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Research Paper

Performance of a domestic refrigerator using selected hydrocarbon working fluids and TiO_2–MO nanolubricant

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HIGHLIGHTS

- TiO_2 concentration significantly affect thermo-physical properties of TiO_2/MO Nano lubricant.
- Energetic performance of domestic refrigerator varies directly with nanolubricant viscosity.
- Energetic performance of R600a driven refrigerator is found better than LPG.
- Compressor Discharge temperature with R600a is found lower than LPG.
- Significant improvement in pull-down time is observed with R600a driven refrigerator.

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ABSTRACT

In this work, the steady state energetic performance of selected mass charges (40, 60 and 80 g) of R600a refrigerant and varying concentrations of TiO_2 based nano-lubricant (0, 0.2, 0.4 and 0.6 g/L) within a domestic refrigerator was investigated and compared with the performance of a domestic refrigerator using LPG refrigerant from authors' previous publication. Additionally, the effect of the TiO_2 concentrations on the thermo-physical properties of the nano-lubricants under similar conditions was investigated. The results reported compressor discharge temperature, compressor power consumption and pull-down time within the R600a-based refrigerator were lower by about 41.92%, 33.33% and 21.05% respectively compared to the LPG-based refrigerator. Moreover, refrigeration capacity and COP of the R600-based refrigerator were higher when compared to LPG-based refrigerator, by about 17.39% and 62.54% respectively. Overall, energetic performance of the R600a-based domestic refrigerator was better than that of baseline (LPG) at optimal concentration of 0.2 g/L of TiO_2 and 40 g charge of R600a refrigerant, under similar operating conditions.

1. Introduction

The deadline for the developing and developed nations to phase out and restrict the application of harmful conventional working fluids (refrigerant) like chlorofluorocarbons (CFCs), hydro-chloro-fluorocarbons (HCFCs) and hydrofluorocarbon (HFCs), that are having either ozone depleting characteristic or high global warming potential or both in refrigeration systems, are justifying the on-going researches using natural refrigerants (especially hydrocarbons based types) as retrofit in refrigeration industry [1]. Restrictions among the manufacturers of refrigeration systems, are in adherence to the United Nation Montreal and Kyoto protocols and emission gap reports, on their stated aims for achieving safe emission targets by year 2100, to ameliorate present devastating effects of climate change [2–4].

Although hydrocarbons have been reported in several literatures as excellent replacement option to conventional refrigerants due to their: (i) close thermodynamic properties, (ii) compatibility with existing refrigeration system (aided with or without modifications), (iii) non-

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ozone depleting characteristics, and (iv) advantages of having almost neutral global warming potential; their utilizations are limited, due to flammability concerns. In the work of Corberán et al. [5], the fear of flammability associated with the utilization of hydrocarbon based refrigerants for small scale domestic refrigerators with charges below 150 g, can be disregarded because: (i) the utilized charge of refrigerant is limited, (ii) the operating ventilation temperatures and pressures conditions are safe, (iii) a typical vapour compression refrigeration system has minimized number of connections and is properly sealed off, and (iv) accessibility to open flame or source of ignition can be controlled. Hence, hydrocarbon based domestic refrigerators can be placed in any location within households. However, some drawbacks have been noted in the experimental and theoretical hydrocarbon applicability in domestic applications. In the work of Fatouh et al. [6], Medhi et al. [7], and Mohamed [8], the following were observed: (i) high discharge pressure and temperature, (ii) low coefficient of performance, (iii) need for compressor oil change from POE to mineral oil, and (iv) the need for the adoption of HC (hydrocarbon) compressor in place of HFC types. These are some of the difficulties being addressed in recent literatures to ensure the sustainability of domestic refrigerators [9]. Moreover, Ghorbani et al. [10] reported that R600a (iso-butane) is an environmentally friendly refrigerant and has superior energy characteristics when compared to other natural refrigerants including R134a [11,12],[13]. Hence, R600a was selected for this work and thereafter compared with LPG refrigerant on the basis of the economic advantage of the latter.

The addition of nanoparticles in domestic refrigerators (homogenised with compressor lubricant or refrigerant and referred to as nanolubricant or nanorefrigerant) have shown that such applications can remove all above-stated shortfalls, hence ensuring more sustainable domestic refrigerators [14–17]. Nanoparticles have been put into several applications to enhance the performance of engineering systems. In the work of Elcock [18], TiO_2 nanoparticle was used as additives to enhance the solubility of mineral oil in hydrofluorocarbon (HFC) refrigerant. It was observed in the work that the refrigeration systems using a mixture of R134a (HFC) and mineral oil (MO) with TiO_2 nanoparticles appear to give better performance by returning more lubricant oil to the compressor, and having similar performance with system using R134a and MO. The work of Bi et al. [19] experimentally investigated the performance of a domestic refrigerator with SUNISO 3GS mineral oil and TiO_2 nanoparticles in the working fluid. The results indicated that the energy consumption of the HFC134a refrigerant using SUNISO 3GS mineral oil and 0.06% mass fraction of TiO_2 nanoparticle mixture as lubricant, reduced the energy consumption by 21.2% when compared to HFC134a and POE oil system. Furthermore, an experimental study on the performance of a domestic refrigerator using Al_2O_3-R134a nano-refrigerant as working fluid was carried out in the work of Senthilkumar and Elansezhian [20]; it was observed that the performance of Al_2O_3-R134a system was better than that of pure lubricant with R134a refrigerant, and giving about 10.30% reduction in energy with 0.2% vol. concentration, while at the same time increasing the heat transfer coefficient. Several other works were conducted on different application of nanoparticles to improve the performance of several processes (e.g. Jwo et al. [21], Peng et al. [22], Kumar and Elansezhian [23]). Recently, Gill et al. [24] experimentally investigated the energetic performance of a domestic refrigerator using LPG with TiO_2 based nano-lubricant as replacement to R134a refrigerant; it was observed that the cooling capacity and COP of TiO_2–LPG refrigerator system were higher than that of R134a with pure lubricant by around 18.74–32.72% and 10.15–61.49% respectively. Additionally, Gill et al. [25] studied the irreversibility analysis of domestic refrigerator system using LPG with TiO_2 based nano-lubricant as replacement for R134a refrigerant. The results revealed that the total irreversibility of LPG-TiO_2 systerm was lower than R134a by around 3.05–4.68%, while the second law efficiency was higher by 4.91–13.38%. The reports further revealed that the performance of the domestic refrigerator system using LPG with TiO_2 nano-lubricant was better than that of R134a under similar operating conditions.

Authors are aware that the work of Bi et al. [26] investigated TiO_2-R600a nano-refrigerant in a domestic refrigerator. We found that the work only assessed the test rig pressures (suction and discharge), temperatures (i.e. evaporation, fresh food storage and frozen food storage compartment), and energy consumption, but did not study the effect of the concentrations of TiO_2 in nano-lubricant on certain energetic performance parameters such as COP and pull-down time of domestic refrigerator. Moreover, LPG based domestic refrigerator along with TiO_2-Mineral oil (MO) nano-lubricant performed safely and efficiently in authors' previous publication (see Gill et al. [24]). Additionally, Bi et al. [26] did not compare the performance of R600a-based domestic refrigerator using TiO_2-Mineral oil (MO) nano-lubricant with performance of other hydrocarbon based domestic refrigerator under similar operating conditions. Hence, in order to expand the research work in Bi et al. [26], this paper studied the effect of TiO_2 nanoparticle concentrations on those energetic performance parameters, that were not considered in Bi et al. [26]. Apart from this, the performance of the R600a-based domestic refrigerator with TiO_2-MO nano-lubricant was analyzed and compared with the performance of a LPG-based domestic refrigerator as assessed by Gill et al. [24], using the optimum charge of LPG and optimum concentration of TiO_2 in nano-lubricant. The test parameters utilized in this study for comparisons were compressor power consumption, refrigeration capacity, coefficient of performance, compressor discharge temperature and pull down time in line with recent studies (see Ohunakin et al. [27], Adelekan et al. [28], Gill and Singh [29,30]). These parameters were measured at 180 min steady state run without ON-OFF cycle. In addition, the influence of increasing the concentration of TiO_2 nanoparticle within the compressor lubricant on selected thermophysical properties (i.e. thermal conductivity, viscosity, lubricity coefficient) was investigated, under similar conditions as carried out in Gill et al. [24].

2. Preparation and stability of TiO_2 based nanolubricant

Titanium dioxide (TiO_2) nanoparticles (5–15 nm) with 99.5% purity obtained from Aldrich Chemical were dispersed in mineral oil (MO) to prepare nano-lubricant according to the procedure adopted in Gill et al. [24]. The characteristics of the mineral oil and TiO_2 particles utilized in this study were already discussed in authors' previous publication [24]. The SEM and EDX diagram of the TiO_2 nanoparticles are shown in Figs. 1 and 2. The stability of the nano-lubricant must be guaranteed before it is infused into the compressor; Thus, a visual sedimentation

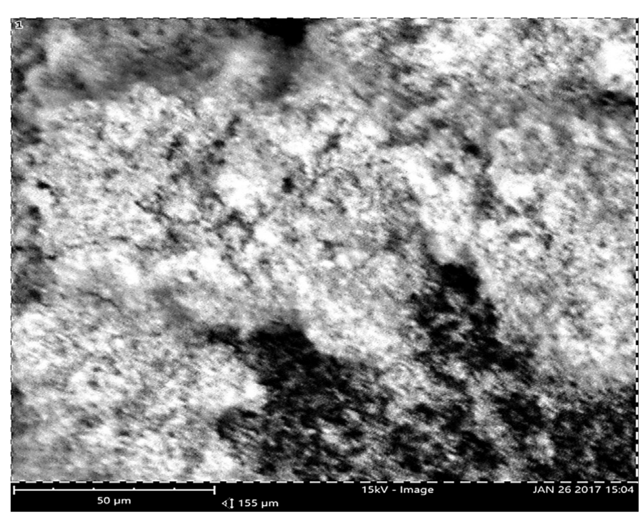

Fig. 1. Scanning Electron Microscopy Image of TiO_2 Nanoparticles (15 nm) [24].

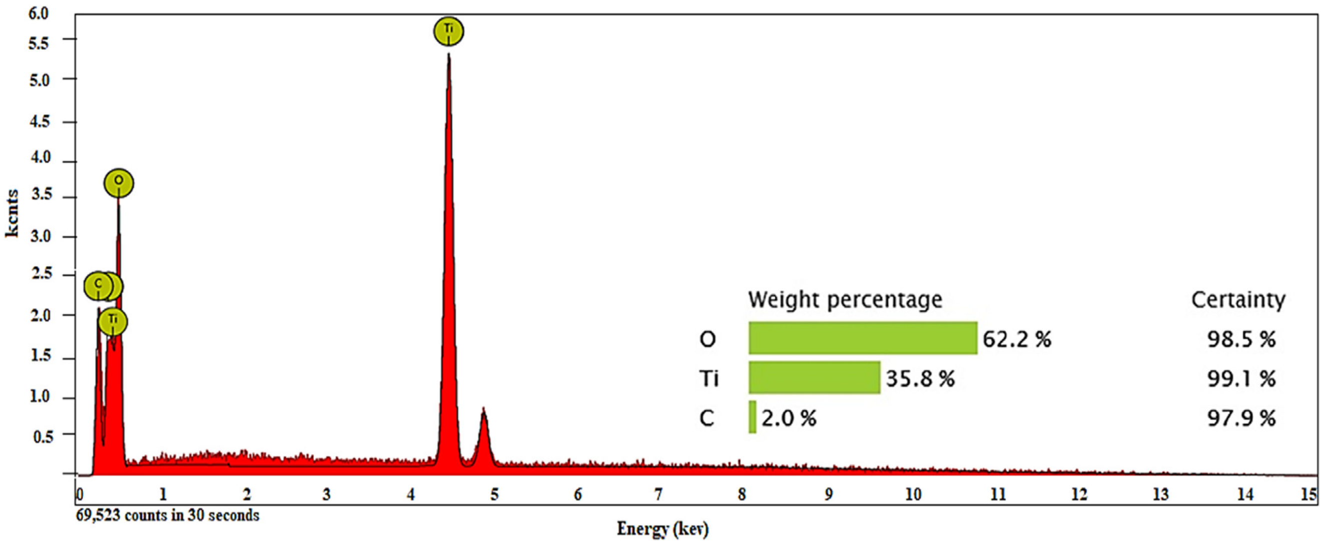

Fig. 2. EDX Diffractogram of TiO_2 Nanoparticles [24].

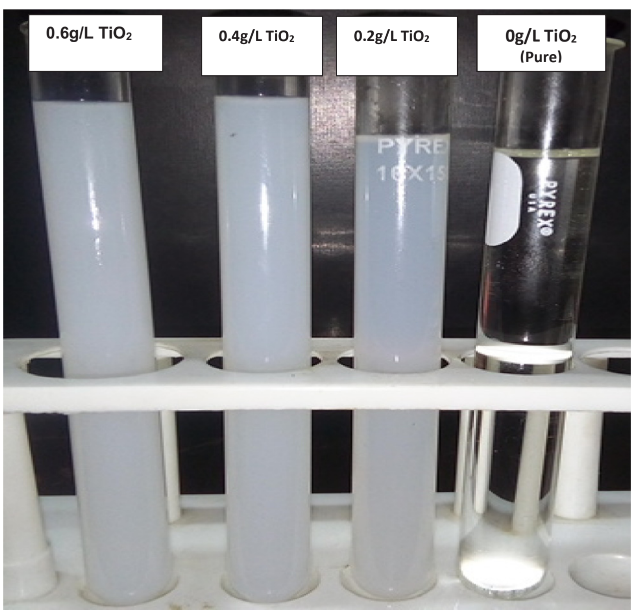

Fig. 3a. Homogenized nano-lubricants after 2 h.

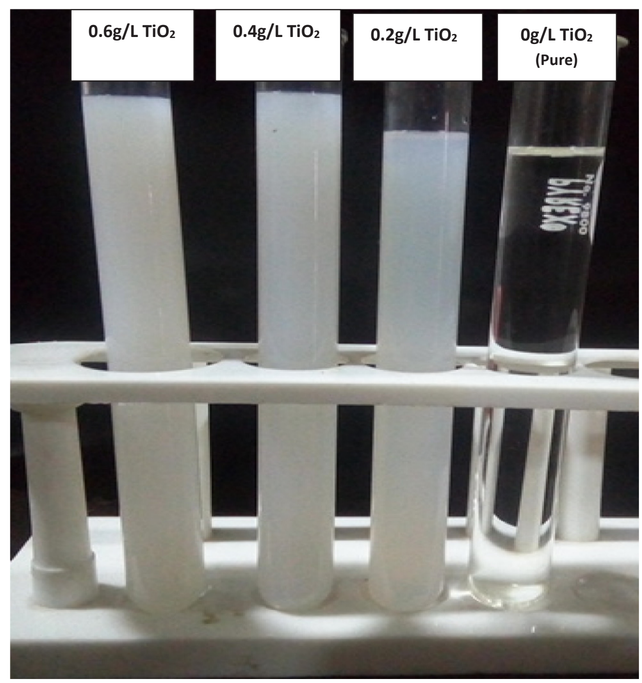

Fig. 3b. Homogenized nano-lubricants after 30 days.

test was carried out of pre-prepared nano-lubricant in accordance with Sharif et al. [39].Observation of the sample showed a slight sedimentation of the nanoparticles, as shown in Figs. 3a and 3b. In addition, an analysis of spectral absorption was performed using a Genesys 10 UV–visible spectrometer to study the deposition of nanoparticles in the prepared mixtures of nanoparticles with lubricant (TiO_2-MO). The equipment measured the absorption of incident light emitted by various mixtures of TiO_2 nanoparticles and lubricants. The high absorption result shown in Fig. 3c confirms a slight sedimentation of nanoparticles in the prepared nanolubricants. In addition, at the peak wavelength (290 nm), the change in absorption as a function of the concentration of nanoparticles shows a direct fit, see Fig. 3d, which corresponds to the Beer-Lambert relationship.

3. Experimental set-up and methodology

The systematic diagram of the experimental setup is shown in Fig. 4, whereas the detailed description of the experimental setup can be found in the previous publication of the authors (see Gill et al. [24]). The procedure for infusing the TiO_2 based nano-lubricant in the compressor was already discused in authors previous publication (see Gill et al. [24]). However, fresh set of experiments were performed with different charges of R600a (40, 60 and 80 g) and concentrations (0, 0.2, 0.4 and 0. 6 g L^{-1}) of nano-lubricants based on TiO_2, to evaluate the test parameters including: compressor power consumption, cooling capacity, COP, compressor discharge temperature, and pull-down time according to the procedure described in previous publication of authors (see Gill et al. [24]). After each test, repeated flushing and evacuation of the compressor with clean mineral oil was carried out until the system becomes clean and free of any left-over nanoparticle in preparation for another trial. Furthermore, the range of experimental conditions utilized for this study is shown in Table 1. The thermal conductivity (K), and viscocity (V) of various concentration of TiO_2 based nano-lubricant were evaluated using KD2 Pro Thermal property analyzer, and Brookfield DV-E rotary viscometer respectively, as mentioned in the procedure of Nabil et al. [31]. However, the lubricity

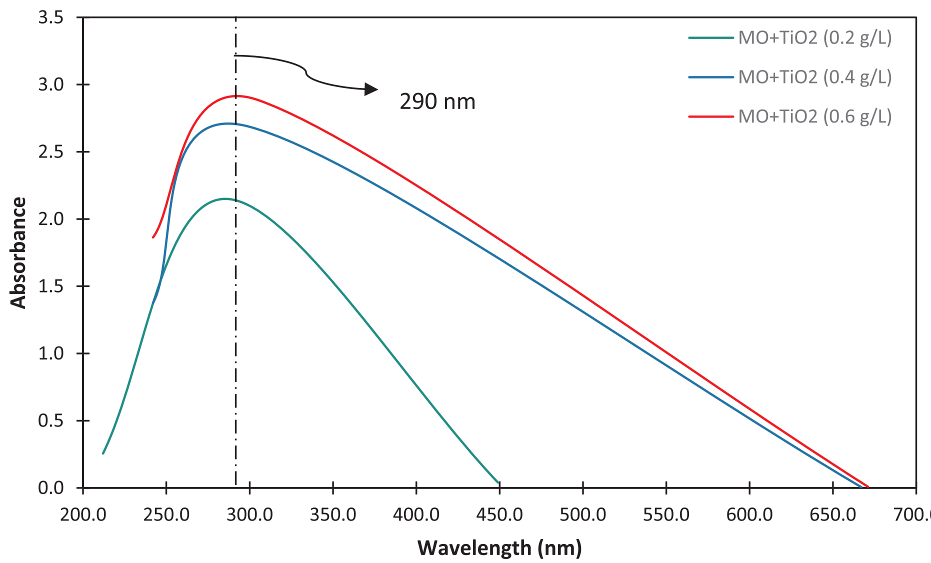

Fig. 3c. Absorbance of various TiO_2 Nanoparticles-lubricant Mixtures.

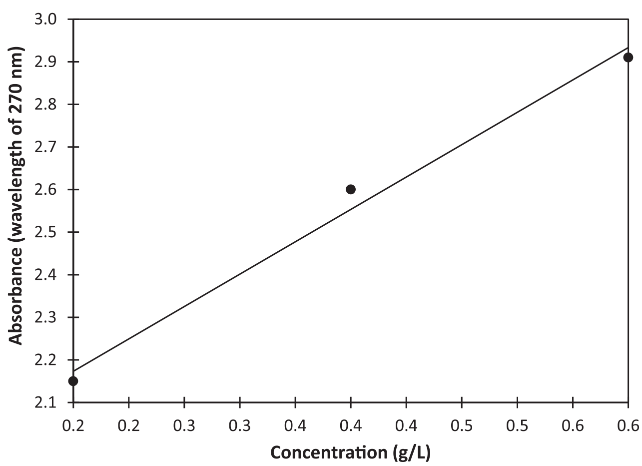

Fig. 3d. TiO_2/MO nanolubricant absorbance with different concentration of TiO_2.

coefficent (L) was measured using an OFITE EP lubricity tester (see manufacturer's manual [32]). Furthermore, each trial was carried out three times and the mean value was noted.

3.1. Uncertainty analysis

The uncertainty of measuring instruments can be found in Table 2; they were estimated in accordance to Schultz and Cole [33] methodology as utilized in a recent work done by Ohunakin et al. [34]. Furthermore, the estimation of the required uncertainty parameter R was computed using Equation (1) as expressed in Schultz and Cole [33] and Sheikholeslami and Ganji [35] methodologies.

$$U_R = \left[\sum_{i=1}^{n}\left(\frac{\partial R}{\partial_{V_i}}U_{V_i}\right)^2\right]^{\frac{1}{2}} \tag{1}$$

where U_R represent the total uncertainty, U_{V_i} is the uncertainty of each independent variable and n is the total number of variables. The uncertainties of the parameters can be seen in Table 3. The maximum percentage uncertainty across all investigated parameters was less than 3%.

3.2. Analysis of variance and multiple regression

The significance of varying the concentration of TiO_2 in the compressor lubricant (i.e. 0, 0.2, 0.4 and 0.6 g/L) and mass charges of the refrigerant (i.e. 40, 60 and 80 g), on the performance of the test rig, were investigated using one-way analysis of variance (ANOVA). The cumbersome and error magnification characteristics of pairwise comparison of means observations greater than two, were the justifications for adopting one-way ANOVA in this study. Table 4 shows the summary of the one-way ANOVA. The null hypothesis was rejected when $F > F_{critical}$. Also, the null hypothesis was valid and accepted when $F < F_{critical}$. Therefore, the hypothesis can be summarized as:

Null hypothesis: H_o: $\mu_1 = \mu_2 = \mu_3 \cdots\cdots\cdots\cdots = \mu_n$; There are no significant differences if$F < F_{critical}$.
Alternate hypothesis: H_1: $\mu_1 \neq \mu_2 \neq \mu_3 \cdots\cdots\cdots\cdots = \mu_n$; There are significant differences if $F > F_{critical}$.

Inferences from Table 4 showed that significant changes were seen in the measured power consumption, cooling capacity and discharge temperature of the system by varying the nanolubricant concentrations; by increasing the refrigerant mass charge, only the pressure ratio of the system was significantly affected. However, the coefficient of performance of the system was not influenced by varying the nano-lubricant concentration and refrigerant mass charge.

Multiple regression was utilized: (i) to determine the significances of the thermo-physical characteristics (i.e. thermal conductivity, lubricity coefficient, and viscosity) in predicting the system energy performance considered to be significant when the P value ≤ 0.15, and (ii) to develop a regression model with selected significant thermo-physical characteristics. The summary of the multiple regression analysis is described in Table 5.

4. Results and discussion

The thermo-physical properties of the nano-lubricants prepared with varied concentrations of TiO_2 nanoparticles, were evaluated experimentally and compared with properties of baseline mineral oil (MO) lubricant under similar operating conditions; their influence on the R600a refrigerant based domestic refrigerator were measured using the selected test parameters and compared with performances in the work of Gill et al. [24].

Figs. 5, 7 and 9 compared the thermo-physical properties (i.e.

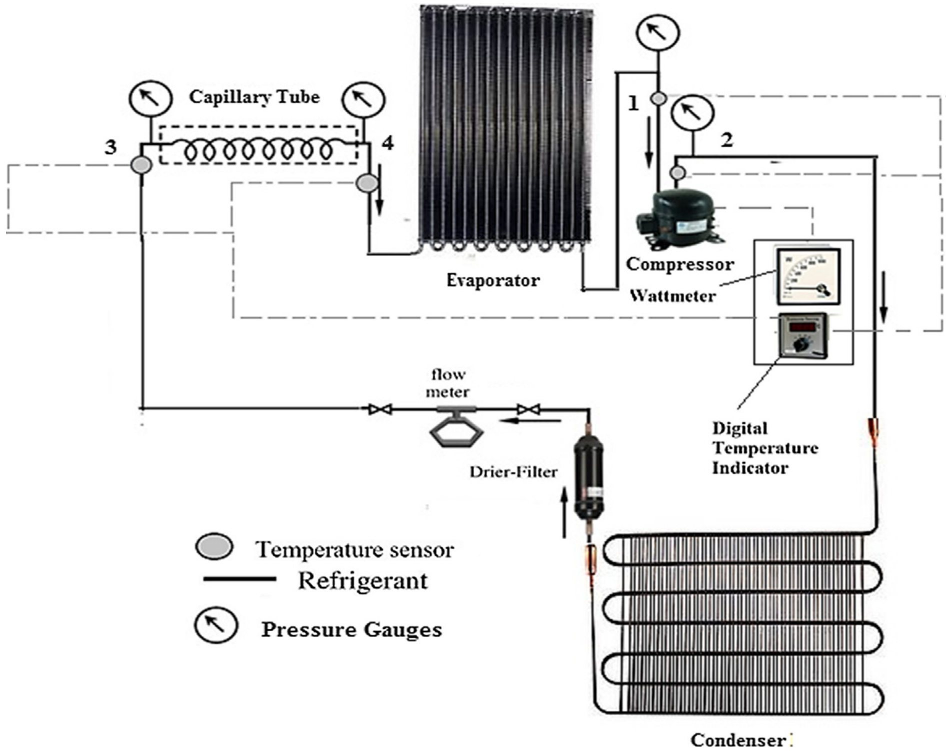

Fig. 4. Schematic Diagram of Experimental Test rig [24].

Table 1
Range of experimental conditions.

S/N	Parameter range of experiment		
1	Refrigerant name	R600a	LPG (60:40 Propane–Butane Mixture)
2	Refrigerant charge	40,60,80 g	40 g
3	Compressor lubricant	Mineral oil, TiO_2–MO nanolubricants	TiO_2–MO nanolubricants
4	Concentration of TiO_2 nano-lubricant	0.0–0.6 g/L	0.4 g/L
5	Test environment temperature	32 °C	32 °C
6	Capillary tube length	2 m	2 m
7	Evaporator type	Air cooled	Air cooled

Table 2
Characteristics of the measuring instruments.

S/N	Measured data	Manufacturers specification	Range	Uncertainty
1	Temperature	Digital thermocouple K	−50 °C to 750 °C	± 1 °C
2	Pressure	Digital pressure gauge	5–5000 kPa	± 1%
3	Power consumption	Digital Watt/Watt-h-meter	1–3000 W (0.0001–999.9 kW h)	± 1%
4	Flow meter	Digital flow meter	0–20 g/s	± 0.2%

Table 3
Uncertainty in evaluated parameters.

S/N	Parameters	Absolute uncertainty
1	T_1	± 0.2 °C
2	T_2	± 0.2 °C
	T_3	± 0.2 °C
3	T_4	± 0.2 °C
4	P_1, P_4	± 2 kPa
5	P_2, P_3	± 5 kPa
6	COP	± 2.11%

Table 4
Summary of ANOVA analysis.

S/N	Parameter	Between	F	$F_{critical}$	F < $F_{critical}$	Significant difference
1	COP	Concentration	2.13	4.07	Yes	No
		Mass	1.54	5.14	Yes	No
2	Power consumption	Concentration	5.17	4.07	No	Yes
		Mass	1.95	4.26	Yes	No
3	Cooling capacity	Concentration	6.08	4.07	No	Yes
		Mass	0.58	4.26	Yes	No
4	Discharge temperature	Concentration	5.24	4.07	No	Yes
		Mass	2.01	4.26	Yes	No
5	Pressure Ratio	Concentration	0.15	4.07	Yes	No
		Mass	77.3	4.26	No	Yes

thermal conductivity, viscosity and lubricity cofficent) of the selected concentrations of TiO_2 based nano-lubricants and pure mineral oil based lubricant. The thermal conductivity of TiO_2–MO nano-lubricant, and mineral oil evaluted using KD2 pro can be found in Fig. 5. The

Table 5
Summary multiple regression analysis.

S/N	Parameter	P value ≤ 0.15			Regression model equation	Predicted	Actual	% deviation
		K	L	V				
1	COP	0.75	0.87	0.04	Y = 5.60–0.12 V	2.72	2.74	0.7299
2	Power Consumption	0.33	0.57	0.04	Y = 51.99 + 0.55 V	65.19	69.69	6.4572
3	Cooling Capacity	0.37	0.52	0.13	Y = 268.55–4.02 V	172.07	190.95	9.8874
4	Discharge Temperature	0.53	0.75	0.01	Y = 6.32 + 1.92 V	52.4	51	2.7451
5	Pressure Ratio	0.96	0.91	0.67	N/A	N/A	N/A	N/A

Where N/A implies not applicable. Since the estimated P values for pressure ratio were all greater than 0.15. Kindly note that the corresponding thermal conductivity, lubricity coefficient and viscosity were denoted as K, L and V.

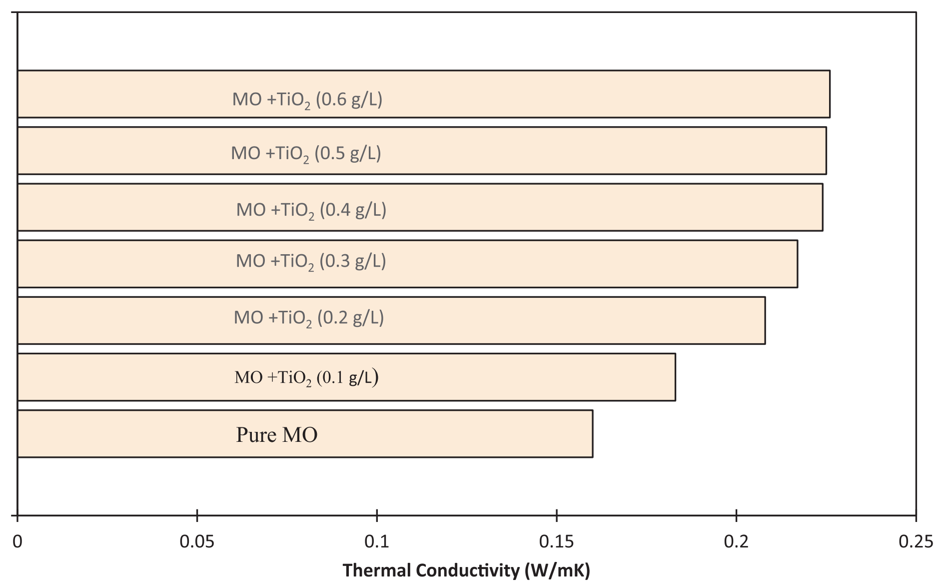

Fig. 5. Comparison of thermal conductivity of TiO_2-MO nano-lubricant with varying concentration of TiO_2 (i.e. from 0.1 to 0.6 g/L) and pure mineral oil lubricant under similar conditions.

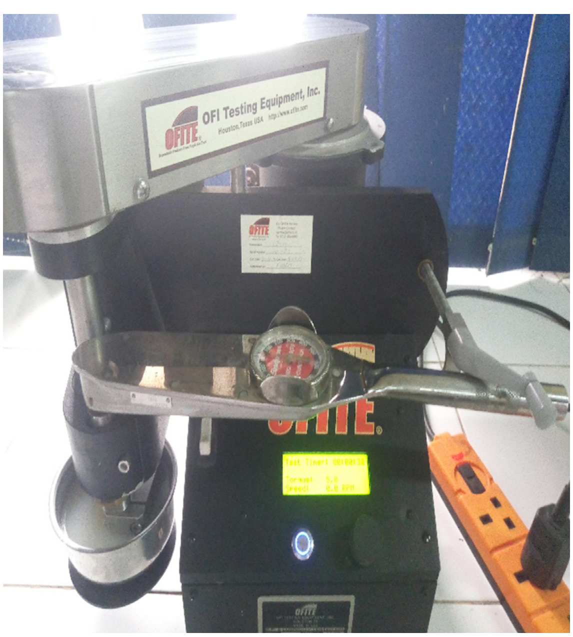

Fig. 6. Measurement with OFITE EP- lubricity tester.

thermal conductivities of the TiO_2–MO nano-lubricants were higher than baseline MO lubricant by about 14.37–41.25%. These were due to Brownian motion and slip mechanisms between the base-liquid layers and the TiO_2 nanoparticles as explained in Ohunakin et al. [34]. The figure further shows that the thermal conductivity of TiO_2 based nano-lubricant was enhanced by about 23.49% with increase in the concentration of TiO_2 from 0.1 to 0.6 g/L in nano-lubricant. The observed enhancement in thermal conductivity was due to increase in the number of nanoparticles in the fluid which increased the surface to volume ratio and the number of collusions [36]. However, no significant enhancement in the thermal conductivity was observed beyond 0.4 g/L concentration of TiO_2 because the increase in the number of particles in the nano-lubricant exceeded limits capable of sustaining increasing number of collusions [36].

Nanoparticles have been shown to play important roles in improving lubricating properties of lubricating oils. These lubricating properties affects compressor power consumption; hence, the effect of TiO_2 nanoparticle concentrations on lubricity coefficient of lubricating oil, is an important aspect of the study. The lubricity coefficient of TiO_2–MO nano-lubricant at selected concentrations of TiO_2 were determined using OFITE EP- lubricity tester (Fig. 6) at controlled room temperature in accordance to manufacturer's requirement [32]. Fig. 7 shows the changes in the lubricity coefficents of the TiO_2-MO nano-lubricants with increasing concentrations of TiO_2 nanoparticles when compared with baseline mineral oil. It can be seen from Fig. 7 that the coefficient of lubricity decreases with increasing concentration of TiO_2 nano-lubricant from 0.1 to 0.4 g/L, and thereafter increased with increasing concentrations of TiO_2 nano-lubricant from 0.4 to 0.6 g/L. The decrease in the lubricity coefficients were due to third body rolling effects between the sliding surfaces of the nanoparticles and the lubricant at lower concentration levels (0.1–0.4 g/L), whereas at larger

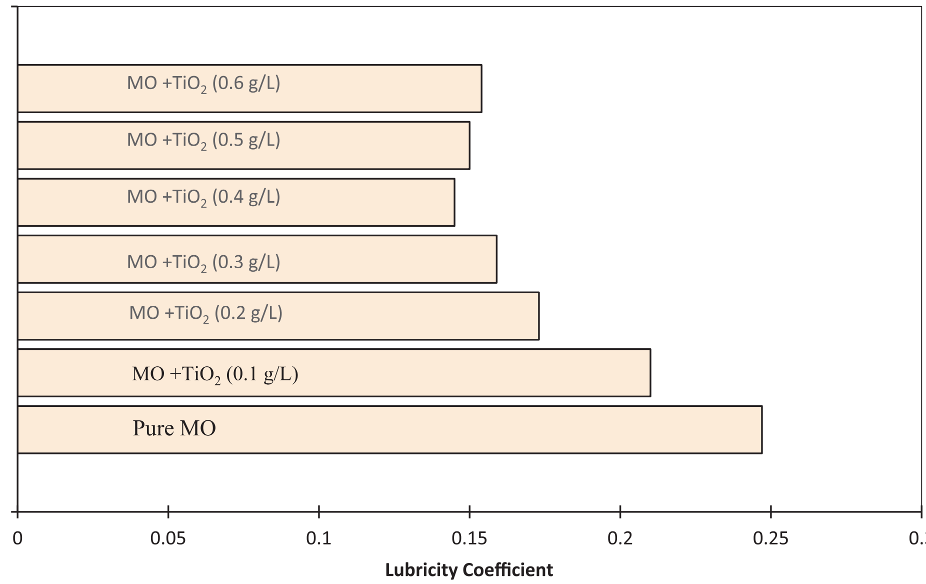

Fig. 7. Comparison of the lubricity coefficient of TiO_2-MO nano-lubricant with different concentration of TiO_2 (0.1–0.6 g/L) and pure mineral oil lubricant under similar operating conditions.

Fig. 8. Measurement with Brookfield DV-E Viscometer.

concentrations (0.4–0.6 g/L), the lubricity coefficient increased because of particle-particle interactions resulting from agglomeration [37]. Furthermore, the least value of lubricity coefficient was observed at 0.4 g/L of the TiO_2–MO nano-lubricant concentration (see Fig. 6). Additionally, the lubricity coefficient of the TiO_2–MO nano-lubricant was lower than baseline mineral oil by about 14.97–41.29%.

The viscosity of TiO_2-MO nano-lubricant using selected concentrations of TiO_2 and with pure mineral oil was measured at room temperature using a Brookfield DV-E Viscometer (Fig. 8). Fig. 9 shows the changes in the viscosity of the TiO_2-MO nano-lubricant within the selected concentrations of TiO_2 nanoparticles in comparison with that of pure MO. We found in Fig. 9 that the viscosity of TiO_2-MO nano-lubricant at 0.1–0.6 g/L concentration were lower than that of pure MO by about 2–6%. It can be observed from the result that viscosity of nano-lubricant decreased with increasing concentration of TiO_2 in the nano-lubricant up to from 0.2 g/L, and thereafter rose with increasing concentration of TiO_2 to peak the viscosity value at 0.6 g/L. This reduction in viscosity of nano-lubricant up to 0.2 g/L was due to infusion of nanoparticles between the layers of the lubricant oil, thus acting as bridge which reduces the viscous friction between the layers [38]. Furthermore, the observed enhancement in viscosity of the nano-lubricants at concentration of TiO_2 beyond 0.2 g/L, was due to the significant developments of agglomeration within nano-lubricants at higher volume concentrations (see Sharif et al. [39]).

The test parameters of the R600a (present work) (i.e. pressure ratio, compressor power consumption, compressor discharge temperature, refrigeration capacity, COP and Pull-down time) and LPG driven domestic refrigerator in Gill et al. [24], were compared in Figs. 10–14.

Fig. 10 shows the change in the pressure ratio for the R600a based domestic refrigerator system when infused with R600a (varying charges from 40 to 80 g) and TiO_2 nano-lubricants with concentrations ranging from 0 to 0.6 g/L; this change in pressure ratio was compared with the previous work of Gill et al. [24]. It was concluded in authors' previous study [24] that the LPG based domestic refrigerator system with 40 g of LPG and 0.4 g/L of concentration of TiO_2 gave the highest value of COP under similar conditions of test. The result illustrates that pressure ratio within the R600a based domestic refrigerator system at 40 g of refrigerant charge, and 0–0.6 g/L of TiO_2 concentrations were lower than the baseline LPG based domestic refrigerator system (i.e. LPG (40 g) at 0.4 g/L of TiO_2) by about 0.60–3.06% due to lower discharge pressure. Furthermore, the pressure ratio within the R600a based domestic refrigerator system (R600a (60–80 g) at 0–0.6 g/L concentration of TiO_2) were higher than the baseline configuration (i.e. LPG (40 g) at 0.4 g/L of TiO_2) by about 1.18–6.21% due to higher discharge pressure. In addition, the least value of pressure ratio of 4.84 was observed in R600a based domestic refrigerator system when infused with R600a (40 g) and 0.2 g/L concentration of TiO_2. In the work of Gill et al. [24], similar decrease in pressure ratios were attributed to low discharge pressures.

The compressor power consumption of R600a based domestic refrigerator system (R600a (40–80 g) at 0–0.6 g/L of TiO_2) and LPG based domestic refrigerator system (LPG (40 g) at 0.4 g/L of TiO_2) were compared in Fig. 11. It can be seen from Fig. 11 that the compressor power consumption of R600a based domestic refrigerator system decreases with increase in the concentration of TiO_2 nanoparticles from 0 to 0.2 g/L for a fixed charge of R600a refrigerant. The reduction in the compressor power consumption may be due to the reduction in pressure ratio (see Fig. 10) and reduction in load of the compressor; this is made

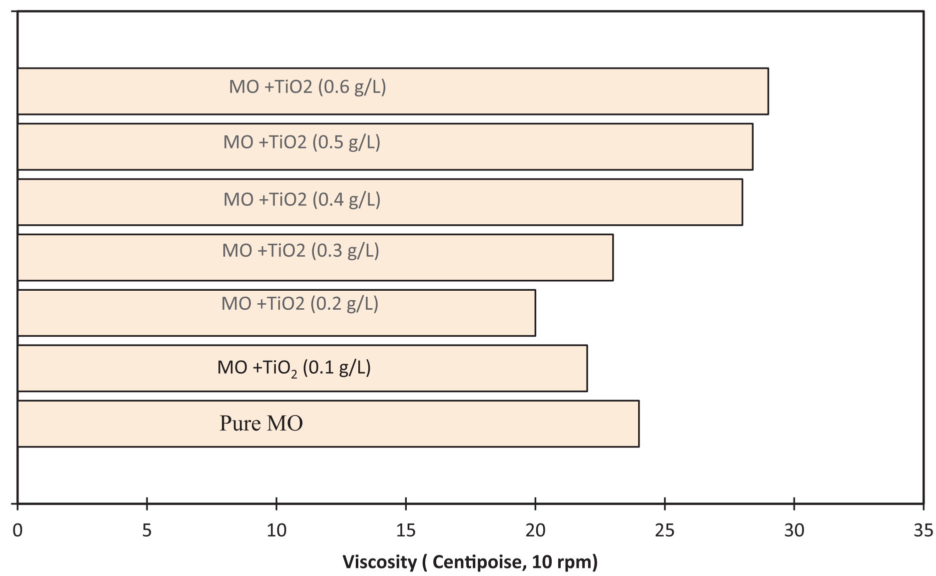

Fig. 9. Comparison of the viscosity of TiO_2-MO nano-lubricant with different concentration of TiO_2 (0.2–0.6 g/L) and pure mineral oil lubricant under similar operating conditions.

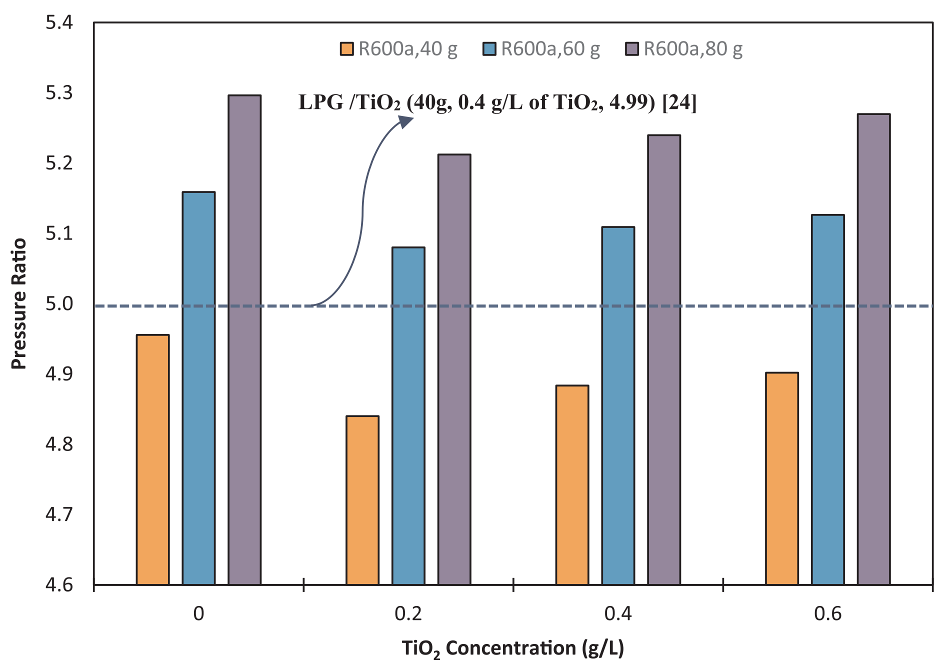

Fig. 10. Comparison of the pressure ratio in R600a and LPG based domestic refrigerator systems under similar operating conditions.

possible by a fall in the viscosity of R600a nano-lubricant mixture (see Fig. 9). Moreover, the compressor power consumption increased with increase in concentration of TiO_2 nanoparticle from 0.2 to 0.6 g/L due to increase in the pressure ratio and viscosity of nano-lubricant of the R600a-nano refrigerant mixture in line with the work of Lou et al. [40]. In addition, the compressor power consumption of the R600a refrigerator system was increased by adding more refrigerant to the system in line with the work of Gill et al. [24]. It can be further observed from Fig. 11 that R600a based domestic refrigerator system with R600 (40 g) at 0.2 g/L of TiO_2 mixture, has the minimum compressor power consumption due to having the least pressure ratio within the test rig. Apart from this, the results showed that the compressor power consumption of the system with R600 (40–80 g) at 0.2 g/L of TiO_2 mixture was lower than LPG-based domestic refrigerator compressor power consumption by about 1.94–33.33% (witnessing lesser pressure ratio) as shown in Fig. 10.

The compressor discharge temperatures of the R600a based domestic refrigerator system (R600a (40–80 g) at 0–0.6 g/L of TiO_2) and that of LPG based domestic refrigerator system (LPG (40 g) at 0.4 g/L of TiO_2) [24] were compared in Fig. 12. It can be observed from Fig. 12 that the compressor discharge temperatures of the R600a-based refrigerator system decrease with increase in concentration of TiO_2 from 0 to 0.2 g/L. This is attributed to noticeable reductions in lubricity coefficient, pressure ratio and viscosity of nano-lubricants. The reduction in lubricity coefficient brought about a reduction in heat generation via friction within the compressor, whereas the reduction in viscosity of nano-lubricant oil resulted in increased dissipation of heat within the compressor, due to enhancement in the heat transfer coefficient (see Sharif et al. [39], Azmi et al. [15]); hence, the compressor discharge temperatures reduce. Furthermore, compressor discharge temperature of R600-based refrigerator system increased with increase in the concentration of nanoparticles in lubricant from 0.2 to 0.6 g/L.

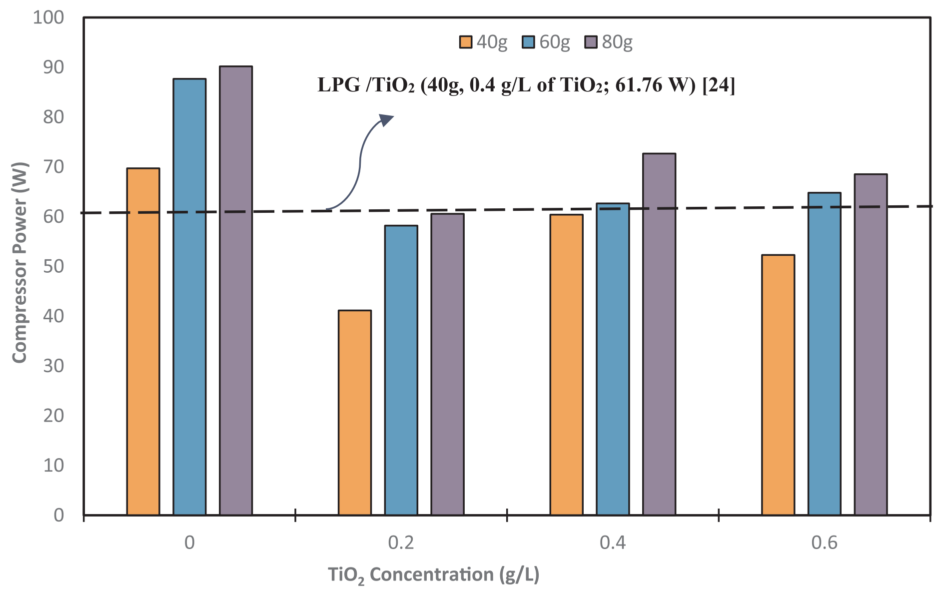

Fig. 11. Comparison of the compressor power consumption in R600a and LPG based domestic refrigerator systems under similar operating conditions.

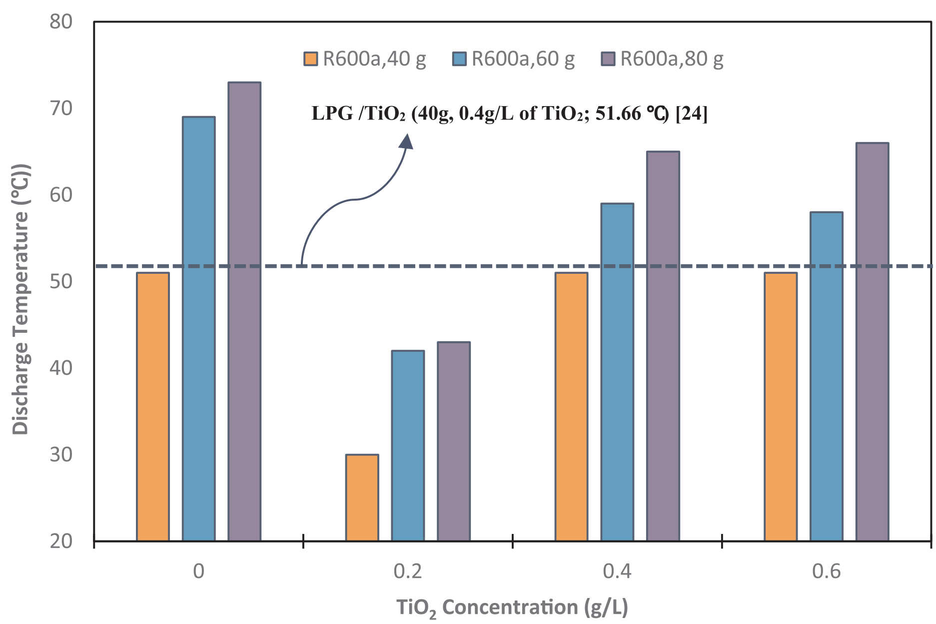

Fig. 12. Comparison of the compressor discharge temperature in R600a and LPG based domestic refrigerator systems under similar operating conditions.

The rise in discharge temperatures were insignificant beyond 0.4 g/L (see Fig. 12). This rise in the compressor discharge temperature may be due to increase in pressure ratio, and viscosity of the nano-lubricant. In addition, increase in viscosity of the nano-lubricant may increase the compressor load, thus bringing about a rise in heat generation within the compressor and ultimately lead to a rise in the discharge temperature. Under selected operating conditions, the compressor discharge temperature of the R600a based refrigerator system (R600a (40 g) at 0.2 g/L of TiO_2), gave the least discharge temperature (30 °C). However, it was also observed that increasing the charges of R600a refrigerant brought about a rise in compressor discharge temperature. This behaviour was also noted in the work of Gill and Singh [29] and Gill et al. [21]. In addition, the compressor discharge temperature of the R600a based refrigerator system using 40 g charge of R600a refrigerant at 0.2 g/L of TiO_2 nano-refrigerant mixture, was lower than that of LPG based refrigerator system (LPG (40 g) at 0.4 g/L of TiO_2) by about 21.66 °C (41.92%) . Hence, the stator winding temperature of the compressor using R600a is expected to be lesser than that of the LPG driven system, due to lower compressor discharge temperature. This is necessary in order to improve the stability, efficiency, and durability of R600a-compressor motor and extend the life of compressor using R600a refrigerant, under similar operating conditions.

The refrigeration capacity and COP of the R600a-based domestic refrigerator system (R600a (40–80 g) at 0–0.6 g/L of TiO_2) and LPG-based domestic refrigerator system (LPG (40 g) at 0.4 g/L of TiO_2) are shown in Figs. 11 and 12. The figures show that the refrigeration capacity and COP of R600a based domestic refrigerator system (R600a (40 g) at 0–0.6 g/L of TiO_2) increased with increase in the concentration of TiO_2 from 0 to 0.2 g/L; after achieving the peak values within the system, both the refrigeration capacity and COP decreased as the concentration of TiO_2 rose beyond 0.2 g/L. The observed increase in refrigeration capacity with increasing concentration of TiO_2 nanoparticles from 0 to 0.2 g/L is mainly due to improved heat transfer characteristics and fluidity of the R600a-nano lubricant mixtures that resulted from

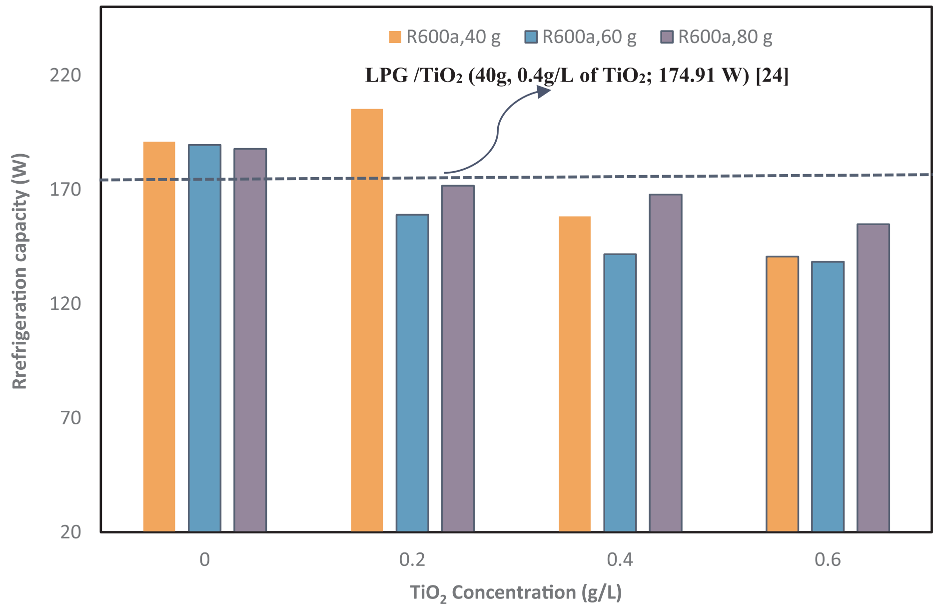

Fig. 13. Comparison of the refrigeration capacity in R600a and LPG based domestic refrigerator systems under similar operating conditions.

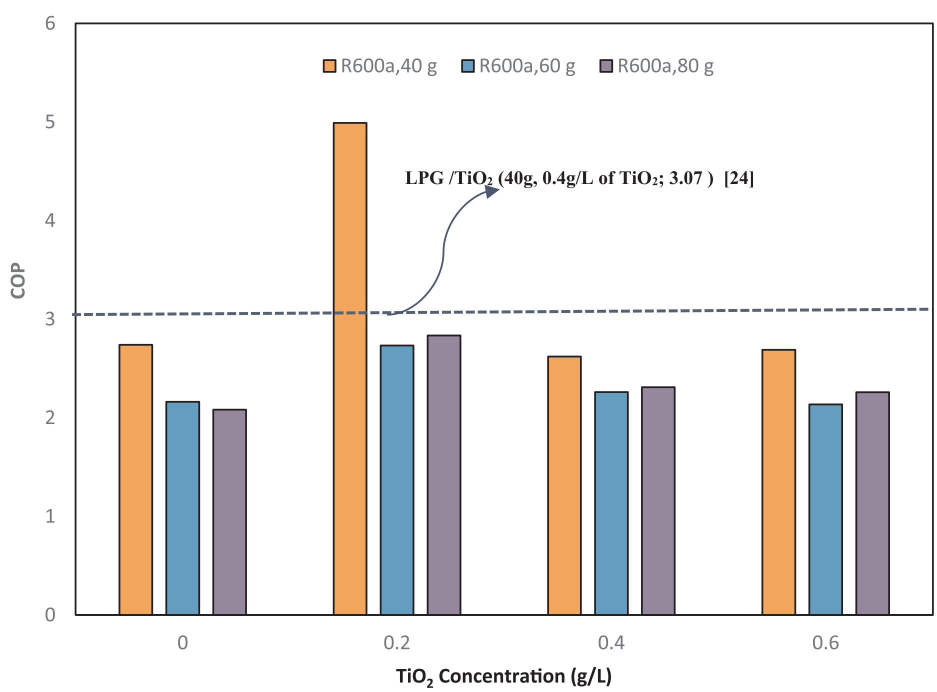

Fig. 14. Comparison of the COP in R600a and LPG based domestic refrigerator systems under similar operating conditions.

decrease in the viscosity of nano-lubricant [34,38]. Moreover, the enhancement in COP of the system (R600a (40 g) at 0–0.6 g/L of TiO_2) with an increase in concentration of TiO_2 from 0 to 0.2 g/L, was mainly due to a rise in the refrigeration capacity and decrease in the compressor power consumption of the domestic refrigerator. Despite the noticeable increase in the thermal conductivities of the nano-lubricants with increasing TiO_2 concentration, a reduction in refrigeration capacity of the system (R600a (40 g) at 0–0.6 g/L of TiO_2) was observed with increasing concentrations of TiO_2; this is due to the drop in convective heat transfer of the R600a based nano-fluid, because of the rise in their viscosities [41]. Furthermore, observed decrease in refrigeration capacity of the system (R600a (60–80 g) at 0–0.6 g/L of TiO_2) with increasing concentration of TiO_2 nanoparticles from 0 to 0.6 g/L is mainly due to decreased enthalpy difference across the evaporator coil.

The COP of R600a based domestic refrigerator system (R600a (40 g) at 0–0.6 g/L of TiO_2), also dropped with increase in concentration from 0.2 to 0.6 g/L due to the decline in refrigeration capacity, and enhancement in the compressor power consumption (see Figs. 11 and 13). In addition, the refrigeration capacity and COP of R600a based domestic refrigerator system (R600a (40 g) at 0.2 g/L of TiO_2) were higher than that of LPG based domestic refrigerator system (LPG (40 g) at 0.4 g/L of TiO_2) by about 17.39% and 62.54% respectively (see Fig. 14). Similar trend in refrigeration capacity and COP were observed in this work and that of Gill et al. [24].

Concerning the maximum values COP per concentration as shown in Fig. 14, all the 40 g charges of R600a refrigerant for the selected TiO_2 concentrations (i.e. 0–0.6 g/L) were selected for the evaluation of pull-down time, in line with the work of Ohunakin et al. [34]. Fig. 15

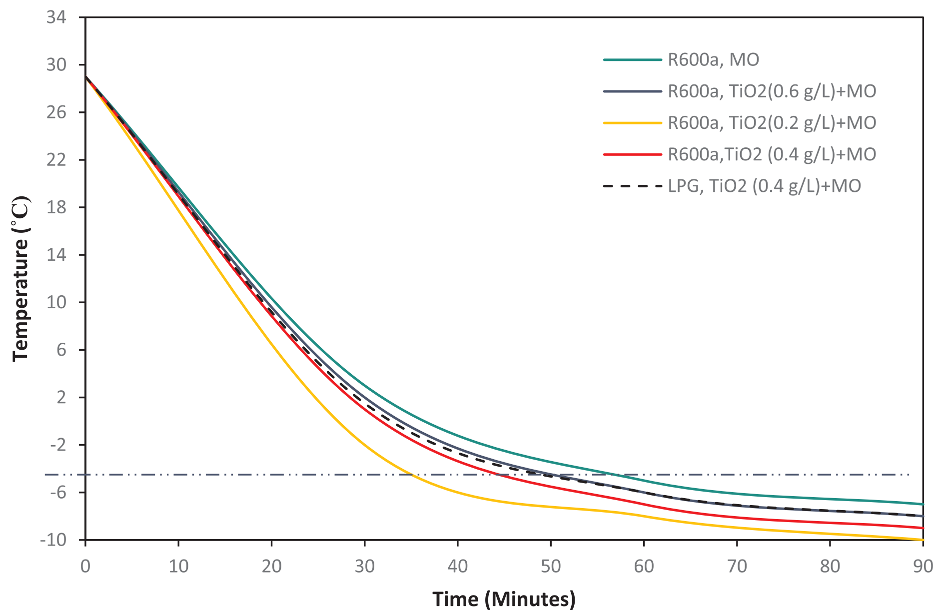

Fig. 15. Comparison of the pull downtime in R600a and LPG based domestic refrigerator systems under similar operating conditions.

showed the least and highest pull-down time in comparison with the baseline (LPG 40 g at 0.4 g/L of TiO_2) within the domestic refrigerator system. It can be seen that the infusion of 40 g charge of R600a refrigerant using 0.2 g/L, and 40 g charge of R600a using 0 g/L nanofluid mixtures gave the coldest and hottest cabinet air temperatures of -10 and -6 °C within the refrigerator. Overall, the use of R600a within the system gave lower pull-down time in comparison to the baseline (LPG 40 g at 0.4 g/L of TiO_2); this observed behaviour was attributed to improved heat transfer characteristics and lower viscosities, as found in a similar work by Beheshti et al. [38]. The estimated pull-down time using R600a refrigerant with nano-lubricant when compared with the baseline system (LPG 40 g at 0.4 g/L of TiO_2) was 5.26–21.05%.

5. Conclusion

This work compared the energetic performance of a domestic refrigerator that is charged with R600a and LPG refrigerants, and infused with varying concentration of TiO_2 based nano-lubricants. The following conclusions were drawn:

- All selected mass charges of R600a refrigerant with varying concentrations of TiO_2 nanoparticle within the domestic refrigerator worked safely. The effects of varying the concentration of TiO_2 nanoparticle within the compressor lubricant, were significant on the thermo-physical properties.
- The energetic performance of R600a-TiO_2 nano-refrigerant driven refrigerator varies directly with nano-lubricant viscosity. The pressure ratio of the system gave a reduction in the range of 0.60–3.06% for all TiO_2 concentrations and 40 g charge of R600a refrigerant, when compared to LPG refrigerant.
- The power consumed within the system for all charges of R600a refrigerant and 0.2 g/L concentration of TiO_2 nano-lubricant, were about 1.94–33.33% lower than the baseline LPG refrigerant. Also, all charges of R600a refrigerant at 0.2 g/L concentration of TiO_2 nano-lubricant, gave the least discharge temperature within the system when compared with the baseline (LPG).
- The highest value of refrigeration effect was 205.34 W while that of COP was 4.99, for 40 g charge of R600a refrigerant at 0.2 g/L concentration of TiO_2 mixture. Significant improvement in pull-down time of the system was observed with the utilization of R600a-TiO_2 nano-lubricants, when compared with the baseline (LPG 40 g at 0.4 g/L of TiO_2).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.applthermaleng.2019.114004.

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