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Research article

Performance of a domestic refrigerator in varying ambient temperatures, concentrations of TiO_2 nanolubricants and R600a refrigerant charges

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ABSTRACT

This study investigates the effect of varying test conditions including ambient temperature (19, 22, and 25 °C), mass charges of R600a refrigerant (40, 50, 60, and 70 g), and concentrations of TiO_2 nanolubricant (0, 0.2 and 0.4 g/L) on the performance of a slightly modified 100g R134a domestic refrigeration system. The investigated parameters include evaporator air temperature, energy consumption, coefficient of performance, and second law efficiency of the system. The results showed that the performance of the refrigeration system at 0.2 and 0.4 g/L concentrations of TiO_2 nanolubricant, improved at optimum ambient temperature and R600a mass charge conditions. At optimum conditions, the evaporator air temperature and energy consumption reduced within the range 5.26 to 26.32 %, and 0.13 to 14.09 % respectively, while the coefficient of performance and second law efficiency increased within the range 0.05 to 16.32 %, and 2.8 to 16 %, respectively. However, at other conditions (non-optimum), the energy consumption and evaporator air temperature were higher and within the range 0.28 to 8.26 %, and 5 to 40 % respectively, while the coefficient of performance and second law efficiency reduced within the range 2.99 to 10.94 %, and 0.55 to 13.43 % respectively. In conclusion, we observed variations in the performance of the refrigerator with varying test conditions.

1. Introduction

Replacement of conventional refrigerants such as R134a and R12, in domestic refrigerators is essential and currently ongoing. This effort is to reduce: (i) the impact of conventional refrigerants on climate change (especially Ozone depletion and/or high global warming) [1], (ii) high energy consumption and exergy destruction [2], thereby enabling compact design of refrigerator systems [3], and (iii) rate of refrigerant leakage to the environment [4]. Design simplicity and economic advantage of domestic refrigerators are increasing their applications in households, and commercial buildings. According to International Institute of Refrigeration (IIR), more than 17 % of energy consumption globally are from refrigeration and air conditioning systems [5]. Therefore, environmental protection protocols and directives have commenced the restrictions of conventional refrigerants such as hydrochlorofluorocarbons (HCFCs), chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). Interest in the adoption of hydrocarbon (HC) compounds as working fluids is rapidly growing in recent decades, despite their flammability side-effects [6]. Many studies discussed the safe and efficient applications of hydrocarbon refrigerants in domestic refrigerators [4, 7, 8]. The work of Corberán et al. [9], considered the safety of using charges of hydrocarbon-based refrigerants that are less than or equal to 150g in any domestic refrigerator when their operating temperature, pressure, and ventilation/airflow conditions were reached. Fire incidence in hydrocarbon-based refrigerators can only occur under the following conditions: (i) fire sources should be greater than 290 kJ and 768K, (ii) concentration of the leaked hydrocarbon refrigerant in the enclosed space must be higher than its low flammability limit, and (iii) proper air-hydrocarbon mixture [6]. Across many European countries, the use of hydrocarbon refrigerants in domestic refrigerators is

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prohibited. However, effort to model the flammability of hydrocarbon refrigerant is increasing. Rasti et al. [8] concluded that charges and flammability limit of hydrocarbon refrigerants correlate directly. Hydrocarbon refrigerants are also found to be suitable retrofits to conventional refrigerants. They are environmentally benign with neutral reaction with the Ozone layer and having low global warming potential [6]. Hydrocarbon refrigerants are compatible with non-hygroscopic mineral-based compressor oils and existing vapor compression refrigeration sub-components [6]. An attempt to improve the performance of a deliberately lowered (i.e., 40g charge) liquefied petroleum gas (LPG) refrigerant in a domestic refrigerator infused with TiO_2 based nano-lubricants, was effective in the work of Adelekan et al. [4]. A review of the adoption of hydrocarbon refrigerants in heating, ventilation and air conditioning systems (HVAC) was carried out in the work of Harby [6]. Improvement in the environmental efficiency, energy efficiency, coefficient of performance, reduction in refrigerant mass charges and drop in compressor discharge temperature were observed in the systems. However, the work of Fatouh and Kafafy [10] observed some shortcomings in domestic refrigerators being substituted experimentally and theoretically with LPG and R600a refrigerants. In the work of McLinden et al. [11], similar deficiencies were described as factors limiting hydrocarbon refrigerant applications in refrigeration and air conditioning systems. The need to efficiently optimized safety, performance and economy of hydrocarbon refrigeration systems operated across wide range of ambient temperatures have recently increased the consideration of pure and mixture of R600a refrigerant (See Table 1). In addition, the need for increased efficiencies in hydrocarbon R600a refrigerant driven refrigeration systems, has justified the applications of nanofluids.

Recently, applications of nanofluids in domestic refrigerators have shown numerous prospects [17, 18]. Nanofluids are stable suspensions of nanoparticles within suitable base fluids (e.g., engine oil, compressor lubricants, ethylene glycol, water, refrigerant, etc.); they are ensured to be homogenous when dispersed in the base fluid. Nanoparticles are solids with a maximum size range of 1–100nm, and their small dimensions and large specific surface areas enhance efficiencies of thermal systems [19]. Applications of nanoparticles in fluids improve the thermodynamic properties of many base-fluids, and these leads to the initiation of molecular scale thermophoresis and Brownian motion [19]. Since nanoparticles are solids with higher thermal conductivities than liquids or gaseous fluids, their mixture produce improve fluids known as nanolubricants or nanorefrigerants. While nanolubricant is a mixture of nanoparticles and compressor lubricant, nanorefrigerant is a mixture of nanoparticles and refrigerant. Nanolubricant induces rolling friction effects within compressors thereby increasing the durability and efficiency of refrigerators [18]. In the work of Ohunakin et al. [20], the energetic performance of a domestic refrigerator infused with SiO_2 based nanolubricants was found to improve considerably. Nanofluids in domestic refrigerators found applications: (i) to enhance the energetic and exergetic performances of refrigerators [21], (ii) refrigerants forced boiling and convective heat transfer [22], (iii) reduction in discharge temperature [4], (iv) compressor lubricant tribology characteristics in [23]; and (v) reduction in refrigerant charges [4]. In the work of Gill et al. [21], an experimental substitution of R134a working fluid with LPG refrigerant using TiO_2, Al_2O_3, and SiO_2 nanolubricants in a domestic refrigerator was found to improve the energetic and exergetic performance of the system. Similarly, the application of selected concentrations of TiO_2 nano-lubricants in a domestic refrigerator using R600a refrigerant were observed to work safely and also enhance the energetic performance in Bi et al. [7].

In this study, the authors investigated the influence of TiO_2 nanolubricants, ambient temperature, and mass charges of R600a refrigerant in a domestic refrigeration system. This study aims to examine the effect of these factors on energy and exergy characteristics like evaporator air temperature, energy consumption, coefficient of performance, and second law efficiency, respectively. The sparse investigations on the influence of the selected factors on the performance of refrigeration systems is the major justification for this work (See Table 2).

2. Materials and method

2.1. Experimental test rig and instrumentation

In this work, the test rig was a modified 100g R134a domestic refrigerator having appropriate valves along the compressor suction and discharge lines. These modifications enabled fitting of digital pressure gauges and charging and discharging of spent refrigerant from the system. Digital type K thermocouples (Victor DM 1502) having measurement accuracy of ± 0.2 °C and a wattmeter (RoHS-D02A) with (± 0.4 W) were attached to the system (See Figures 1 and 2 for experimental schematic diagram and setup respectively). HONGSEN HS-5100L and HS-5100H digital pressure gauges were used to measure the refrigerant suction (P_1) and discharge (P_2) pressures respectively, while the installed thermocouples monitored the suction (T_1), discharge (T_2), condensing (T_3) and cabinet air (T_{air}) temperatures of the refrigerant. Watt meter was connected to capture the instantaneous energy consumption of the system (See Table 3 for test rig description and measuring instrument details).

The modified test rig consists of built-in evaporator, R134a compressor, air-cooled condenser, a non-adiabatic dryer, and a capillary tube. The compressor of the test rig receives the refrigerant at low pressure and temperature saturated vapor state from the evaporator, and delivers it as compressed superheated high pressure and temperature vapor state to the condenser. Heat rejection to the environment occurs as the superheated vapor state refrigerant moves through the condenser at

Table 1. Application and Performance of Pure and Mixture of R600a refrigerant.

S/N	Refrigerant	Author(s)	Description	Conclusion
1	R600a	Hossain et al. [12]	Development of a solar-powered R600a refrigerator	The SAR system attained at least -15 °C and functioned adequately as a vaccine storage device
2	R600a and R290	Zhongcheng et al. [13]	Theoretical evaluation of parallel compression refrigeration system	The system considerably minimized the evaporator heat transfer irreversibility.
3	R600a	Susanto et al. [14]	Investigated the influence of R600a refrigerant mass charge on a refrigerator	The optimum mass charge (38g) of R600a gave energy conservation of 28 %–38 % in the refrigerator.
4	R600a, R1234yf, R1234ze and R717	Zhaohu et al. [15]	Performance investigation of refrigerants in an oil-free compression refrigeration system	The refrigerants worked safely in the system
5	R600a	Shono et al. [16]	Evaluated the initiations of wear based on low viscosity lubricant	Proposed an innovative methodology for limiting wear frictions in a compressor using R600a refrigerant

Table 2. Nanolubricants Performance in Pure and Mixture of R600a refrigerant driven refrigerator.

S/N	Refrigerant	Author(s)	Description	Conclusion
1	R600a	Okotie et al. [24]	Investigated influence of TiO_2 nanolubricants on the energy performance of a refrigerator	The use 0.6 g/L gave the best energy performance in the system
2	R600a and LPG	Gill et al. [25]	Evaluated performance of TiO_2 nanolubricant in a refrigerator using R600a and LPG refrigerant	The nanolubricant improved tribological and energy performance
3	R600a	Adelekan et al. [26]	Graphene-based nanolubricant was tested in a refrigerator using R600a refrigerant	The nanolubricant worked safely and efficiently
4	R600a and LPG	Ajuka et al. [27]	Energy and exergy performance of a refrigerator using TiO_2 nanolubricant was studied	The nanolubricant improved the energy and exergy performance of the system at optimal charges of the refrigerant
5	R600a	Lou et al. [28]	Evaluated the performance of graphite nanolubricants on a domestic refrigerator using R600a	Pull downtime, and suction, discharge, cabinet temperature, and pressures of the system reduced considerably.

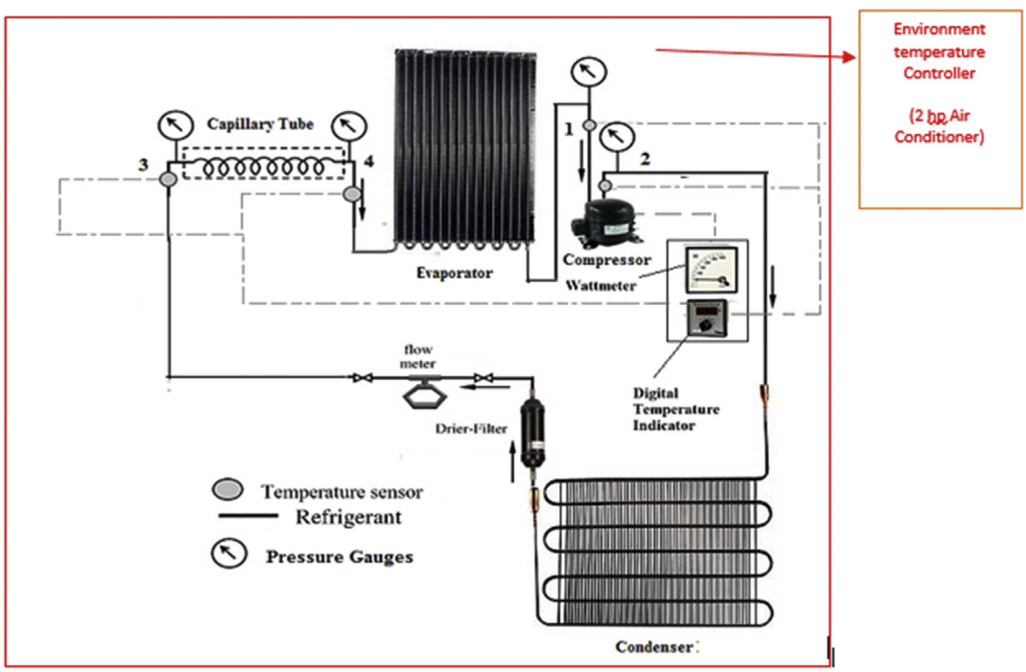

Figure 1. Schematic of the refrigeration system (Source: Gill et al. [21]).

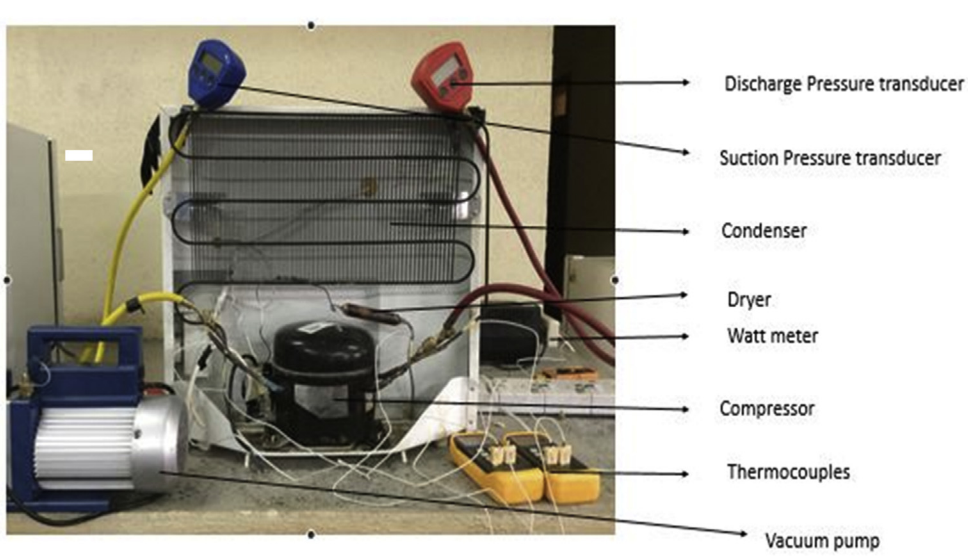

Figure 2. Experimental Setup of Test Rig (Source: Ohunakin et al. (2018)).

Table 3. Test Rig Description and Measuring Instrument Details.

S/N	Detail	Description	Specification
A	Test Rig	Evaporator	Plate type
		Refrigerant	R134a
		Refrigerant Mass Charge	100g
		Condenser	Fin on tube Air cooled
		Compressor Oil	POE
		Dryer	Non-Adiabatic
		Capillary tube Length	2m
		Compressor	HFC
		Number of Doors	1
B	Measuring Instrument	Pressure Gauge	Digital
		Thermocouple	Digital (Victor DM1502)
		Refrigerant Weighing Scale	Camry (ASC-10-ZC)
		Nanoparticle Weighing Scale	OHAUS PA114
		Wattmeter	1 - 3000 W
		Refrigerant Flow meter	Coriolis

constant pressure (that is an isobaric process). At the exit of the condenser, the working fluid flows to the dryer as a saturated liquid. The dryer then expands the high pressure saturated liquid refrigerant to low pressure saturated liquid/vapor mixture at constant enthalpy (an isenthalpic process). The evaporator receives the low pressure uniformly flowing saturated liquid/vapor mixture refrigerant from the capillary tube. The refrigerant absorbs heat at constant pressure as it moves through the evaporator, where it changes to a saturated vapor state. The refrigerant undergoes a continuous repetition of the process cycle as it enters the compressor. The test environment is a closed door environment equipped with a 2-horsepower air-conditioning system to stabilize the required ambient temperature. The environment also had surface thermometers for monitoring the average ambient tempetrature of the test environment during the investigation. The relative humidity condition of the test environment is 75%.

2.2. Nanolubricant preparation

In preparing the nanolubricants, 15nm TiO_2 nanoparticle (procured from Aldrich Chemistry) is dispersed in locally purchased mineral-based compressor lubricants. Figures 3 and 4 shows the scanning electron micrograph and distribution of the TiO_2 nanoparticle. As illustrated in Figure 3, the TiO_2 nanoparticle is spherical in shape and agglomerate naturally. Since agglomeration initiate clustering and sedimentation of nanoparticles within nanofluids, ultrasonicating the TiO_2 nanoparticle-compressor lubricant mixtures is necessary. Figure 4 confirms that the nanoparticle contains very high purity of TiO_2 compound. Sonification is a known method of eliminating clustering and sedimentation within nanofluids [25]. Sonification of the respective nanoparticles and compressor lubricant mixtures were carried out using Branson M2800H ultrasonicator. Prior to sonification, mass fractions of nanoparticles were obtained using a digital weighing balance (Ohaus Pioneer TM PA114) while a measuring cylinder was used to measure the required volume of mineral oil compressor lubricant. We evaluated the stability of the nanofluids after sonification using sedimentation and spectral analysis. Sedimentation observation results of the sonicated samples at 0 and 24 h is shown in Figures 5 and 6. The high resolution digital camera image of the sonicated samples shows stability with negligible nanoparticle sedimentation. Furthermore, the absorbance spectral of the nanolubricants over a range of wavelengths were obtained from UV visible spectrometer (HELIOS ZETA UV VIS). The standard deviations in the respective absorbance coefficients of the prepared nanolubricants were found to be less than 5 % during the test investigation period. Inference from estimating the standard deviations of the absorbance coefficient substantiates stability within the nanolubricants. Authors' previous study of the stability of nanolubricants in accordance to Beer law, authenticate high stability (See Figure 7 and Gill et al [29]).

2.3. Theory/calculation

The equation adopted to calculate performance of the TiO_2 nanolubricants, mass charges and ambient temperatures in the test refrigerator are given as Eqs. (1), (2), and (3):

Energetic Characteristics

$$\text{Coefficient of Performance} = COPc = \frac{q}{w} = \frac{\dot{m}(h_1 - h_3)}{\dot{m}(h_2 - h_1)} = \frac{(h_1 - h_3)}{(h_2 - h_1)} \tag{1}$$

$$\text{Carnot Coefficient of Performane} = COP_{carnot} = \frac{Te}{T_c - T_e} \tag{2}$$

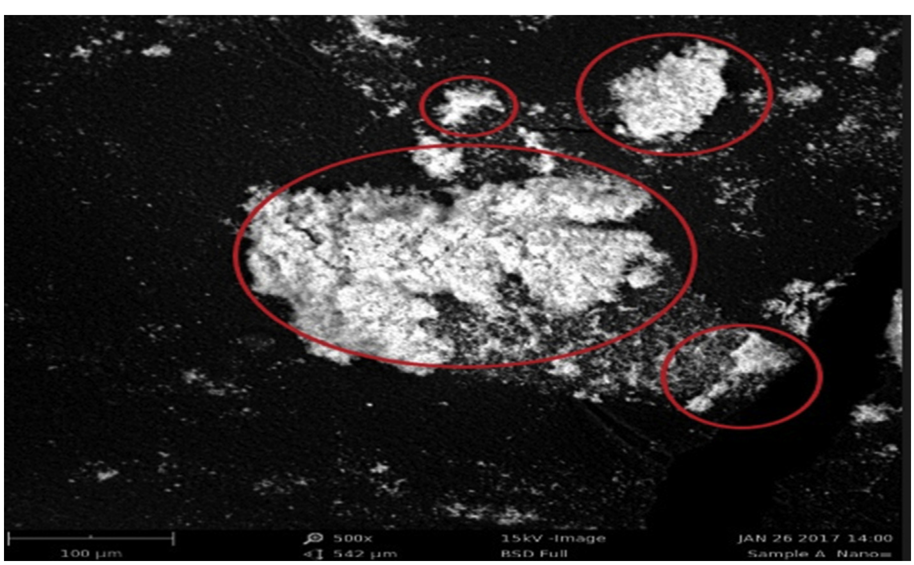

Figure 3. TiO_2 nanoparticles Image from Scanning Electron Microscope.

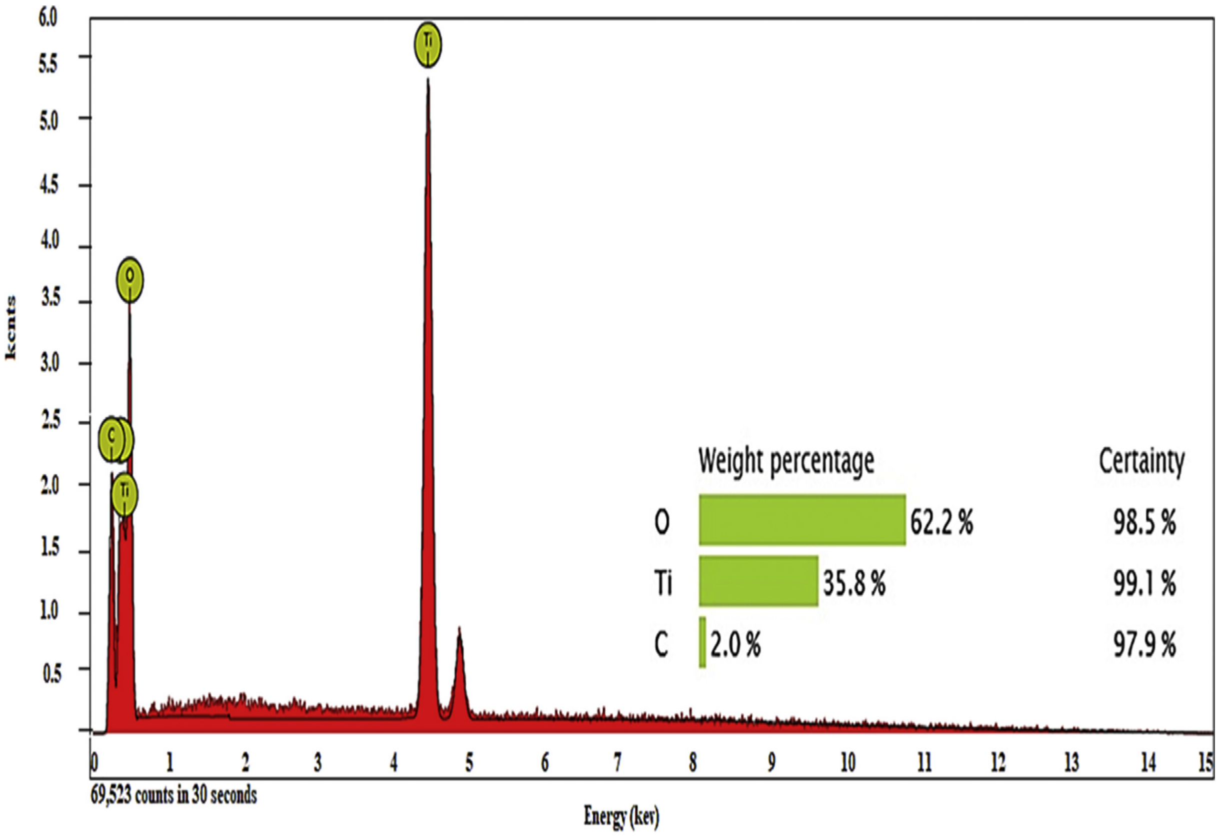

Figure 4. EDX analysis of the TiO_2 nanoparticle (Source: Gill et al. [21]).

$$\textit{Second law efficiency} = \frac{COP_c}{COP_{carnot}} \tag{3}$$

where $\dot{m}$ is the refrigerant mass flow rate (kJ/m^3), h_1 is saturated vapor enthalpy (kJ/kg), h_2 is superheated vapor enthalpy (kJ/kg), h_3 is the saturated liquid enthalpy (kJ/kg), T_e is the refrigerant evaporating temperature (K), T_c is the refrigerant condensing temperature (K). All estimations were carried out under the following assumptions: (i) steady state condition, (ii) an equal discharge, and condensing pressures, and (iii) equal condensing and evaporator inlet enthalpies.

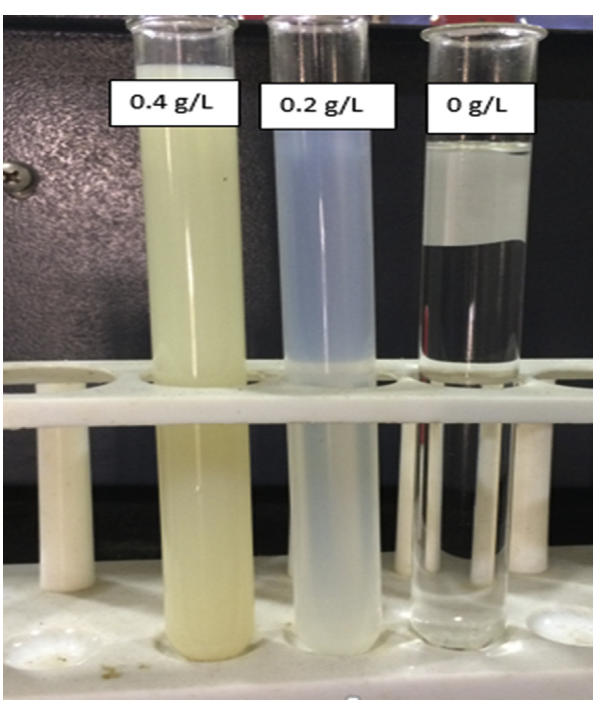

Figure 5. Ultrasonificated nanolubricants After 24 h.

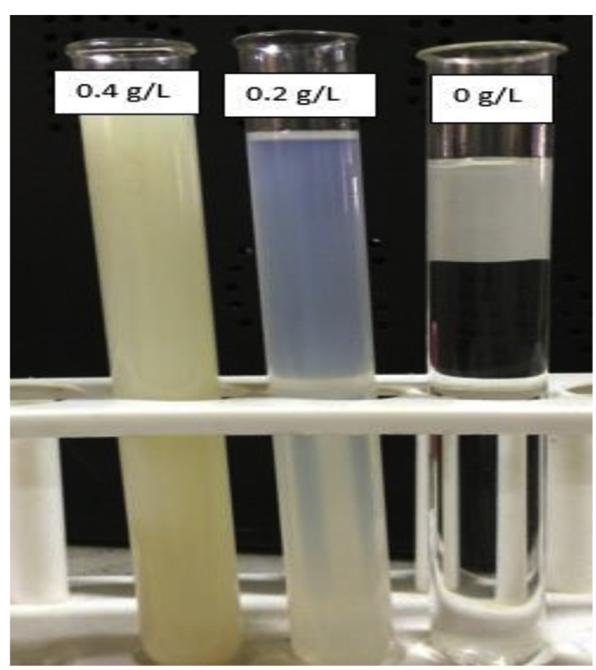

Figure 6. Ultrasonificated nanolubricants at 0 h.

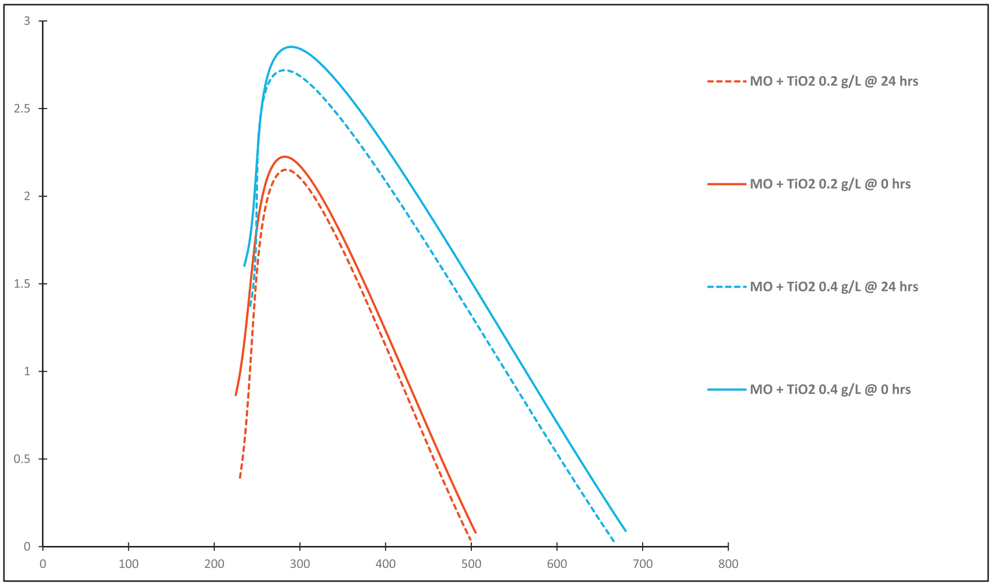

Figure 7. Variation of the nanolubricant absorbance.

2.4. Experimental procedure

In conducting this experiment, a slightly modified 100g R134a refrigerator is retrofitted with charges of R600a refrigerant ranging from 40 to 70 g at varying concentrations of TiO_2 nanolubricants (0. 0.2 and 0.4 g/L) and selected ambient temperatures (19, 22 and 25 °C). All experimental trials were under a no-load, continuous operation of the compressor. Variation of pressures (P_1, P_2), temperatures (T_{air}, T_1, T_2, T_3), mass flow rates, and compressor power consumptions of the system is observed at 4 h of steady-state condition. After obtaining relevant refrigerant properties (i.e., suction vapor enthalpy (h_1), superheated vapor enthalpy (h_2), and saturated liquid enthalpy (h_3)) from NIST Ref-Prop 9.1 software, the required energy characteristics and second law efficiency were estimated. Furthermore, each trial was carried out three times to ascertain the integrity of the experiments.

2.5. Uncertainty of measured parameters

In this study, the uncertainties of the measured parameters were estimated using methodology of measurement uncertainties in Schultz and Cole (1979). Methods described in Schultz and Cole method [30] and Ohunakin et al. [31] defined uncertainty of the desired parameter like U_F using Eq. (4):

$$U_F = \left[\sum_{i=1}^{n}\left(\frac{\partial F}{\partial_{V_i}}U_{w_i}\right)^2\right]^{0.5} \tag{4}$$

where U_F is the total uncertainty, U_{w_i} is the uncertainty of each independent variable and n is the number of total variables (see Gill et al. [25]). Table 4 illustrates the uncertainties of the parameters. For all the parameters, the maximum percentage uncertainty was less than 3%in accordance to all range of experimental conditions described in Table 5.

2.6. Regression model

The need for the significances of the test conditions (that is nanolubricant concentration, R600a mass charge and ambient temperature) in determining the investigated parameters (evaporator air temperature, power consumption, coefficient of performance and second law efficiency) for the refrigeration system, justified the analysis of variance and regression model estimations provided in Table 6a-d. The developed regression models validity was determined by respective statistical coefficient of correlation R^2 and hypothetical P values (where maximum R^2 and P value ≤ 0.05 are desirable). It was observed from the result provided in Table 6a-d that the output evaporator air temperature, power consumption, coefficient of performance and second law efficiency of the refrigeration system were significantly influenced by the test conditions.

3. Results and discussion

The steady state experimental and regression model results of the modified domestic refrigerator across selected ambient temperatures, TiO_2 nanolubricant concentrations and R600a refrigerant mass charges is shown in Table 7.

Table 5. Range and condition of experiment.

S/N	Test	Details	Range and Condition
1	Nanoparticle	Type	TiO_2
		Size	15nm
		Shape	Spherical
		Nanolubricant concentration	0, 0.2, and 0.4 g/L
2	Refrigerant	Type	R600a
		Mass charge	40, 50, 60 and 70 g
3	Compressor Lubricant	Mineral Oil	250 ml
4	Environment	Temperature	19, 22, and 25 °C
		Relative humidity	75 %

Table 4. Uncertainty analysis of measuring instruments.

Parameter	T_1	T_2	T_3	T_{air}	P_1	P_2
Uncertainty (±)	0.2^{O}C	0.2^{O}C	0.2^{O}C	0.2^{O}C	2kPa	4kPa

Table 6a. Evaporator air temperature statistical summary.

Evaporator Air Temperature					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	179.592	29.932	12.88	0.000
Mass charge	1	35.260	35.260	15.17	0.001
Concentration	1	23.328	23.328	10.04	0.004
Ambient temperature	1	9.600	9.600	4.13	0.051
Mass charge*Mass charge	1	40.111	40.111	17.26	0.000
Concentration*Concentration	1	21.125	21.125	9.09	0.005
Concentration*Ambient temperature	1	12.250	12.250	5.27	0.029
Error	29	67.408	2.324		
Total	35	247.000			
Coefficients					
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.41	8.31	0.17	0.867	
Mass charge	-1.092	0.280	-3.89	0.001	152.25
Concentration	-47.7	15.1	-3.17	0.004	93.67
Ambient temperature	0.333	0.164	2.03	0.051	2.50
Mass charge*Mass charge	0.01056	0.00254	4.15	0.000	152.25
Concentration*Concentration	40.6	13.5	3.01	0.005	13.00
Concentration*Ambient temperature	1.458	0.635	2.30	0.029	83.17

Regression Equation:
Evaporator Air Temperature = 1.41–1.092 Mass charge - 47.7 Concentration +0.333 Ambient temperature +0.01056 Mass charge*Mass charge +40.6 Concentration*Concentration +1.458 Concentration*Ambient temperature.

3.1. Variation of evaporator air temperature

The effect of varying TiO2 nanolubricants concentrations (0, 0.2 and 0.4 g/L), mass charges of R600a refrigerant (40, 50, 60 and 70 g) and ambient temperatures (19, 22 and 25 °C) on the evaporator air temperatures of the system is shown in Figure 8(a-c). It can be observed that the interactions between the selected mass charges of R600a refrigerant, ambient temperatures, and nanolubricant concentrations significantly influenced the evaporator air temperature of the system. Increasing the mass charge of R600a refrigerant and TiO2 nanolubricant concentrations, brought about a reductions and increase in the evaporator air temperature of the system. But, increasing the ambient temperature increased the evaporator air temperature of the refrigerator. The least evaporator air temperature of the system is -24 °C at 40g R600a, 0.2 g/L nanolubricant and 19 °C ambient temperature, while the maximum is got as -9 °C at 70g R600a, 0.4 g/L and 25 °C ambient temperature. The use of 0.2 g/L nanolubricant resulted in lower evaporator air temperatures than other concentrations regardless of the charge of refrigerant. However, at ambient temperature of 19 °C, more concentration of TiO2 nanolubricant (i.e., 0.4 g/L) gave the least evaporator air temperatures.

Table 6b. Coefficient of performance statistical summary.

Coefficient of Performance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.64282	0.10714	5.52	0.001
Mass charge	1	0.39270	0.39270	20.23	0.000
Concentration	1	0.15291	0.15291	7.88	0.009
Ambient temperature	1	0.01080	0.01080	0.56	0.462
Mass charge*Mass charge	1	0.40111	0.40111	20.66	0.000
Concentration*Concentration	1	0.10967	0.10967	5.65	0.024
Concentration*Ambient temperature	1	0.07701	0.07701	3.97	0.056
Error	29	0.56297	0.01941		
Total	35	1.20579			
Coefficients					
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.320	0.760	0.42	0.676	
Mass charge	0.1153	0.0256	4.50	0.000	152.25
Concentration	3.86	1.38	2.81	0.009	93.67
Ambient temperature	0.0112	0.0150	0.75	0.462	2.50
Mass charge*Mass charge	-0.001056	0.000232	-4.55	0.000	152.25
Concentration*Concentration	-2.93	1.23	-2.38	0.024	13.00
Concentration*Ambient temperature	-0.1156	0.0581	-1.99	0.056	83.17

Regression Equation.
Coefficient of Performance = 0.320 + 0.1153 Mass charge +3.86 Concentration +0.0112 Ambient temperature - 0.001056 Mass charge*Mass charge - 2.93 Concentration*Concentration - 0.1156 Concentration*Ambient temperature.

Table 6c. Energy consumption statistical summary.

Energy consumption					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	219.87	54.97	5.39	0.002
Mass charge	1	167.10	167.10	16.40	0.000
Concentration	1	43.80	43.80	4.30	0.047
Mass charge*Mass charge	1	170.30	170.30	16.71	0.000
Concentration*Concentration	1	48.51	48.51	4.76	0.037
Error	31	315.90	10.19		
Total	35	535.77			
Coefficients					
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	136.4	15.7	8.70	0.000	
Mass charge	-2.378	0.587	-4.05	0.000	152.25
Concentration	-24.4	11.7	-2.07	0.047	13.00
Mass charge*Mass charge	0.02175	0.00532	4.09	0.000	152.25
Concentration*Concentration	61.6	28.2	2.18	0.037	13.00

Regression Equation.
Energy Consumption = 136.4–2.378*Mass charge - 24.4*Concentration +0.02175 Mass charge*Mass charge.
+ 61.6 Concentration*Concentration.

Overall, infusion of TiO2 nanolubricant to the refrigeration system reduced the evaporator air temperatures by 5.26 to 26.32 % when compared to the pure lubricant. This result affirms that nanorefrigerant heat transfer rate varies with temperature and nanorefrigerant concentration. As established in the work of Ohunakin et al. (2017), adding TiO2 nanoparticles to the compressor lubricant enhanced the evaporator boiling heat transfer rate via thermophoresis and Brownian motion initiation. These conditions were primarily driven by improved refrigerant–compressor oil solubility and working fluid thermal conductivity. However, at high ambient temperature, intensified thermal penetration or infiltration through the refrigerator walls increased the heat gain and evaporator air temperature of the system (see Harrington et al. 2018). In addition, increasing the R600a refrigerant mass charge increased the evaporator pressure and decreased the degree of superheating due to refrigerant flooding of the evaporator; thus resulting to increasing evaporator air temperature (see Belman-Flores et al, (2017)).

3.2. Variation of energy consumption

Figure 9(a-c) describes the steady-state energy consumption of the system. The energy consumptions of the refrigeration system vary differently across the selected ambient temperatures, nanolubricant concentrations, and charges of R600a refrigerant. Increasing the mass charges of R600a refrigerant decreased and increased the energy consumption of the refrigerator regardless of the selected ambient temperature and TiO_2 nanolubricant concentrations. Furthermore, reducing ambient temperature, will increase energy consumption of the refrigeration system. We observed a reduction in the energy consumptions with applications of TiO_2 nanolubricants within the test rig especially at ambient temperatures of 19 °C and 22 °C. More energy was required at 25 °C of ambient temperature operation of the refrigerator with 0.2 g/L and 0.4 g/L concentrations of TiO_2 nanolubricants, when compared to that of the pure lubricant (i.e., 0 g/L). The least energy consumption within the

Table 6d. Second law efficiency statistical summary.

Second law efficiency					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.048897	0.012224	6.77	0.000
Mass charge	1	0.029785	0.029785	16.49	0.000
Concentration	1	0.009816	0.009816	5.43	0.026
Mass charge*Mass charge	1	0.031211	0.031211	17.28	0.000
Concentration*Concentration	1	0.013612	0.013612	7.54	0.010
Error	31	0.056003	0.001807		
Total	35	0.104900			
Coefficients					
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.178	0.209	-0.85	0.401	
Mass charge	0.03174	0.00782	4.06	0.000	152.25
Concentration	0.365	0.156	2.33	0.026	13.00
Mass charge*Mass charge	-0.000294	0.000071	-4.16	0.000	152.25
Concentration*Concentration	-1.031	0.376	-2.75	0.010	13.00

Regression Equation.
Second law efficiency = -0.178 + 0.03174 Mass charge +0.365 Concentration.
- 0.000294 Mass charge*Mass charge - 1.031 Concentration*Concentration.

Table 7. Experimental Performance of the modified domestic refrigerator in the selected operating conditions.

S/N	Ambient temperature	Nano. Conc.	R600a Mass	Experimental				Regression Model			
				Evap. air Temp.	COP	Power	2nd %	Evap. air Temp.	COP	Power	2nd %
1	19	0	40	-19	3.42	77.4	0.62	-19.05	3.46	76.08	0.62
2	19	0.2	40	-24	3.66	74	0.68	-21.42	3.67	73.66	0.65
3	19	0.4	40	-20	3.8	73.8	0.6	-20.55	3.65	76.18	0.6
4	19	0	50	-20	3.73	72.7	0.65	-20.46	3.66	71.88	0.67
5	19	0.2	50	-21	4.03	65.7	0.75	-22.84	3.87	69.46	0.71
6	19	0.4	50	-22	3.81	72.9	0.64	-21.97	3.85	71.97	0.66
7	19	0	60	-20	3.65	74.3	0.63	-19.77	3.65	72.02	0.67
8	19	0.2	60	-20	3.7	70.7	0.7	-22.14	3.86	69.6	0.7
9	19	0.4	60	-22	3.83	72	0.66	-21.27	8.85	72.12	0.65
10	19	0	70	-19	3.32	82	0.56	-16.96	3.43	76.52	0.6
11	19	0.2	70	-16	3.64	75.3	0.58	-19.33	3.64	74.1	0.64
12	19	0.4	70	-20	3.47	82.4	0.52	-18.46	3.63	76.61	0.58
13	22	0	40	-17	3.55	76.1	0.6	-18.05	3.49	76.08	0.62
14	22	0.2	40	-19	3.67	73.5	0.64	-19.55	3.63	73.66	0.65
15	22	0.4	40	-18	3.55	75	0.63	-17.8	3.55	76.18	0.6
16	22	0	50	-20	3.56	74.1	0.66	-19.46	3.69	71.88	0.67
17	22	0.2	50	-22	3.69	74	0.65	-20.96	3.84	69.46	0.71
18	22	0.4	50	-19	3.63	73	0.66	-19.22	3.75	71.97	0.66
19	22	0	60	-18	3.61	73.1	0.65	-18.77	3.68	72.02	0.67
20	22	0.2	60	-20	4.2	62.8	0.78	-20.27	3.83	69.6	0.7
21	22	0.4	60	-19	3.78	70.8	0.67	-18.52	3.74	72.12	0.65
22	22	0	70	-18	3.59	72.2	0.68	-15.96	3.46	76.52	0.6
23	22	0.2	70	-19	3.7	70.4	0.7	-17.46	3.61	74.1	0.64
24	22	0.4	70	-16	3.59	74.9	0.6	-15.71	3.52	76.61	0.58
25	25	0	40	-16	3.41	75.2	0.64	-17.05	3.52	76.08	0.62
26	25	0.2	40	-18	3.71	71.8	0.65	-17.68	3.6	73.66	0.65
27	25	0.4	40	-15	3.31	80.9	0.55	-15.05	3.44	76.18	0.6
28	25	0	50	-18	3.67	67.9	0.75	-18.47	3.72	71.88	0.67
29	25	0.2	50	-21	3.78	70	0.71	-19.09	3.8	69.46	0.71
30	25	0.4	50	-17	3.72	70	0.68	-16.47	3.64	71.97	0.66
31	25	0	60	-17	3.95	70.2	0.62	-17.77	3.72	72.02	0.67
32	25	0.2	60	-19	3.52	76	0.62	-18.4	3.79	69.6	0.7
33	25	0.4	60	-17	3.73	71.1	0.66	-15.77	3.64	72.12	0.65
34	25	0	70	-15	3.51	74.3	0.63	-14.96	3.5	76.52	0.6
35	25	0.2	70	-16	3.43	76.4	0.61	-15.59	3.57	74.1	0.64
36	25	0.4	70	-9	3.46	74	0.59	-12.97	3.42	76.61	0.58
R^2								**0.85**	**0.27**	**0.64**	**0.68**
MPE (%)								**0.51**	**0.0074**	**0.51**	**0.005**
RMSE								**1.22**	**0.125**	**2.96**	**0.039**

Where MPE is mean percentage error, RMSE is root mean square error, R^2 coefficient of correlation.

refrigeration system was obtained as 62.80 W at 60 g charge of R600a, 0.2 g/L nanolubricant concentration, and at 22 °C of ambient temperature condition, while 70g charge of R600a, 0.4 g/L nanolubricant concentration, at 19 °C ambient temperature condition gave the highest energy consumption of 82.4 W. A reduction in energy consumption was observed within the range 0.13 to 14.09 % at appropriate concentration of TiO_2 nanolubricant, ambient temperature and R600a charge respectively. A slightly higher energy consumptions ranging within 0.28 to 8.26 % were observed at non-optimum conditions. Regardless of the mass charges of R600a refrigerants within the refrigeration system, the use of 0.2 g/L of TiO_2 nanolubricant gave the least energy consumption at 19 °C and 22 °C of ambient temperatures. However, the refrigeration system with 0.2 g/L and 0.4 g/L nanolubricants, consumed more energy than the pure lubricant at 25 °C ambient temperature. These results obtained show that energy consumption of refrigerators are influenced by varying ambient temperatures, nanolubricant concentrations and refrigerant mass charges. Conventionally, energy consumption of refrigerators varies directly with pressure ratio as established in the work of Gill et al. (2018). Thus, results indicate that increasing the R600a mass charge slightly decrease and increase with both pressure ratio and energy consumption of the system. While, increasing the surrounding ambient temperature of the refrigerator invariably increased the condensing temperature, and condenser and evaporator pressures. As reported by Harrington et al. [32], these increased pressures invariably reduce the compressor volumetric efficiency and mass flow rate of flowing refrigerant; thus prolonging compressor run time and increasing energy consumption. Application of TiO_2 nanoparticles to the system further reduced the pressure ratio and energy consumption of the refrigerator. Inference from existing studies attributed these reductions to minimized friction, rubbing and wear effects within the compressor. As suggested by Jia et al. [33], the nanolubricants induced mending, lubricating, polishing, coating and balling bearing effects on moving components of the compressor. This invariably leads to minimized pressure drop and energy consumption within the system.

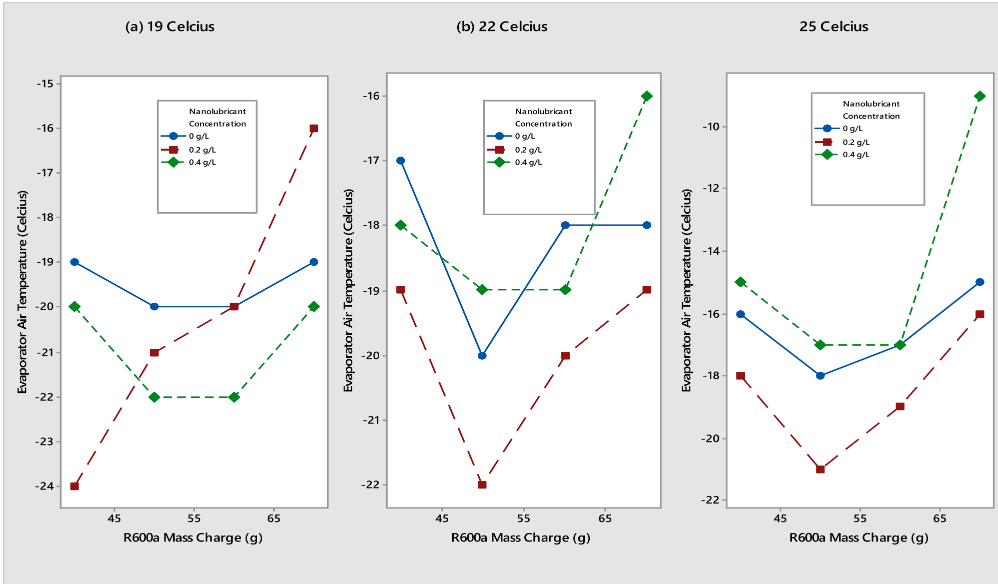

Figure 8. (a–c): Variation of evaporator air temperature across 19, 22 and 25 °C ambient temperatures.

3.3. Variation of coefficient of performance

Figure 10(a-c) illustrates variations in the coefficient of performance of the system. The coefficient of performance of the system increased and decreased with increasing R600a refrigerant mass charges, and TiO_2 nanolubricant concentrations. Comparing the effects of the selected TiO_2 nanolubricant concentrations showed that 0.2 and 0.4 g/L TiO_2 nanolubricants improved the coefficient of performance of the test refrigeration system only at ambient temperatures of 19 °C and 22 °C. At 25 °C ambient temperature, the coefficient of performance of the nanolubricants based refrigerator were lower at charges of R600a refrigerant greater than 50g. The observed enhancement in coefficient of performance of the system was due to the higher cooling capacities and lower compressor work done at steady state conditions. The percentage improvements in coefficient of performance of the system with increasing concentrations of TiO_2 nanolubricants ranged between 0.05 % and 16.32 % when compared to the pure lubricants. On the other hand, reductions within the range of 1.31%–10.94 % in coefficient of performance of the system were observed only at ambient temperature of 25 °C, and non-optimum concentration of TiO_2 nanolubricant, and selected charges of R600a refrigerant, when compared with the base fluids (see Figure 10c). The highest coefficient of performance within the refrigerator was 4.20 for 60g R600a using 0.2 g/L concentration of TiO_2 nanolubricant at 22 °C, while the least coefficient of performance is 3.31 for 40g R600a using 0.4 g/L concentration of TiO_2 nanolubricant at 25 °C ambient temperature. Overall, the highest and least coefficient of performance of the refrigerator was obtained using 0.2 g/L and 0 g/L respectively,

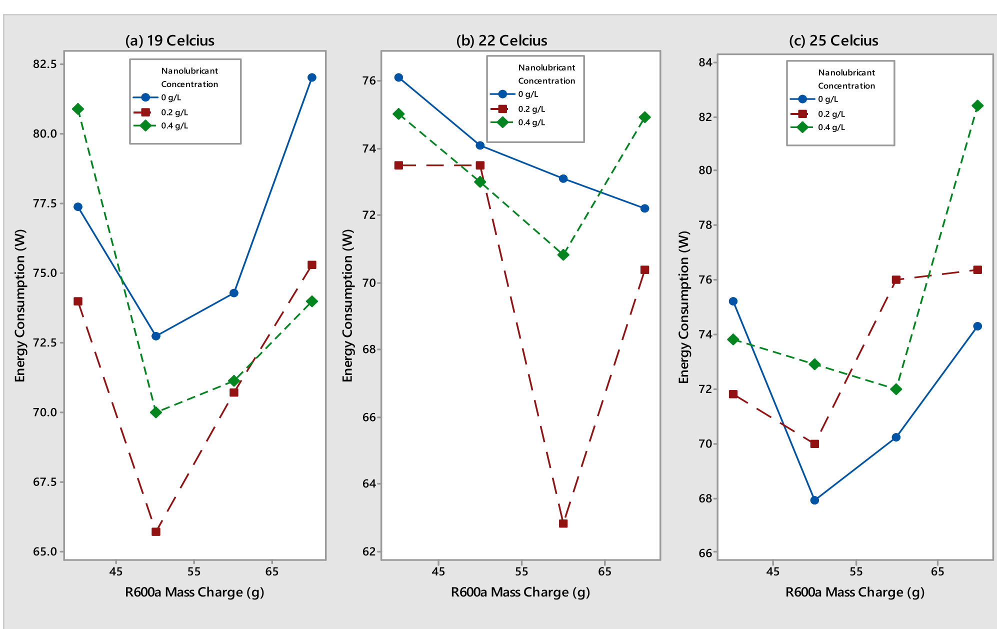

Figure 9. (a–c): Variation of energy consumption across 19, 22 and 25 °C ambient temperatures.

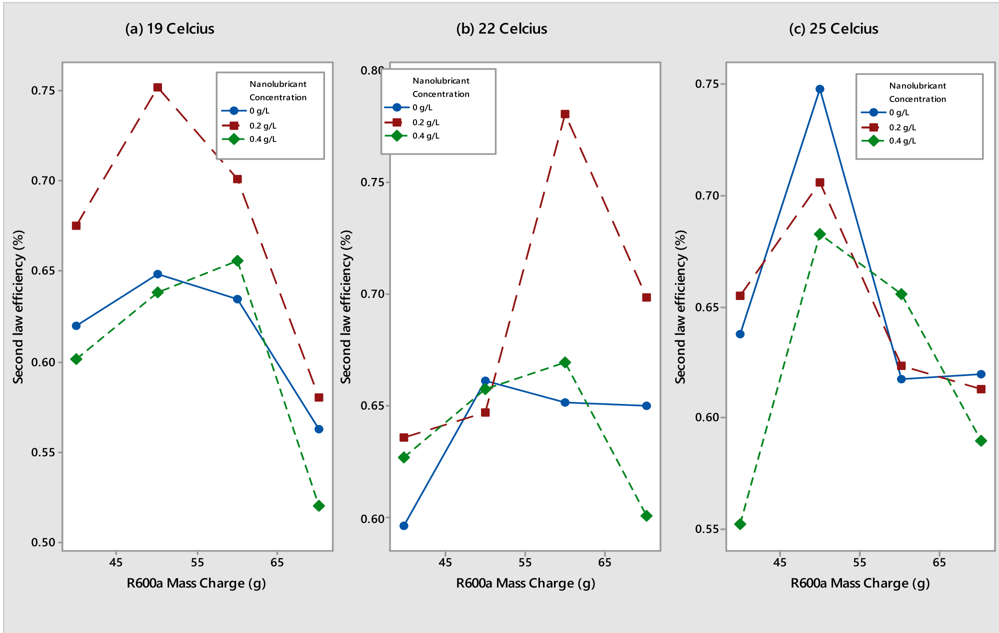

Figure 10. (a–c): Variation of coefficient of performance across 19, 22 and 25 °C ambient temperatures.

at 22 °C ambient temperature. Observation revealed that the cumulative effects of lowered energy consumptions and evaporator air temperatures impacted by the TiO_2 nanolubricants yielded higher cooling capacity which invariably increased the coefficient of performance of the system.

3.4. Variation of second law efficiency

Variation of second law efficiency of the refrigeration system is shown in Figure 11(a-c). Increasing the mass charge of the refrigerant in the system, increased and decreased the second law efficiency of the refrigerator. The second law efficiency of the system at 0.2 g/L and 0.4 g/L TiO_2 concentrations of nanolubriants was found to be better than the baseline (0 g/L) at ambinet temperatures of 19 °C and 22 °C, and worse at 25 °C. The comparison of the second law efficiencies of the nanolubricants increase within the range 2.8 to 16 %, and reduce within the range 0.5 to 11 %, when compared to the baseline. Improvements in the second law efficiency of the system were due to higher actual coefficient of performance and lower Carnot coefficient of performance. The lowest coefficient of performance of the system was 0.52 at 40g of R600a, 0.4 g/L TiO_2 nanolubricant concentration at 25 °C ambient temperature, and the maximum given as 0.78 at 60g charge of R600a, 0.2 g/L concentration of TiO_2 nanolubriant, at 22 °C. Overall, the use of 0.2 g/L concentration of nanolubicant gave the best performance within the refrigerator.

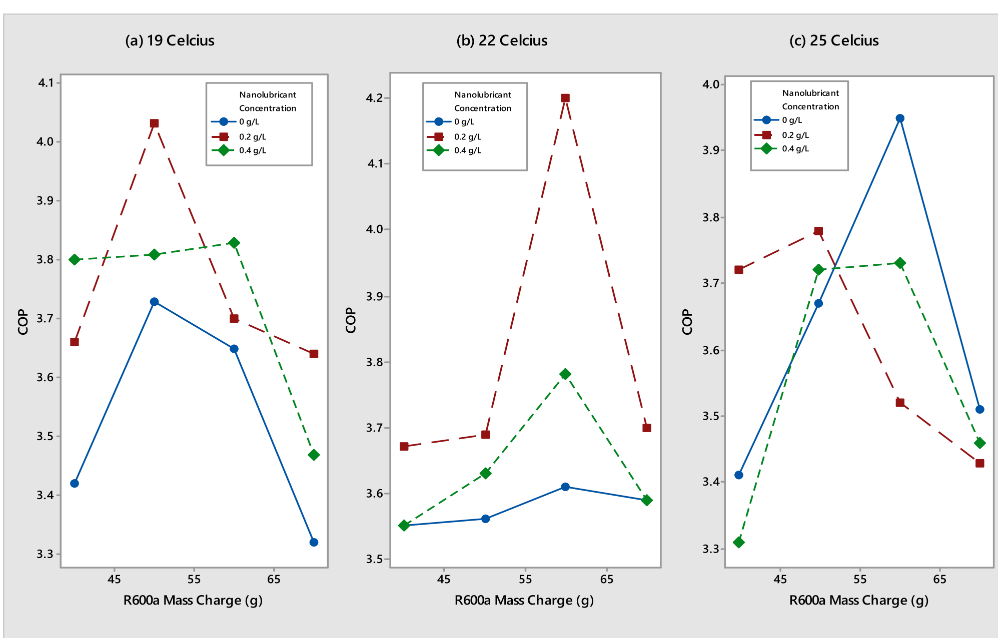

Figure 11. (a–c): Variation of second law efficiency across 19, 22 and 25 °C ambient temperatures.

4. Conclusion

In this study, the performance of a slightly modified domestic refrigerator subjected to varying mass charges of R600a refrigerant, TiO2 nanoparticle concentrations and ambient temperatures was carried out. The following were concluded:

1. The varying charges of R600a, TiO_2 concentrations and ambient temperatures influenced significantly, the performance of the refrigerator. The evaporator air temperature of the refrigerator decreased and later increased with increasing R600a mass charge. The least evaporator air temperature were achieved at 22 °C using 0.2 g/L TiO_2 nanolubricant concentration.
2. The energy consumption of the system at 0.2 g/L and 0.4 g/L concentrations of TiO2 nanolubricant, reduced within the range 0.13 to 14.09 % when compared to the baseline concentration (0 g/L). The lowest value of energy consumption in the system was found to be 62.80 W using 60g charge of R600a refrigerant at 0.2 g/L and 22 °C, while the highest value was obtained as 82.40 W using 70g charge of R600a refrigerant at 0.4 g/L and 19 °C.
3. The highest coefficient of performance in the refrigerator was obtained using 60g charge of R600a, with 0.2 g/L concentration of nanolubricant at 22 °C ambient temperature. The application of 0.2 g/L and 0.4 g/L nanolubricant was found to improve the second law efficiency of the refrigeration system at ambient temperatures of 19 °C and 22 °C, respectively.

Declarations

Author contribution statement

Adelekan D.S: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ohunakin O.S, Nkiko M. O & Atayero A.A: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Oladeinde M.H & Gill Jatinder: Conceived and designed the experiments; Analyzed and interpreted the data.

Atiba O.E: Contributed reagents, materials, analysis tools or data.

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Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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