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Performance of hydrocarbon refrigerants in a refrigerator with liquid line magnet and CNT nano-lubricant

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ABSTRACT

The issues of flammability associated with A3-class hydrocarbon-based refrigerants are controllable by limiting their mass charges. However, these reductions in their mass charge below certain limits deteriorate their performance efficiency. In this experimental study, we analyzed the effects of a liquid line magnetic field (Mag), multi-wall carbon nanotube (CNT) nano-lubricant, and the combination of both (Mag-Nano) on the performance of a very low mass charge (i.e., 30 g) of R600a and LPG refrigerants, as a replacement to the 100 g R134a refrigerant in a domestic refrigeration system. The refrigerants were tested with and without CNT nano-lubricant (pure), two pairs of 3000 Gs liquid line mounted O ring N50 permanent magnets (Mag), 0.2 g/L concentration of CNT nano-lubricant (Nano), and in combination with a liquid line magnetic field and CNT nano-lubricant (Mag-Nano). The performance evaluation of the refrigerants includes the determination of coefficient of performance (COP), evaporator air temperature, volumetric refrigeration capacity, instantaneous power consumption, cumulative energy consumption, and energy cost. A reduction in the COP of R600a and LPG was observed to be about 11–42% and 14–26%, respectively, when compared to R134a. The R134a refrigerant had the lowest evaporator air temperature of −24.5 °C and the highest instantaneous power consumption of 74.6 W. The R600a-Mag-Nano refrigerant is the most efficient option, having the lowest instantaneous power consumption, energy cost, and cumulative energy consumption. The adoption of hydrocarbon refrigerants is more cost-effective than using the R134a refrigerant, resulting in a cost saving of about 8–26%. In conclusion, the proposed methods adopted to enhance the performance of refrigeration system, are very safe and effective.

1. Introduction

Hydrocarbon-based refrigerants are now being utilized to replace conventional refrigerants like chlorofluorocarbons, hydrochlorofluorocarbons, and hydro-fluorocarbons in refrigerators and air-conditioners due to their several advantages including low global warming potential, improved energy-exergy performance, compatibility with compressor lubricants and the prior existing subcomponents, and better performance at low mass charges [1,2]. Refrigerants such as R600a and LPG have similar thermophysical

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properties and higher latent heat of vaporization than already existing conventional refrigerants [3]. The hydrocarbon refrigerants are also found to be compatible with existing compressor lubricants like polyol ester (POE), polyalklene glycol (PAG), and mineral oil [1]. Hydrocarbon refrigerants are cheaper than pure and blended hydro-fluoro-olefins (HFO) refrigerants [2]. In addition, popular hydrocarbon refrigerants like R600a, R290, and LPG are classified as A3 according to ISO 817 recommendations. The A3 class of refrigerants has low toxicity and high flammability characteristics [3]. The flammability concerns of these hydrocarbon refrigerants, especially R600a, R290, and LPG, can be controlled economically using ultra-low mass charges. The flammability limits of hydrocarbon refrigerants are directly related to their mass charges [4,5]. However, deterioration of performance efficiency is a common problem in refrigerators at charges lower than their optimum requirement [2].

The recent work in literature focuses on addressing the flammability of hydrocarbon refrigerants used in refrigerators [4,6–8]. The incorporation of gas leak fire alarms, detectors, ultrasonic sensors, and ventilator devices in refrigerator systems can be cumbersome and expensive to manage flammability [9]. The work of Ref. [8] found that applying R134a refrigerant as a flame retardant in flammable R600a and R290 refrigerants can improve fire inhibition characteristics, the solubility of compressor oils in refrigerants, and the overall performance of refrigerators. The flammability of hydrocarbon refrigerants directly correlates with operating ambient air relative humidity and temperature [4]. The poor performance of the low charges of hydrocarbon-based refrigerants in refrigeration and air-conditioning systems can be significantly improved via different mechanisms e.g., with the adoption of nanoparticles, liquid line magnet, phase change materials etc. Promoting energy efficiency in domestic refrigerators must improve safety, operational performance, and cost reduction at varying ambient temperatures, relative humidity, refrigerator compartment temperature, and door opening frequency. Also, the work of Ref. [4] expressed that energy conservation motivates new refrigeration system designs. However, available techniques for performance improvements of refrigerators involving sub-component redesigns or modifications could be more challenging and expensive to implement [1,10].

Nanofluids have been successfully applied in refrigeration systems to achieve (i) reduction in power consumption, especially at low concentrations [11], (ii) reduction in pumping work [12], and (iii) enhancement in heat transfer rate [13]. These performances hinged on high thermal conductivity, thermophoresis, and Brownian flow movement inducements for better heat transfer, and induction of slip mechanisms to enhance ball-bearing, rolling, and mending effects in the compressor of the refrigeration system. Alawi et al. [14] reviewed nanofluid applications in refrigeration, air-conditioning, and heat pump systems. The authors discovered that the shape of CNT nanoparticles enables better compatibility and stability with hydrocarbon refrigerants compared to other nanoparticles. This performance initiates better boiling and condensing heat transfer in the evaporator and condenser components and improves the tribology characteristics of the compressor. Kumar et al. [15] observed that the application of nanoparticles into refrigerants in refrigeration systems increases pool boiling coefficient, two-phase flow heat transfer, coefficient of performance, and energy conservation. A study on the simulation of molecular dynamics to determine the effects of the addition of iron-oxide nanoparticles to ammonia refrigerant by Ref. [16] gave rapid phase change and heat transfer performances. The enhancements in the performance of refrigerators and other thermal systems, aided by the use of nano-lubricants are attributable to the positive thermal conductivity and augmentation of viscosity of their circulating working fluids [17,18].

Researchers have observed similar performance benefits in various refrigeration systems when applying magnetic fields to circulating refrigerants. Tipole et al. [19] investigated the effect of magnetic field strength on energy characteristics in a refrigeration system. The magnetic field initiates intermolecular forces that reduce the viscosity of circulating refrigerant in the test refrigerator [19]. The reduction in viscosity invariably enhances the pumping power, heat transfer efficiency, and compressor energy consumption, and also increases the coefficient of performance. Zhou et al. [20] observed the same behaviour in a magnetorheological fluid flowing through a microchannel under the influence of a magnetic field. In the experimental investigation to determine the effects of the magnetic force on flowing fluids by Ref. [21], the magnetic force affects the heat and fluid flow properties of a paramagnetic fluid moving within a pipe. The magnet also influences the mass flow rate of the circulating fluid. Hence, the circulating fluid mass flow rate varies with the magnetic coil field strength. In the work of Ref. [22], the application of a magnetic field on copper-water nanofluid influences the fluid's thermal characteristics positively.

Furthermore, the adoption of the magnetic field enhances the thermal conductivity of the nanofluids and the thermal efficiency of the heat transfer system. The adoption of 3000 G capacity of magnetic field strength along the liquid line of an R404a refrigerator by Ref. [23], improved the energy performance of the refrigeration system. Tipole et al. [19] studied the effect of varying magnetic field strength along the liquid line of a refrigeration test rig separately infused with R600a and R134a refrigerants. Tipole et al. [19] observed improvement in energy characteristics resulting from the viscosity reduction of the working fluids. In addition, enhancement in the behaviour of similar thermal systems occurs with the application of 0–3 pairs of 3000 Gauss permanent magnets [19,24].

The only available study on nanofluids-based magnetic fields utilized metallic nanoparticles to produce ferromagnetic fluids [25]. However, there has been no investigation into the effect of non-metallic carbon nanotube (CNT) nanoparticles with or without liquid line magnetic field on the performance of refrigeration systems. Hence, this work experimentally investigates the improvement in the energy performance of a 100g R134a domestic refrigerator retrofitted to work with ultra-low 30g R600a and LPG refrigerants. It explores enhancing the refrigerator's safety and energy performance by adding CNT nano-lubricants (0–0.2 g/L), hydrocarbon refrigerants, and liquid line magnets (0–2 pairs). This work further provides the enhancement limit of ultra-low 30g R600a and LPG refrigerants in the 100g R134a refrigerator. The parameters tested include the evaporator air temperature, instantaneous and cumulative power consumption, coefficient of performance, and energy cost, without compromising safety characteristics of the system.

2. Methodology

2.1. Experimental Setup

The experimental test rig is made of a built-in 98W R-12 compressor, air-cooled condenser, plate-type evaporator, adiabatic dryer, and a 2 m capillary tube (See Fig. 1). The rig was modified to include valves at the suction and discharge ends of the compressor to provide for digital pressure gauges (HONGSEN HS-5100H and HS-5100L), and to serve as channels for the charging and evacuation of refrigerant. A digital wattmeter (multifunctional mini ammeter D02A) measures the system's instantaneous and cumulative energy consumption after working for 4 h. The temperatures of the refrigerants in the test rig, including evaporator air temperature, discharge temperature, and condensing temperature, were measured using Type K digital thermocouples (Vici 6902 Digital Thermocouple K). This experiment was conducted at an ambient temperature of 29 °C (monitored using a surface temperature thermometer) and relative humidity of 73% (monitored using Brannan hygrometer). The test environment is equipped with a 5 Hp air-conditioner to maintain the ambient temperature throughout the experiments. The ranges of the measuring instruments and standard uncertainty are available in Table 1. The uncertainty of the parameters is calculated following the work of Refs. [26,27]. The specification of the test rig is shown in Table 2. All experimental tests in the refrigerator were under ISO 8187 standard for the steady-state operation described in Ref. [28].

2.2. Experimental Procedure

The test refrigeration system was run continuously for 4 h at closed-door, at no-load, and without ON/OFF operation. All readings were taken from the thermometers, watt-meter, and pressure gauges to measure the performance of the test refrigerator. The refrigerants used in the system included 100g of R134a, 30g of R600a, and 30g of LPG refrigerants. The system compressor has varying mixtures of mineral oil, compressor lubricant, and CNT nanoparticles for the nanofluid tests. The stability of CNT nanoparticles in the

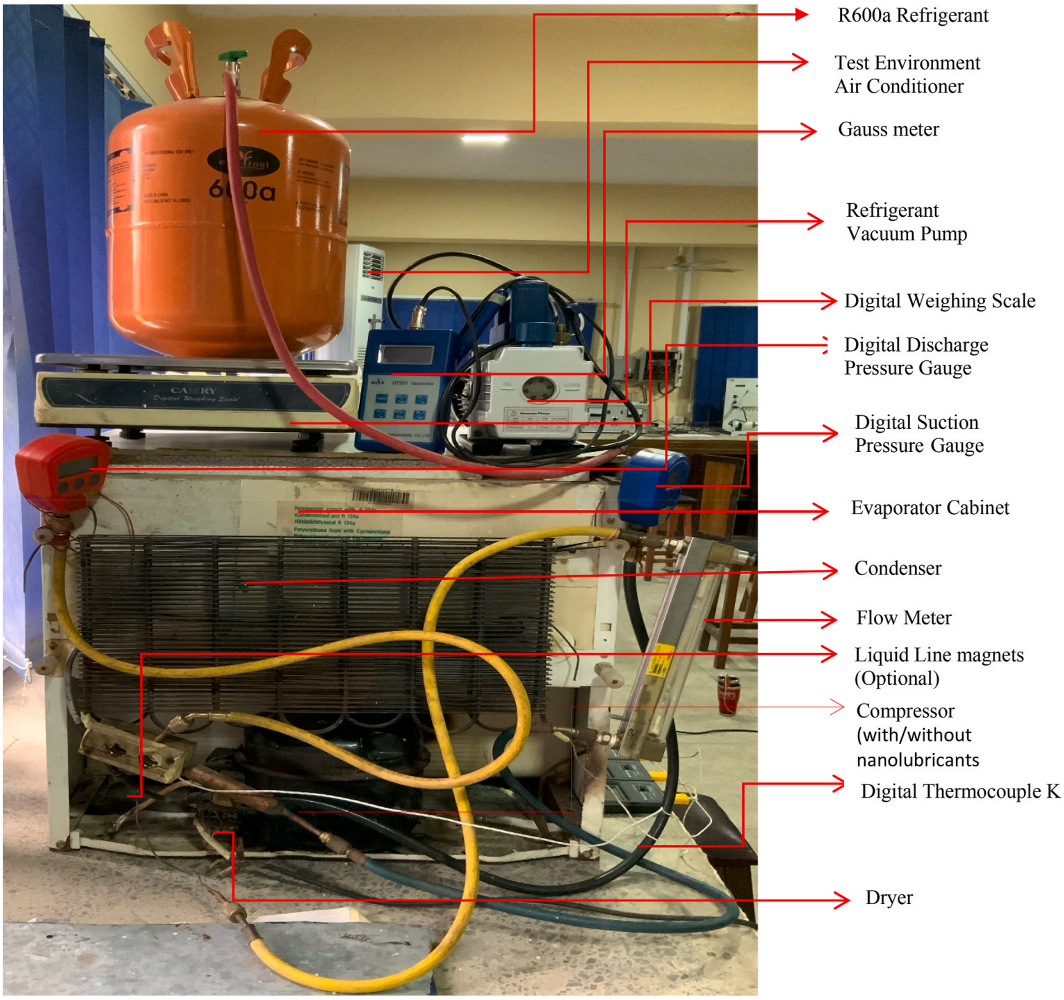


Fig. 1. Experimental Setup.

Table 1
Specification of the measuring instruments and estimated parameters.

S/Nos	Characteristics	Range	Instrument error	Standard Uncertainty
1	Power	0-5000 Watts	±1 %	3.69 Watts
2	Pressure	0–2500 kPa	±2 kPa	0.63 kPa
3	Temperature	−50 - 750 °C	±0.2 °C	0.07 °C
4	Mass flow rate	0.01–38 g/h	±2 g/h	0.09 g/h
5	Refrigerant Mass	0–3000 g	±10 °C	9.33 g

Table 2
Specification of the test rig.

S/N	Components	Unit
1	Evaporator size	50 L
2	Compressor type	R-12
3	Defrost type	Manual
4	Condenser type	Air-cooled
5	Refrigerant types	R134a, LPG and R600a
6	Freezing power	6kg/34hrs
7	Frequency type	50Hz
8	Power rating	98 W
9	Door type	Single

mineral oil-based lubricant of the compressor was confirmed using sedimentation and UV spectrometer tests recommended by Adelekan et al. [26]; the test was carried out after the homogenization of the CNT nano-lubricant using Branson M2800H ultrasonic homogenizer to mix the CNT nanoparticles and compressor mineral oil (see Fig. 2(a and b)). A visible spectrometer (HELIOS ZETA) was used to ensure the stability of the nano-lubricant (see Table 3 for the absorbance of the CNT nano-lubricant). A sedimentation test was done to validate the stability of the CNT nanoparticles after 30 days. The CNT nanoparticles have 98 % purity, multi-wall, with 4.5 nm ± 0.5 nm internal and 10 nm ± 1 nm external diameters, and were procured from Aldrich Sigma. The pure tests involve performance tests of the original refrigerator with the refrigerants (i.e., 100g R134a, and 30g of both R600a and LPG refrigerants). For the magnetic field tests, the liquid line of the refrigerator was coupled to 2 pairs of 3000 Gauss (Gs) magnets as described in the work of Ref. [19]. The ‘nano-mag’ test considers the refrigeration system’s performance with CNT nano-lubricant and liquid line magnets. The pair of magnets was N50 neodymium O ring type having 20 mm inner- and 25 mm outside diameters. The influence of aiding the refrigerator with liquid line magnetic field and CNT nano-lubricant is thus investigated. A comparative analysis of the continuous operation of the test rig for 240 min with the separately infused refrigerants was estimated. Each experimental trial was repeated three times, and the average data of the repeated tests were recorded every 10 min and every 1 °C drop in the refrigerator’s evaporator temperature (T_{air}). After the completion of the experiment, the average data captured at 240 min were used to estimate the refrigerant vapour enthalpy, coefficient of performance, volumetric refrigeration capacity, instantaneous and cumulative energy consumption, and cost of energy used by the refrigerator. The estimation of these parameters was evaluated using Equations (1)–(3).

2.2.1. *Governing equations*

$$\text{Volumetric Refrigeration C apacity } (Q_e) = \text{VRC} = \rho(h_1 - h_3)\ \text{kJ} / \text{m3} \tag{1}$$

$$Compressor\ power\ input = W_d = \dot{m}(h_2 - h_1)\ \text{kJ} / \text{s} \tag{2}$$

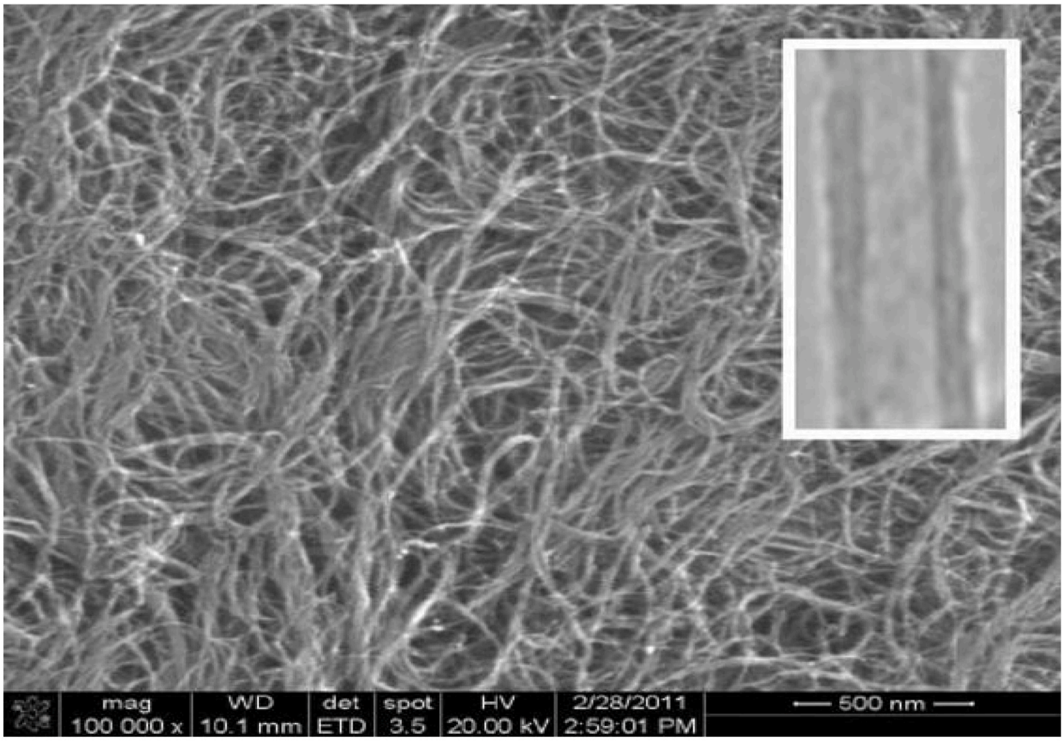
$$Coefficient\ of\ Performance = COP = \frac{\dot{m}(h_1 - h_3)}{\dot{m}(h_2 - h_1)} \tag{3}$$

Q_e is the volumetric refrigeration capacity, ρ is the refrigerant saturated vapour density, h_1 is the refrigerant saturated vapour enthalpy, h_2 is the superheated vapour enthalpy, h_3 is the saturated liquid enthalpy, $\dot{m}$ is the refrigerant mass flow rate.

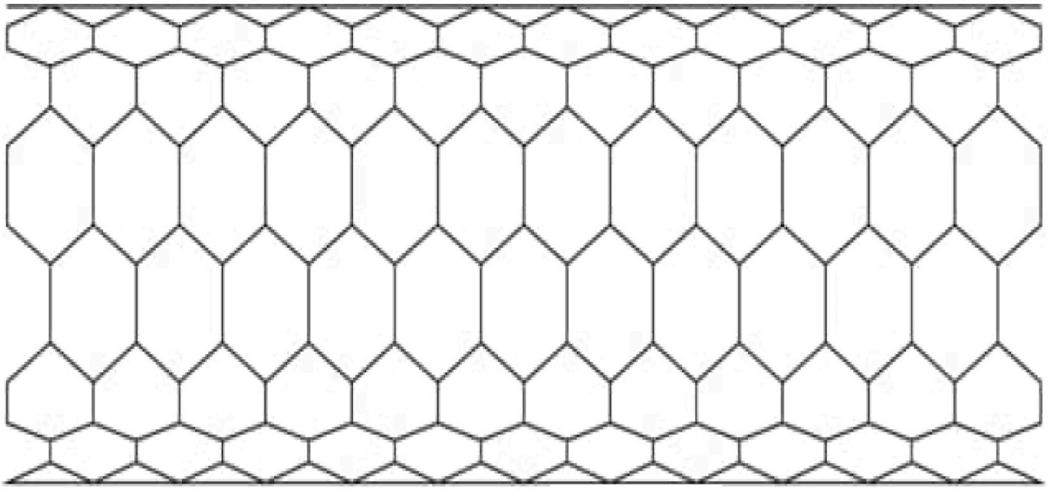
3. Results and discussion

This study considered different test configurations for 30g R600a and 30g of LPG refrigerants as alternatives to a 100g R134a refrigerant in a refrigeration system. The test configurations include (i) baseline tests of the refrigerants with pure mineral compressor oil and no-magnetic field, (ii) the refrigerants with two pairs of liquid line mounted 3000Gs magnets and pure mineral compressor oil, (iii) the refrigerants with 0.2 g/L CNT based nano-lubricant, and (iv) combination of test configurations (ii) and (iii). The R134a refrigerant is investigated only under test configurations (i) and (ii).

Fig. 3 depicts the variations in the coefficient of performance (COP) of the test rig under the test configurations. We observed that 100g-R134a performed better than the 30g-R600a and 30g of LPG refrigerants in the system. For test configurations (i) and (ii), the reductions in COP for the R600a and LPG refrigerants compared to the R134a refrigerant range between 11-41 % and 12–42 %,



a: SEM Image of the MWCNT Nanoparticle.



2b: Structural Image of MWCNT Nanoparticle.

Fig. 2a. SEM Image of the MWCNT Nanoparticle. Ref. [29]. b: Structural Image of MWCNT Nanoparticle. Ref [29].

respectively. We also found that applying the magnetic field along the refrigerator's liquid line improved the system's coefficient of performance for only 100g R134a and 30g LPG refrigerants. This noticeable improvement is a result of the reduction in viscosity and the increased mass flow rate [19]. The COP of the refrigerator using R134a, and LPG, with the magnetic field along the liquid line of the refrigerator, increased by 1% and 15% compared with their respective baseline test conditions. At the same time, the COP of the refrigeration system with R600a was reduced by 15%. The improvement validates the assertion in the work of Ref. [22] that application of a magnetic field improves the thermal conductivity of refrigerants. The refrigerator's performance using LPG and R600a refrigerants under test configurations (iii) and (iv) is found to be better than the baseline test; also, the performance of the hydrocarbon-based refrigerants varies significantly when compared with R134a. The maximum COP for the hydrocarbons across all test conditions was found to be 2.90 for LPG under test configuration (ii), while it is 3.02 for R600a refrigerant under test configuration (iii) (see Fig. 3). Also, in Fig. 3, it can be seen that the use of CNT nano-lubricant gave the lowest improvement for the 30g-LPG

Table 3
Absorbance of 0.2 g/L CNT nano-lubricant.

S/N	Wavelength (nm)	Absorbance
1	192	4.42
2	198	4.237
3	229	4.237
4	233	4.432
5	246	4.18
6	253	4.569
7	268	4.509
8	275	4.959
9	286	4.347
10	309	3.11

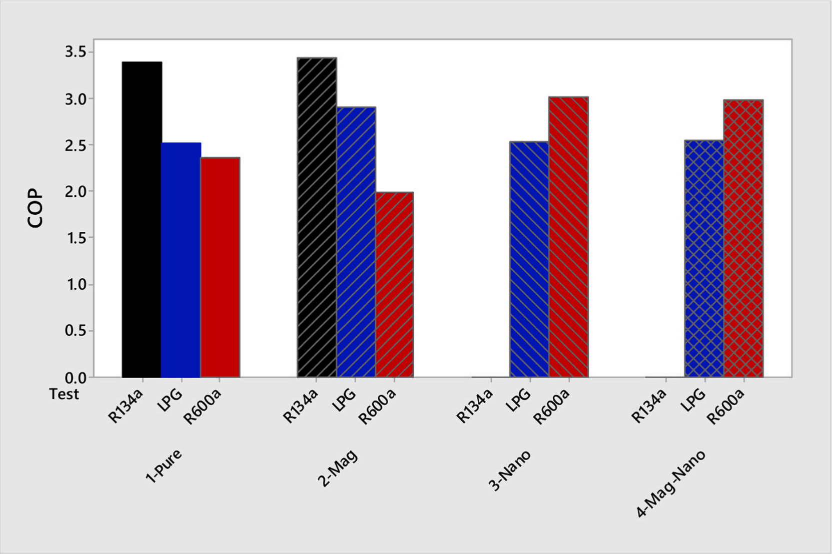


Fig. 3. Coefficient of performance.

refrigerant, while the use of liquid line magnetic field gave the least COP for 30g-R600a refrigerant. An improvement in the COP of the system with LPG refrigerant under test configurations (ii), (iii), and (iv) were found to be 15%, 0.2%, and 1.03% when compared to baseline tests. Similarly, the COP of the system with R600a refrigerant decreased by 15.52% and increased by 28.11% and 26.39%, respectively under test configurations (ii), (iii), and (iv). The reduction observed with the R600a refrigerant under test condition (ii) was due to the high compressor power input, discharge pressure, and temperature.

The variation in the evaporator air temperature of the refrigerator is described in Fig. 4. The pure R134a refrigerant reaches the

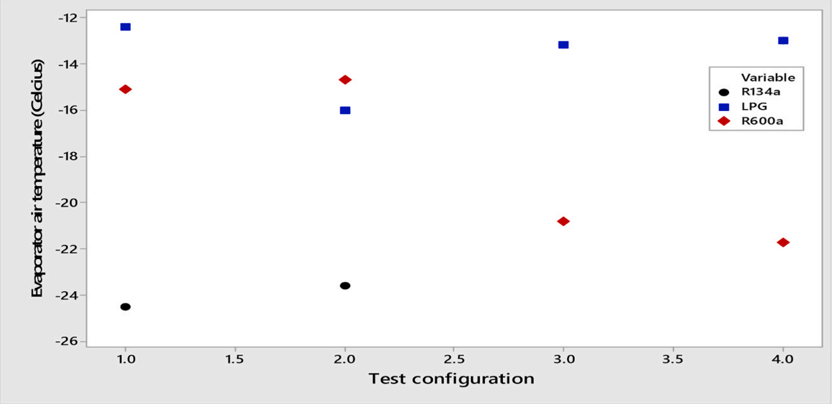


Fig. 4. Evaporator air temperature.

lowest attainable evaporator air temperature of −24.5 °C. Upon the application of a magnetic field to the system, a negligible increase of 0.9 °C in evaporator air temperature (i.e., a 3.67% increase) was observed in the refrigerator. When compared to baseline R134a refrigerant, the evaporator air temperatures with baselines R600a and LPG refrigerants increased by 38% and 49%, respectively. Although the application of LPG and R600a refrigerants gave higher evaporator air temperatures in the system when compared to R134a refrigerant, we observed reductions of about 29.03%, 6.45%, and 4.84% in the evaporator air temperature of the refrigerator with the LPG refrigerant, when LPG is aided with liquid line magnetic field, CNT nano-lubricant, and both (i.e., a combination of liquid line magnetic field and CNT nano-lubricant), respectively. The evaporator air temperature of the refrigerator using R600a refrigerant slightly increased from the baseline test by 2.65% with the magnetic field, reduced by 37.75% with CNT nano-lubricant, and a further reduction by 43.71% with the combination of liquid line magnet and CNT nano-lubricant (Mag-Nano). We infer that R134a refrigerant invariably gave the highest boiling heat transfer coefficient within the evaporator of the refrigeration system [1]. The evaporator air temperature of the refrigerants also varies with the application of the liquid line magnetic field (Fig. 4).

The evaporator air temperatures of the system with R134a and R600a refrigerants increased while a reduction was observed with LPG refrigerant (see Fig. 4). The evaporator air temperatures of the system increased by 3.67% and 2.65% under the magnetic field for the R134a and R600a refrigerants, respectively. In contrast, LPG refrigerants gave a 29.03% reduction compared to the baseline test. The application of CNT nano-lubricant in the system reduced the evaporator air temperatures by 6.45% and 37.75% for the LPG and R600a refrigerants, respectively, when compared to the baseline test. Hence, there is a good evaporator heat transfer rate with the R600a and LPG nano-lubricants (Fig. 4). We observed a maximum reduction of about 4.84% with 30g-R600a refrigerant under the influence of the magnetic field, while the 30g-LPG nano-lubricant under the magnet field gave a reduction of about 43.71 %. The least evaporator air temperature, which invariably corresponds to peak boiling heat transfer across the refrigerants, is found with the baseline test of R134a refrigerant, LPG nano-lubricant under a magnetic field, and R600a refrigerant under a magnetic field. According to the work of Ref. [19], these performances are due to better thermal conductivity within refrigerants.

The variations in the volumetric refrigeration capacity of the refrigerants under the test conditions are shown in Fig. 5. The baseline test shows that LPG refrigerant has the highest volumetric refrigeration capacities (i.e., 795 kJ/m^3), while those of R134a and R600a refrigerants are 758 kJ/m^3 and 625 kJ/m^3, respectively. Despite the lower saturated vapour densities of the hydrocarbons (i.e., 2.5 kg/m^3 for R600a, and 3.1 kg/m^3 for LPG) in comparison with 5.6 kg/m^3 for R134a, we observed that the higher saturated vapour refrigeration effect of 254.1 kJ/m^3 for LPG resulted in it having the highest volumetric refrigeration capacity in the system. Applying the liquid line magnetic field on the refrigerants improves the volumetric refrigeration capacities of R134a by 3.87% when compared to its baseline. However, due to the lower saturated vapour density, reductions in the volumetric refrigeration capacity of about 4.9% and 0.9% with the LPG and R600a refrigerants were attained when compared to their baseline test. We found that the subjection of R134a refrigerant to the magnetic field is about 4.01% and 21.28% better than LPG and R600a refrigerants under magnetic fields. The volumetric refrigeration capacity of the LPG refrigerant improved with the application of CNT nano-lubricant in comparison with the performance of its baseline test. We observed that LPG refrigerant with CNT nano-lubricant improved by 5.73% when compared to its baseline performance (Fig. 5). In comparison to the baseline of R134a refrigerant, the LPG refrigerant with CNT nano-lubricant improved by 10.85%, while a reduction of about 33.62% was observed with R600a aided with CNT nano-lubricant. Further improvement is found with the LPG refrigerant when under the magnetic field influence and aided with CNT nano-lubricant. A slight reduction in volumetric refrigeration capacity of about 3.41% occurs with the R600a refrigerant under similar conditions.

The instantaneous power consumption of the refrigeration system is shown in Fig. 6. We found that R134a refrigerant at baseline test, and R134a subjected to magnetic field consumed approximately equal instantaneous power. An instantaneous power consumption of about 74.4 W was obtained at the baseline test with the pure R134a.

refrigerant, while with magnetic field influence, R134a refrigerant gave 74.6 W. The R134a refrigerant consumed the highest

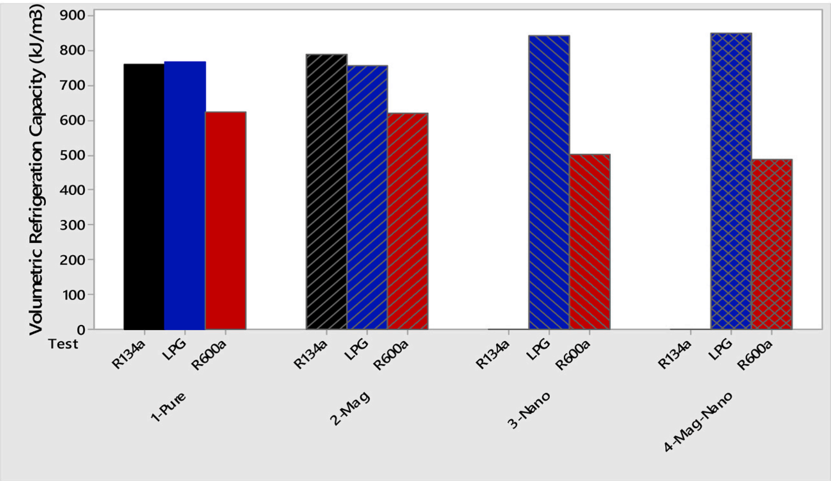


Fig. 5. Volumetric refrigeration capacity.

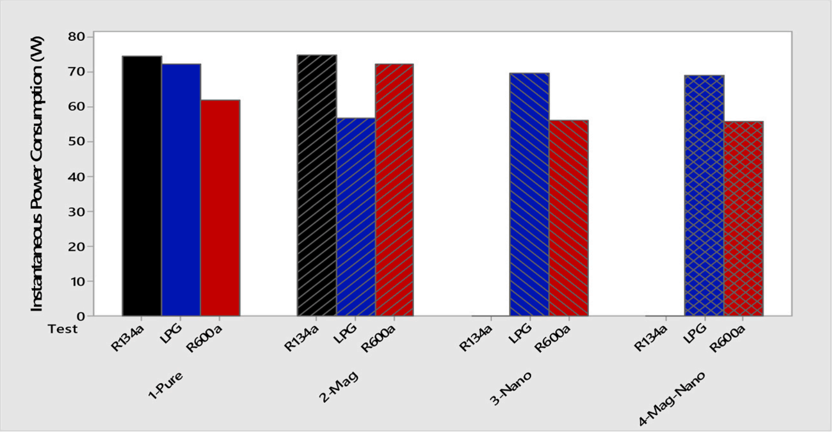


Fig. 6. Instantaneous power consumption.

instantaneous power in the refrigerator. The refrigeration system using R600a with CNT nano-lubricant under a magnetic field consumed the least amount of energy of 55.7 W. The least power consumed among the different configuration tests of LPG refrigerants is 56.8 W with LPG refrigerant under magnetic field conditions. The reduction in the power consumption of the system with LPG refrigerant ranged between 3.23% and 23.66%. Similarly, there is a reduction in power consumption from 3.09 to 25.13% with R600a refrigerant when compared to R134a refrigerant. The observed low power consumption of the system with hydrocarbon refrigerants resulted from low viscosity and pressure drop [30,31].

Fig. 7 depicts the cumulative energy consumption of the refrigerants within the refrigeration system. R134a refrigerant utilized more energy than either R600a or LPG refrigerant during the 240 min investigation period. The reduction in the energy utilized by the refrigerator with the LPG and R600a refrigerants ranged from 9.59 to 25.57%, and 7.67–25.97%, respectively.

The energy reduction of the refrigeration system is improved by aiding the 30g-LPG refrigerant with nano-lubricant and magnetic field. Also, for the trials using R600a hydrocarbon, R600a refrigerant under a magnetic field is the only test that consumed more energy by about 15.60% than the R600a baseline. The R600a refrigerant under the magnetic field invariably gave the highest cost of electricity when compared to the R600a baseline test (see Fig. 8). The adoption of hydrocarbon refrigerants is economically better than the R134a refrigerant. The average cost of residential electricity in Nigeria is 60 (1 US Dollars equals 415) [32]. The application of LPG and R600a refrigerants in the domestic refrigerator reduced the cost of electricity. The cost reduction with hydrocarbon refrigerants ranged between 9.59% and 25.57% when compared to the pure R134a refrigerant, and was also found to range from 7.63% to 25.98% when compared to R134a refrigerant under the magnetic field. The summarized values are shown in Table 4.

4. Conclusion

From the experimental investigation of the effect of liquid line magnets (magnetic field), CNT nano-lubricant, and both (i.e., the combination of magnetic field and CNT nano-lubricant) on the R134a refrigerator system retrofitted with LPG and R600a refrigerants at 30 g mass charge, the following findings were concluded.

- The proposed enhancement techniques (magnetic field, CNT nano-lubricant, combination of magnetic field, and CNT nano-lubricant) worked safely and efficiently in the refrigeration system.
- The hydrocarbon refrigerants were observed to consume lesser energy than the R134a refrigerant in the system. Overall, the least instantaneous power consumption in the system is 55.7 W with R600a-Mag-Nano.
- R134a refrigerant gave the least evaporator air temperature of −24.5 °C and consumed the highest energy of 74.4 W in the refrigerator.
- LPG under the magnetic field with CNT nanolubricant gave the highest volumetric refrigeration capacity of 848 kJ/m^3 in the refrigeration system.
- The energy cost within the refrigeration system ranged between 14.41 for R600a with 0.2 g/L CNT nano-lubricant and 19.53 for R134a under the liquid line magnetic field.

Finally, determining the enhancement threshold for cost-effective hydrocarbon refrigerant charges below 150g in domestic refrigerators is essential for future improvements. This includes investigating the effects of both nanolubricants and liquid line magnets to optimize the performance of the system.

Funding statement

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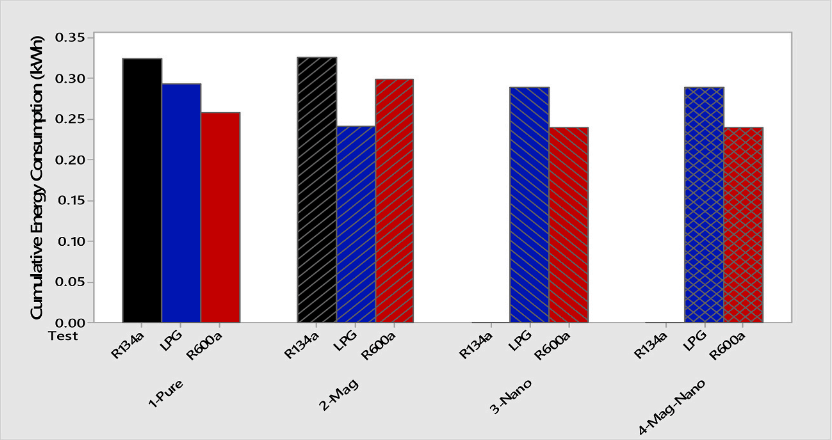

Fig. 7. Cumulative energy consumption.

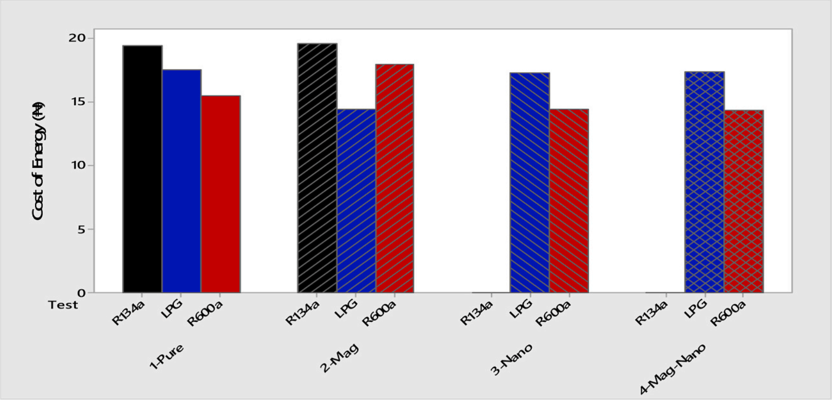

Fig. 8. Cost of energy.

Table 4
Experimental values.

Configuration	Refrigerant	COP	Volumetric refrigeration Capacity (kJ/m^3)	Evaporator Temperature (°C)	Power (W)	Energy Consumption (kWh)	Cost of energy (₦) [1 US Dollar equals 415]
Baseline	R134A	3.392	758	−24.5	74.4	0.3234	19.40
	LPG	2.525	795	−12.4	72	0.2924	17.54
	R600A	2.357	625	−15.1	61.7	0.2584	15.50
3000Gs Magnetic Field	R134A	3.433	787	−23.6	74.6	0.3255	19.53
	LPG	2.902	756	−16	56.8	0.2407	14.44
	R600A	2.000	620	−14.7	72.1	0.2987	17.92
0.2 g/L CNT	LPG	2.530	840	−13.2	69.5	0.2883	17.30
	R600A	3.019	503	−20.8	56	0.2401	14.41
0.2 g/L CNT+ 3000Gs Magnetic Field	LPG	2.551	848	−13	68.9	0.2891	17.35
	R600A	2.979	486	−21.7	55.7	0.2394	14.36
Standard Uncertainty		0.253	4.628	2.76	3.689	0.018	1.077
Mean Absolute Error		0.3762	1.146	0.4120	0.6896	0.0280	1.678

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

h	Refrigerant enthalpy (kJ/kg)
$\dot{m}$	Refrigerant mass flow rate (kg/s)
P	Pressure (kPa)
ρ	Refrigerant density (kg/m3)
T	Temperature (^{o}C)
COP	Coefficient of performance
Qe	Cooling effect (kJ/kg)
CNT	Carbon nanotube
VRC	Volumetric refrigeration capacity (kJ/m3)
Gs	Gauss
Wd	Compressor power input (kJ/s)

Subscript

1	Suction line
2	Discharge line
3	Liquid line

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