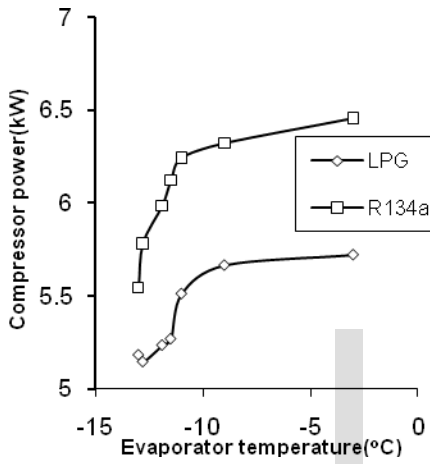**Figure 4: Variation of refrigeration capacity (Q$_{evap}$) with evaporator temperature (Te)**

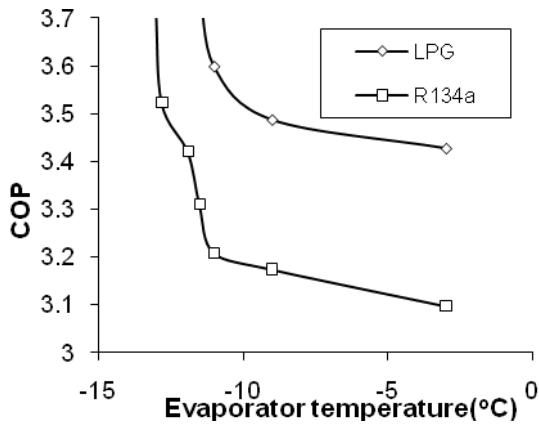**Figure 5: Variation of compressor power (Wc) with evaporator temperature (Te)**

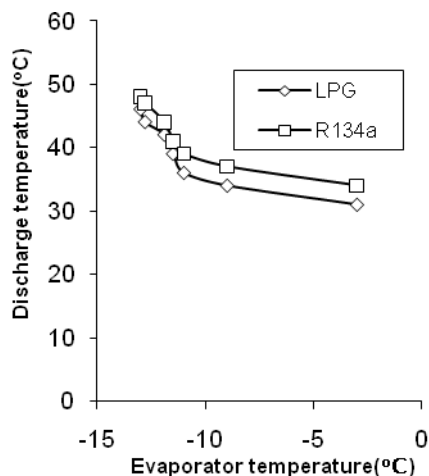**Figure 6: Variation of COP with evaporator temperature (Te)**

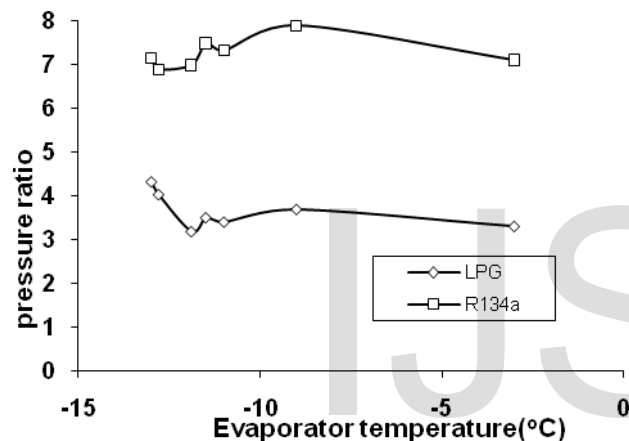**Figure 7: Variation of discharge temperature (Td) with evaporator temperature (Te)**

Figure 8: Variation of pressure ratio (Pr) with evaporator temperature (Te)

The variation of discharge temperature with evaporator temperature for LPG and R134a is shown in Figure 7. It was observed from the figure that the discharge temperature increase with increase in evaporator temperature. At the same evaporator temperature (-3℃), the discharge temperature of LPG is lower than that obtained for R134a by 9.68% and average discharge temperature of 31℃ and 34℃ for LPG and R134a, respectively.

Figure 8 shows the variation of pressure ratio to the evaporator temperature, for the two refrigerants. The figure reveals that as evaporator temperature increases, the pressure ratio changes irregularly, but slightly decreases and increases for LPG and R134a, respectively. The figure also shows a wide gap between the two curves, which is an indication that LPG operates at a relatively very low pressure ratio than R134a. High pressure ratio will affect the systems performance and reliability of the components negatively, while low pressure ratio will prolong the equipment life and greatly improve its performance.
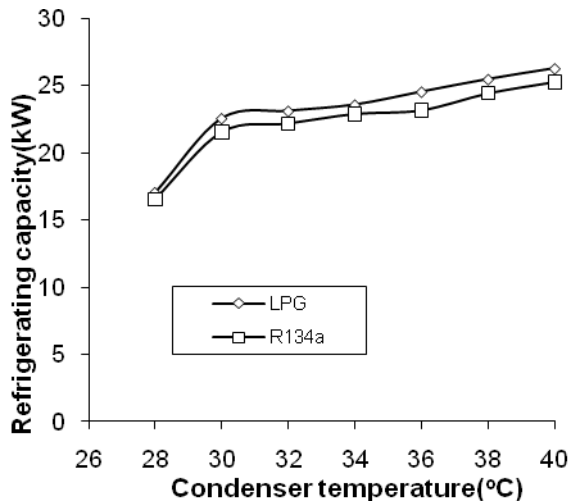
Figure 9: Variation of refrigeration capacity (Qe) with condenser temperature (Tc)

The variation of the refrigeration capacity with condenser temperature for LPG and R134a is shown in Figure 9. It was observed that for the two investigated refrigerants, the refrigeration capacity increase with the increase in condenser temperature. At the same condenser temperature, the refrigeration capacity obtained from LPG is higher than that obtained from R134a by 4.2%.
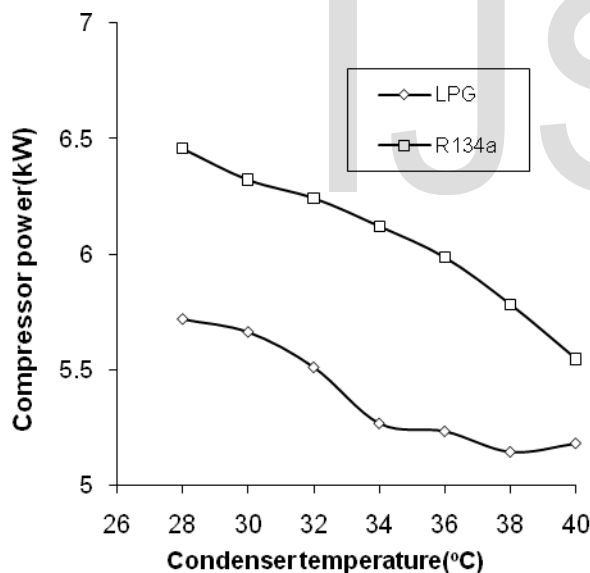

Figure 10: Variation of compressor power (Wc) with condenser temperature Tc

The variation of the compressor power with condenser temperature for LPG and R134a is shown in Figure 10. It was observed that for the two refrigerants, the compressor power input decreases as the condenser temperature increase. At the same condenser temperature, the compressor power input obtained for LPG is lower than that obtained for R134a by 0.68kW
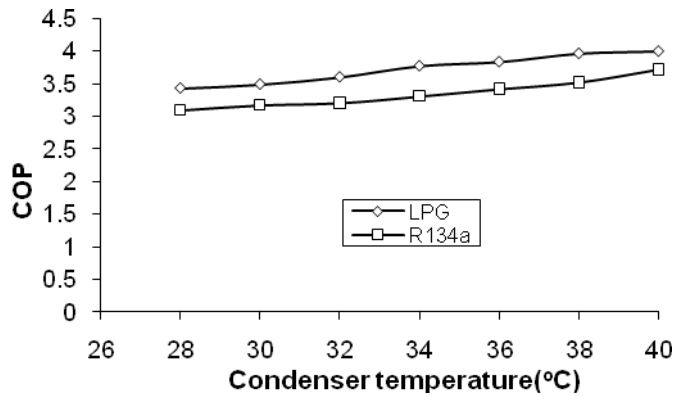
Figure 11: Variation of COP with condenser temperature Tc

Figure 11 shows the variation of the coefficient of performance with condenser temperature for LPG and R134a. As shown in the figure, the coefficient of performance increase with the increase in condenser temperature. At the same condenser temperature, The COP of LPG is higher than that obtained for R134a by 11.16%. Average COP of 3.725 and 3.351 were obtained during the tests using LPG and R134a, respectively.

Conclusion

The performances of LPG refrigerant in terms of refrigeration capacity, compressor power input, pressure ratio and coefficient of performance (COP) were evaluated and compared with those of R134a, the current alternative Refrigerant, using an experimental refrigerator that was developed as a test rig. After the successful investigation of this refrigerant, the following conclusions were drawn based on the results obtained:

- The average coefficient of performance of LPG is higher than that of R134a by 11.16% at COP of 3.725 and 3.351 respectively.
- The compressor power of the system using LPG is about the same with that of R134a with average value slightly lower by 12.5% in favour of LPG.
- The experimental refrigerator was charged with 0.05kg of LPG as against 0.15kg in case of R134a. This is an indication of better performance of LPG as refrigerants.
- The refrigeration capacity was 4.3% higher using LPG when compared to R134a.
- The system using LPG has a relatively low pressure ratio than R134a, which indicates better system performance and reliability of the system using LPG.

The British standard institutions published by ACRIB (2001) allow the use of LPG as refrigerant if small amount of refrigerant is required. This has been justified, in this work, by the high performance of a very low amount of LPG refrigerant charged into the system. LPG refrigerant can be successfully adopted as R134a substitute in vapour compression refrigerating system.

It is recommended that in using LPG refrigerant, the allowable refrigerant charge, flammability properties, safety standard and codes must be taken into consideration. The limiting factors associated with the use of hydrocarbon refrigerants are the refrigerant charge size, the occupancy category and the room size. It is also recommended that workshops and seminars should be organised for the technicians on the need to embrace the use of LPG refrigerant.

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