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Experimental performance of LPG refrigerant charges with varied concentration of TiO_2 nano-lubricants in a domestic refrigerator

Damola S. Adelekan[a,*], Olayinka S. Ohunakin[a,*], Taiwo O. Babarinde[a], Moradeyo K. Odunfa[a,b], Richard O. Leramo[a], Sunday O. Oyedepo[a], Damilola C. Badejo[a]

[a] *The Energy and Environment Research Group (TEERG), Mechanical Engineering Department, Covenant University, Ogun State, Nigeria*
[b] *Department of Mechanical Engineering, University of Ibadan, Nigeria*

A R T I C L E I N F O

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A B S T R A C T

This article present an experimental investigation of varied mass charges of Liquefied Petroleum Gas (40 g, 50 g, 60 g and 70 g) enhanced with varied TiO_2 nanoparticle/mineral oil concentrations (0.2 g/L, 0.4 g/L and 0.6 g/L nano-lubricants) in a R134a compressor of a domestic refrigerator. Performance tests investigated at steady state included: pull down time, power consumption, compressor power input, cooling capacity and coefficient of performance (COP). Analysis was based on temperature and pressure readings obtained from appropriate gauges attached to the test rig. Refrigerant property characteristics were obtained using Ref-Prop NIST 9.0 software. Results obtained showed almost equal evaporator air temperatures and reduction in power consumption for all tested nano-lubricant concentrations except at 70 g charge of LPG using 0.6 g/L nano-lubricant. Furthermore, the lowest compressor power input was found to be 21 W and obtained using 70 g of LPG with either of 0.2 g/L or 0.4 g/L nano-lubricants. At 70 g of LPG using 0.6 g/L concentration of nano-lubricant, highest cooling capacity index of 65 W was obtained while the highest COP of 2.8 was obtained with 40 g charge of LPG using 0.4 g/L concentration of nanolubricant. In conclusion, LPG-TiO_2 nano-lubricant mixture works safely and efficiently in domestic refrigerators without modification of capillary tube length, but requires adequate optimization.

1. Introduction

Recently, the devastating effects of climate change have become a vivid discussion in world leaders meetings. UNEP 2015 gap report affirms concerns stating that the year 2014 emission index was 52.7 gigatonne carbon dioxide ($GtCO_2$) in variance to estimated safe target of 44 $GtCO_2$. Currently, deviation from average global temperature range, of 1.5–2 °C is experienced; hence, aggressive mitigation strategies are required [1]. Domestic refrigerators have been identified as an immense emission contributor globally, by both the Montreal and Kyoto protocols due to their chlorine or fluorine based working fluid (refrigerant). Classes of refrigerant compounds such as: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) were noted to be responsible for Ozone depletion (OD) and global warming effect [2,3]. There is thus the need for replacement that is

* Corresponding authors at: The Energy and Environment Research Group (TEERG), Mechanical Engineering Department, Covenant University, Ogun State, Nigeria.
E-mail addresses: damola.adelekan@covenantuniversity.edu.ng (D.S. Adelekan), olayinka.ohunakin@covenantuniversity.edu.ng (O.S. Ohunakin).

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Table 1
Specification of refrigerant classes.

S/N	Class	Refrigerant	Critical pressure (MPa)	Critical temperature (K)	OD potential (Yes/No)	GW potential	ASHRAE flammability classification
1	CFCs	R32	5.78	351.26	Yes	675	A2
		R22	4.99	369.3	Yes	1810	A1
2	HCFCs	R11	4.41	470.96	Yes	4750	A1
		R12	4.14	384.97	Yes	10900	A1
3	HFCs	R134a	4.06	374.21	No	1430	A1
		R152a	4.52	386.41	No	124	A2
4	HCs	R290	4.25	369.89	No	3	A3
		R600a	3.63	407.81	No	4	A3
6	HC Blend	R436a	4.27	389.04	No	3	A3

environmentally friendly [see Table 1]. Detailed retrofit assessment of past conventional refrigerants with natural refrigerants, especially hydrocarbons due to considerations for environmental and system efficiency optimization can be found in Calm [4]. Recently, workability of hydrocarbons including LPG in existing domestic refrigeration system, with or without slight modification and their high energy efficiency has been the major justification for their application in domestic refrigerators [5–10]. In spite of the fact that flammability of hydrocarbons has been a major concern, maximum charge limit of 150 g has been recommended as a safe limit charge for hydrocarbon refrigerant in domestic refrigerators irrespective of their location [11].

Applications of nanoparticle in refrigeration systems using hydrocarbons have been found to improve their efficiency considerably. Numerous experimental investigations have been performed recently [12]. Venkataramana et al. [13], experimentally studied the effect of using 0.1 g/L TiO_2 nanoparticle and mineral oil mixture as replacement for POE (polyol-ester) oil in a vapour compression domestic refrigerator, charged with different refrigerants (R436A, R436B and R134a), and observed under varied ambient temperature conditions. The reported results showed improved irreversibility and energy efficiency indexes. In the work of Tao et al. [14], the performance of a domestic refrigerator system using varied nano-oil compositions ($MoFe_2O_4$-$NiFe_2O_4$ nanoparticle added with and without fullerene nanoparticle addition in mineral oil) alongside different refrigerant types including: R134a and R600a, were experimentally investigated. Result showed identical behaviour for R134a refrigerant and 5.33% improved coefficient of performance (COP) for R600a refrigerant when working with $MoFe_2O_4$-$NiFe_2O_4$ nano-oil composition. However, research work involving the performance of nanoparticle behaviour in naturally occurring hydrocarbon mixtures like liquefied Petroleum Gas (LPG) is very sparse. This work thus presents an experimental energetic and efficiency study of varied TiO_2 nanoparticle concentrations in mineral compressor oil and varied LPG charges in a domestic refrigerator system.

2. Methodology

2.1. Experimental rig and environment

A 50 l domestic refrigerator originally charged with R134a was employed for this experimental investigation. Technical specification and Instrumentation of the test rig can be found in Table 2 and Fig. 1. The experiment was carried out in a conditioned laboratory space having an ambient temperature range of 29–32 °C controlled using a 10 t HP air conditioner and monitored using Rototherm surface temperature thermometers. The uncertainty and measurement range of measuring instruments such as digital thermocouple K used to observe suction (T_1), discharge (T_2), condensing (T_3) and evaporator air (T_{AIR}) temperatures and digital pressure gauges for suction and discharge pressures (P_1 and P_2) while power consumption of the refrigerator was monitored using a digital wattmeter (see Table 3 for measuring instrument details).

Table 2
Specification of the test rig.

S/N	Components	Units
1	Evaporator Size	50 l
2	Refrigerant type	R134a
3	Compressor type	HFC
4	Defrost Type	Manual
5	Power rating	80 W
6	Frequency rating	50 Hz
7	Freezing power	6 kg/24 h
8	Condenser type	Air cooled
9	Door type	Single

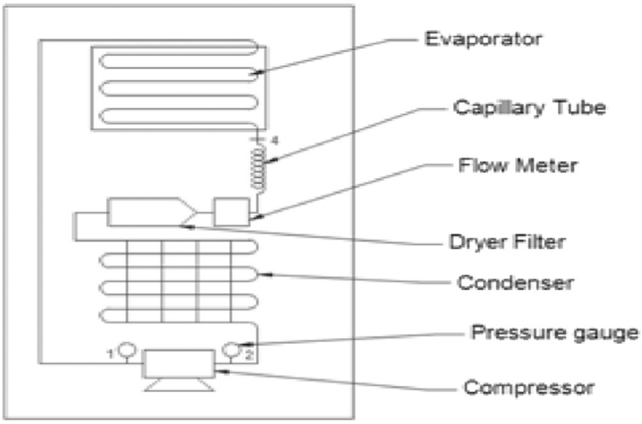

Fig. 1. Schematic diagram of the test rig.

Table 3
Uncertainty and measurement range of instrument.

S/N	Characteristics	Range	Uncertainty
1	Pressure	0–2500 kPa	± 0.1%
2	Temperature	−50 −750 °C	± 0.1%
3	Power	0–5000 W	± 0.1%

2.2. Nano-lubricant preparation

Varied concentrations (0.2 g/L, 0.4 g/L and 0.6 g/L of TiO_2 nanoparticle-Mineral oil mixture) of employed nanolubricants was homogenized using an ultrasonicator (Branson M2800H) to ensure uniform distribution of nanoparticle in the mixture, before introducing it to the compressor. The TiO_2 nanoparticles (15 nm size, 99.7% in purity, and produced by Alfa Aesar) was weighed using a digital weighing balance (OHAUS Pioneer TM PA114) with measurement range of 0.0001–110 g, and added to a measured volume of mineral compressor oil. The test rig was thoroughly evacuated using a vacuum pump before each trial [see Table 4 for mineral oil characteristic].

2.3. Experimental procedure

The experiment was carried out under a continuous, no-load, and closed door without intermittent ON/OFF compressor working condition for all trials. Repeatability of experiment was ensured by repeating each trial 3 times and each mass charge trial was charged using a digital charging system. Analysis was investigated at 240 min steady state performance of observed temperatures, pressures, power consumption and mass flow rate (T_1, T_2, T_3, T_4, P_1, P_2, $\dot{m}$) for all tested mass charges (40, 50, 60, 70 g) of LPG refrigerant working with pure mineral oil and varied concentrations of homogenized TiO_2-mineral oil mixture in the compressor (see Table 5 for ranges and condition of experiment). The observed temperatures and pressures were used to look-up corresponding saturated vapour enthalpy (h_1), superheated vapour enthalpy (h_2) and saturated liquid enthalpy (h_3) using Microsoft Excel 2010 software which had imported thermodynamic property table from NIST RefProp fluid property software version 9.1. The composition of LPG properties used was set at 60/40 propane butane mixture defined under define new mixture option of substance sub-menu in the software. The under-listed governing equations were employed for analysis:

Table 4
Characteristics of the mineral oil.

S/N	Lubricating oil characteristics	Units
1	Oil type	Capella mineral oil
2	ISO viscosity grade	68
3	Density at 15 °C kg/L	0.91
4	Kinematic viscosity (mm2/s) at 40 °C	68
5	Kinematic viscosity (mm2/s) at 100 °C	6.8
6	Flash point	−36 °C
7	Viscosity index	22
8	Code	41562

Table 5
Ranges and condition of experiment.

S/N	Parameter	Range
1	Nano Type	TiO_2
2	Nano Size	15 nm
3	Nano concentration (g/L)	0.2 g/L, 0.4 g/L, 0.6 g/L
4	Refrigerant type	LPG
5	Refrigerant Mass Charges (g)	40 g, 50 g, 60 g and 70 g
6	Capillary Tube length (m)	2 m
7	Ambient Temperature Range	29–32 °C

(i) $Compressor\ workdone = \dot{m}\,(h_2 - h_1)\,W$
(ii) $Cooling\ capacity = \dot{m}\,(h_1 - h_3)\,W$
(iii) $Coefficient\ of\ Performance\,(COP) = \frac{\dot{m}\,(h_1 - h_3)}{\dot{m}\,(h_2 - h_1)}$

where m is the mass flow rate (kg/s), h_1 is the saturated vapour enthalpy (kJ/kg), h_2 is the superheated vapour enthalpy (kJ/kg), h_3 is the saturated liquid enthalpy (kJ/kg).

3. Results and discussion

The performance of tested nano-lubricants for the varied charges of LPG is as illustrated below:

3.1. Pull down time

Pull down time is the duration taken to attain specified evaporator air temperature within the evaporator cabinet [10]. Table 6 shows the pull down time behaviour of various mass charges of LPG using pure mineral oil and varied homogenized concentrations of TiO_2 nanoparticle/mineral oil mixture (nano-lubricant), and R134a with pure mineral oil in the rig. The results revealed evaporator air temperature increases with increase in nano-lubricant concentration, irrespective of the charges of LPG. Also, the evaporator air temperature reduces with increase in time for both refrigerant types and compressor oils. The lowest evaporator air temperature of −18 °C was obtained using both 60 g charge of LPG with pure mineral oil and 70 g charge of LPG with 0.4 g/L nano-lubricant, whereas the highest evaporator air temperature of −11 °C was obtained using 70 g LPG with 0.6 g/L at steady state.

3.2. Power consumption

The power consumption of the refrigerator system (i.e. summation of power input supplied to the compressor) is shown in Fig. 2. It can be observed from Fig. 2 that the lowest power consumption index of 44 W was obtained using 50 g LPG with 0.2 g/L nano-lubricant while 70 g LPG with 0.6 g/L nano-lubricant had highest power consumption index of 55 W at steady state. At 50 g charge of LPG with 0.2 g/L nano-lubricant, there was 13.7% reduction, while about 1.8% increase was observed at 70 g charge of LPG with 0.6 g/L nano-lubricant, when they were both compared with their corresponding pure mineral oil. Furthermore, all tested nano-lubricant had lower power consumptions at steady state except at 70 g with 0.6 g/L nano-lubricant.

3.3. Compressor power input

Fig. 3 illustrates the compressor power input at steady state for all investigation trials. The lowest compressor power input of 21 W was obtained using 70 g charge of LPG with either 0.2 g/L or 0.4 g/L nano-lubricants, while the highest compressor power

Table 6
Evaporator air temperature responses of selected LPG charges using pure mineral oil and varied nano-lubricant concentrations.

	Time (min)	40 g LPG				50 g LPG				60 g LPG				70 g LPG			
		Pure	0.2 g/L	0.4 g/L	0.6 g/L	Pure	0.2 g/L	0.4 g/L	0.6 g/L	Pure	0.2 g/L	0.4 g/L	0.6 g/L	Pure	0.2 g/L	0.4 g/L	0.6 g/L
1	0	24	25	23	25	22	23	25	25	23	25	25	27	24	22	26	25
2	30	−4	−3	−1	0	−5	−4	−1	0	−6	−3	−2	0	−5	−5	−2	1
3	60	−10	−11	−10	−8	−13	−12	−9	−8	−14	−12	−11	−8	−12	−12	−12	−5
4	90	−13	−14	−13	−11	−16	−15	−14	−11	−16	−15	−14	−11	−14	−14	−15	−9
5	120	−14	−15	−14	−12	−17	−16	−15	−13	−17	−16	−15	−13	−15	−15	−17	−11
6	150	−14	−15	−15	−13	−17	−16	−16	−13	−17	−17	−16	−13	−15	−15	−17	−11
7	180	−16	−15	−15	−13	−17	−16	−16	−14	−17	−17	−16	−14	−15	−15	−18	−11
8	210	−16	−16	−15	−13	−17	−16	−16	−14	−17	−17	−16	−14	−15	−15	−18	−11
9	240	−16	−16	−15	−13	−17	−16	−16	−14	−18	−17	−16	−14	−15	−15	−18	−11

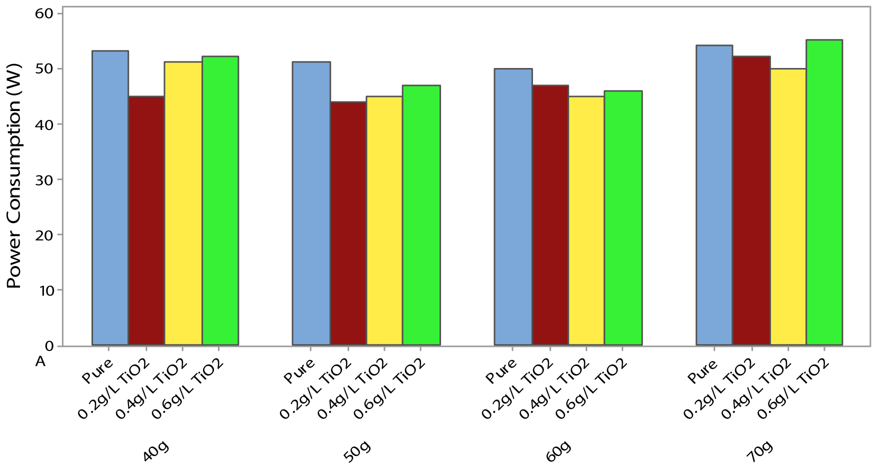

Fig. 2. Power consumption of the varied refrigerant charges based on the pure mineral oil refrigerant and varied concentration of nano-lubricants.

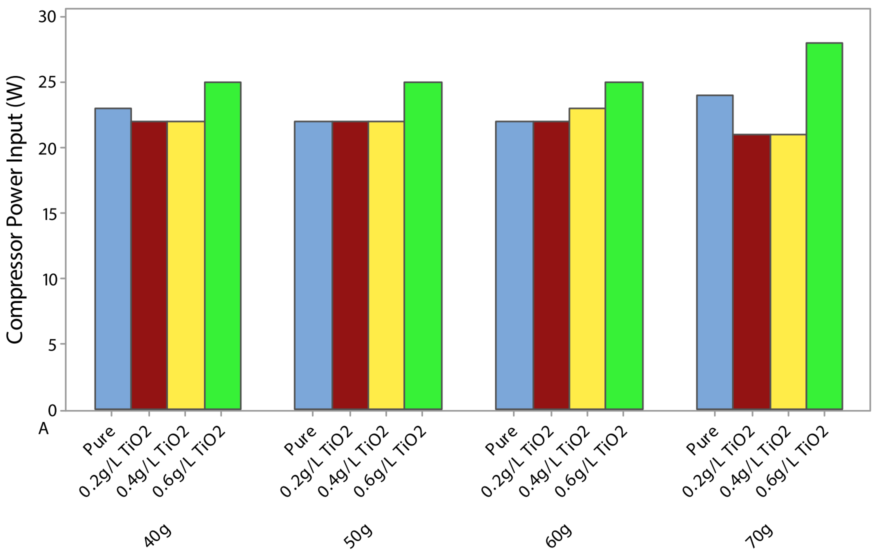

Fig. 3. Compressor power input of the varied refrigerant charges based on the pure mineral oil refrigerant and varied concentration of nano-lubricants.

input of 28 W was obtained using 70 g charge of LPG with 0.6 g/L nano-lubricant. Furthermore, it was observed that all charges of LPG with 0.2 g/L and 0.4 g/L gave slightly lower compressor power input when compared to all charges of LPG using pure mineral oil, except the 60 g charge of LPG using 0.4 g/L which had 4.5% increase in compressor power input.

3.4. Cooling capacity

The average highest cooling capacity (Fig. 4), was obtained using all charges of LPG with 0.6 g/L nano-lubricant. The highest cooling capacity at steady state of 65 W was achieved with 70 g charge of LPG using 0.6 g/L concentration of nano-lubricant; this gave about 16.1% better performance than 70 g charge of LPG of pure mineral oil mixture. Also, the lowest cooling capacity index of 52 W was obtained using 60 g charge of LPG refrigerant with pure mineral oil mixture.

3.5. Coefficient of Performance

It can be seen in Fig. 5, that the highest COP of 2.8 was attained by 40 g charge of LPG using 0.4 g/L concentration of nano-lubricant mixture in the domestic refrigerator system, thus resulting to about 12% improvement when compared to the corresponding pure mineral oil/LPG mixture. The lowest COP value of 2.3, was obtained using 70 g of LPG with 0.6 g/L nano-lubricant mixture. This gave a 4.2% reduction in values, when compared with the corresponding 70 g charge of LPG refrigerant containing pure mineral oil mixture.

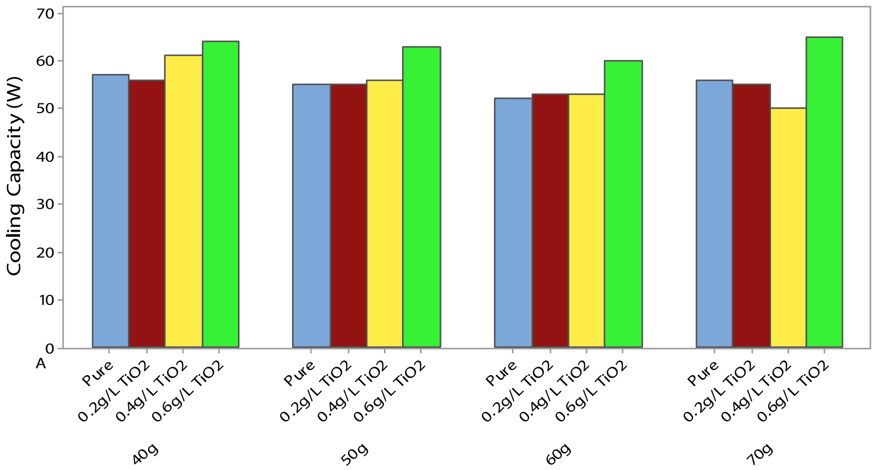

Fig. 4. Cooling capacity of the varied refrigerant charges based on the pure mineral oil refrigerant and varied concentration of nano-lubricants.

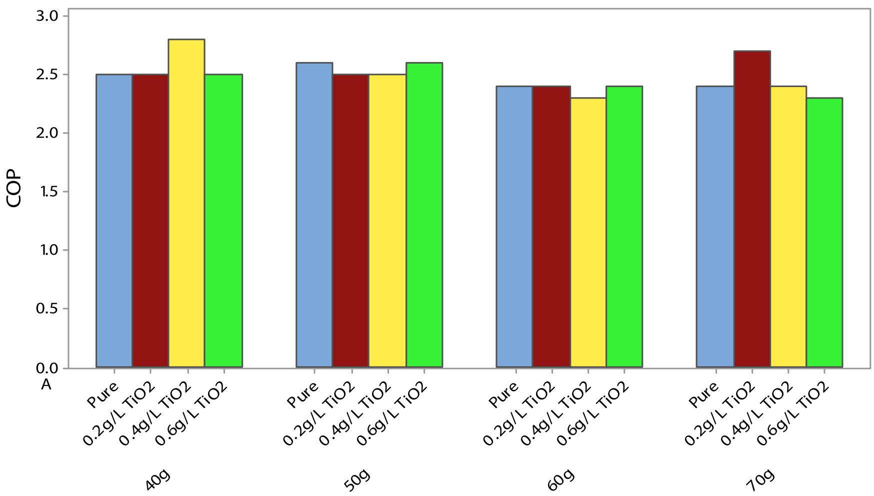

Fig. 5. Coefficient of performance of the varied refrigerant charges based on the pure mineral oil refrigerant and varied concentration of nano-lubricants.

4. Conclusion

From the experimental investigation of optimizing varied concentrations of TiO_2 nanoparticle/mineral oil nano-lubricant in various charges of LPG refrigerant, the following findings were concluded:

- All investigated TiO_2 based nano-lubricants worked safely in the domestic refrigerator.
- All nano-lubricants concentrations had slightly lower steady state evaporator air temperature when compared to pure lubricant for same mass charges of LPG.
- The lowest compressor power input was 21 W, and obtained using 70 g of LPG with either of 0.2 g/L or 0.4 g/L nano-lubricants.
- The highest cooling capacity index of 65 W was obtained at 70 g of LPG using 0.6 g/L concentration of nano-lubricant whereas the highest COP was found to be 2.8 and obtained with 40 g charge of LPG using 0.4 g/L concentration of nanolubricant.

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