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Experimental Investigation of a Vapour Compression Refrigeration System with 15nm TiO_2-R600a Nano-Refrigerant as the Working Fluid

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Abstract

Nanofluids are being considered as an efficient heat transfer fluid in various thermal applications. In this work, an experimental study was conducted on TiO_2 nanoparticle mixed with R600a as the working fluid. TiO_2-R600a nano-refrigerant was used in a domestic refrigerator with little system reconstruction. The refrigerator performance was then investigated using test parameters including: Pull down test, specific compressor work-input, refrigeration effect and coefficient of performance (COP) using steady state analysis. The results indicate that TiO_2-R600a nano-refrigerant works efficiently and safely in the refrigerator and the performance was better than the pure R600a system. Overall, 0.1g TiO_2 in 40g R600a nano-refrigerant mixture had the highest refrigeration effect and COP and gave the least specific compressor work-input within the test rig.

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Keywords: Domestic refrigerator; Nanoparticles; R600a; TiO_2.

1. Introduction

Imminent deadline globally for both developing and developed nations to phase out and restrict application of harmful conventional working fluids (refrigerant) like chlorofluorocarbons (CFCs), hydro-chlorofluorocarbons (HCFCs) and hydrofluorocarbon (HFCs) having either or both Ozone depleting characteristic and high global warming potential in refrigeration systems are justifying natural refrigerant (especially hydrocarbons based types) retrofit researches in refrigeration recently[1]. Restrictions across all refrigeration system manufacturing industries **a**re in line with United Nation Montreal and Kyoto protocols and emission gap reports stated aims for achieving safe emission targets by year 2100 and ameliorating present devastating effects of climate change [2-4].

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Nomenclature

h	refrigerant enthalpy (kJ/kg)
$\dot{m}$	refrigerant mass flow rate (kg/s)
P	Pressure (kPa)
T	Temperature (°C)
COP	Coefficient of performance
Q_e	Refrigerating effect (kJ/kg)
W_c	Specific compressor workdone (kJ/kg)

Hydrocarbons have been reported in several literatures as excellent replacement option to conventional refrigerants based on its close thermodynamic properties and system compatibility without or with slight modifications in conventional refrigeration systems, their non-Ozone depleting characteristics and almost neutral global warming potential advantages; and are justifying its increasing utilization in spite of their flammability concerns. Hydrocarbon utilization flammability fears according to Corbera´n et al., [5], for small scale domestic refrigerators charges (below 150 g) is negligible due to their lower operating temperatures and pressures conditions and can be placed in any location within households. Drawbacks from experimental and theoretical hydrocarbon usage for domestic application according to Fatouh et al., [6], Medhi et al., [7], and Mohamed [8] includes; (i) high discharge pressure and temperature, (ii) low coefficient of performance, (iii) compressor oil change from POE to mineral oil and (iv) compressor change from HFC types to HC (hydrocarbon) types and most experimental attempts in literature optimized performance or reliability indexes for the domestic refrigerator to be considered sustainable in according to Belman-Flores et al., [9].

Numerous nanoparticle additions in domestic refrigerators (that is compressor lubricant or refrigerant called nanolubricant or nanorefrigerant) has shown their application can remove all stated shortfalls and produced more sustainable domestic refrigerators [10-13]. Nanoparticles have been put into several applications to enhance performance of engineering systems. In the work of Elcock [14], TiO_2 nanoparticles was used as additives to enhance the solubility of mineral oil with the hydrofluorocarbon (HFC) refrigerant. It was observed in the work that refrigeration systems using a mixture of HFC134a and mineral oil with TiO_2 nanoparticles appear to give better performance by returning more lubricant oil to the compressor with similar performance to systems using HFC134a. The work of Bi et al., [15] experimentally investigates the performance of a domestic refrigerator with SUNISO 3GS mineral oil and TiO2 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 that of 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 [16]; it was observed that Al_2O_3-R134a system performance was better than pure lubricant with R134a working fluid with 10.30% less energy used with 0.2%vol of the concentration used and also heat transfer coefficient increases with the usage of Nano Al_2O_3. Several other work had been conducted on different application of nanoparticle to improve the performance of several processes (e.g. Jwo et al., [17]; Peng et al., [18]; Kumar and Elansezhian [19]).

In this work, the performance of the domestic refrigerator containing R600a working fluid, was examined. TiO_2-R600a nano-refrigerant was charged into the system and compared with pure R600a. An experimental investigation of parameters including: coefficient of performance, and evaporator air temperature (pull-down time), to attain the specified International Standard Organisation (ISO) requirement for standard evaporator air temperature with small refrigerator size [20] was thus carried out, to compare the refrigerator system performance under nanoparticle-R600a mixtures, and pure R600a refrigerant. These parameters are measured at 180 minutes of test run without ON-OFF cycle.

2. Methodology

The experimental rig (consists of a domestic refrigerator that is made up of 1/10hp scroll compressor, 1m throttle length and 2mm diameter array of fins air cooled condenser design), was integrated with valves that are required for charging and discharging of refrigerant within the compressor. It was designed to operate at -3°C based on ISO requirement for standard evaporator air temperature with small refrigerator size [20]. Digital thermocouples K and pressure gauges are also incorporated on the test rig to measure temperature and pressure of the refrigerant; the power consumption of the refrigerator was measured with a digital Wattmeter having ±1% measurement accuracy.

The schematic diagram of the refrigeration cycle is shown in Figure 1. The thermocouples measure temperatures at the evaporator compartment (T_1), outlet of the compressor (T_2), outlet of the condenser (T_3), outlet of the throttle pipe (T_4), at 30 minutes interval for a total observation period of 180 minutes, for the 40, 60 and 80 g charges respectively. Data were recorded for an isentropic efficiency value of 0.6, volumetric efficiency value of 0.95, and compressor displacement of $0.01m^3/s$. The test environment is a tropical region (Nigeria) with an ambient air temperature of 29°C and relative humidity of 51% throughout the experiment. The room temperature was captured using Rototherm surface temperature thermometers (Model BL301), having a scale range of 0 to 400°C. The room temperature was controlled by an air-conditioner.

R600a refrigerant used for the study was obtained locally and has a purity of 99.7%. Titanium dioxide (TiO_2) nanoparticle (5-15nm) has 99.5% purity and obtained from Aldrich Chemistry. The characteristics of the lubricating oil for the compressor is shown in Table 1. The nanoparticles were measured on a digital weighing balance (OHAUS Pioneer TM PA114) with measuring range of 0.0001 to 110g, while the R600a refrigerant was measured using a digital weighing balance (CAMRY ACS-30-ZC41) with measuring range of 5 to 30000g. Furthermore, the TiO_2 nanoparticle and mineral oil mixture was sonicated using a Branson M2800H ultra-sonicator to ensure proper homogenisation of the mixture and to prevent sedimentation and agglomeration of the nanoparticle within the mixture. A vacuum pump was adopted for extracting spent refrigerant after each trial, in preparation for another experiment. All experimental trials were repeated three times to ensure repeatability of experiment.

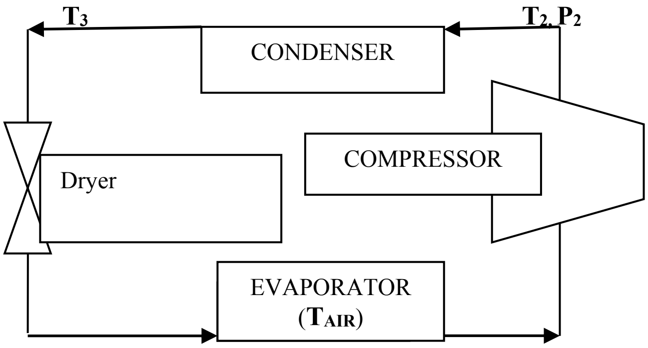

Fig.1. Schematic diagram of the refrigeration cycle

The steady state experimental investigation of varied charges of R600a refrigerant and TiO_2 nanoparticle concentrations specific compressor work-done, refrigeration effect and coefficient of performance indexes were computed using the under-listed equations and assumption;

Equations;

$$W_d = (h_1 - h_3) \quad kJ/kg \tag{1}$$

$$Q_e = (h_2 - h_1) \quad kJ/kg \tag{2}$$

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

Where, $\dot{m}$ (kg/s) is the mass flow rate, h_1 (kJ/kg) is the refrigerant saturated vapour enthalpy at the inlet of the compressor, h_2 (kJ/kg) is the refrigerant superheated vapour enthalpy at the discharge of the compressor, h_3 (kJ/kg) is the refrigerant saturated liquid enthalpy at the condenser outlet. The assumptions considered in this study includes; (i) negligible pressure loss within the system, (ii) The system discharge and condensing pressures within the system are equal, (iii) Condensing and evaporator enthalpies are equal $(i.e\ h_3 = h_4)$, (iv) Exergy and energy losses within the system are negligible, and (iv) No sub-cooling.

3. Results and Discussion

The test analysis results of the domestic refrigerator investigated with varied R600a mass charges and concentration

of pure mineral oil/R600a nano-lubricant are discussed in this section:
As shown in Table 1 the performance of the test rig was influenced by both refrigerant mass charge variation and TiO_2 nanoparticle concentrations. It can be seen that the evaporator air temperature of the test rig decreased with time and refrigerant mass charge for pure compressor based lubricant. Also, all mass charges of R600a refrigerant [40, 60 and 80g] using either pure or varied TiO_2 nanoparticle-mineral oil concentrations exceeded ISO 8187 [20]; standard evaporator air temperature for domestic size refrigerators. According to ISO 8187, a typical small domestic refrigerator is expected to achieve -3°C evaporator air temperature and perform steadily on or before 3 hours. All charges of refrigerant exceeded expected standard evaporator air temperature at steady state. Experimental result finding collates with the work of Adelekan et al. [21], Babarinde et al. [22], Gill et al. [23, 24], and Ohunakin et al. [25, 26] that tested varied mass charge of hydrocarbon blend in a domestic refrigerator.
The variation of specific compressor work-input of the domestic refrigerator can be found in Fig 2. The specific compressor work-done was found to increase with refrigerant mass charges. Also, all R600a-nanoparticle mixture gave lower specific compressor work-input index for all refrigerant mass charges within the test rig. The lowest specific compressor work-done values was found with 0.1 g/L TiO_2-R600a-mineral oil mixtures while pure compressor mineral oil-R600a mixtures had the highest specific compressor work-done. According to Bolaji [27] and Babarinde et al, [22], specific compressor work-input directly impacts on the compressors' durability and reliability. Hence, all TiO_2 nano based mixture increased the durability of the compressor by reducing the compressors' specific work input. Results are in compliance with the work of Adelekan et al. [21], Ohunakin et al. [25, 26], and Shengshan et al. [28].

Table 1: Pull Down Characteristics of Varied Mass Charges of R600a and TiO_2 nanoparticle concentration

S/N	Time	40g R600a				60g R600a				80g R600a			
		Pure	0.1g/L	0.3g/L	0.5g/L	Pure	0.1g/L	0.3g/L	0.5g/L	Pure	0.1g/L	0.3g/L	0.5g/L
1	0	29	29	29	29	29	29	29	29	29	29	29	29
2	30	-4	1	-2	3	-3	-3	-5	1	1	-3	-1	-2
3	60	-9	-2	-8	-5	-6	-10	-10	-9	-3	-6	-5	-6
4	90	-9	-5	-10	-9	-8	-12	-11	-10	-4	-9	-7	-8
5	120	-11	-5	-10	-9	-8	-13	-12	-12	-5	-10	-8	-8
6	150	-12	-5	-12	-11	-8	-13	-13	-12	-6	-10	-8	-8
7	180	-12	-7	-13	-12	-9	-15	-15	-13	-6	-10	-8	-8

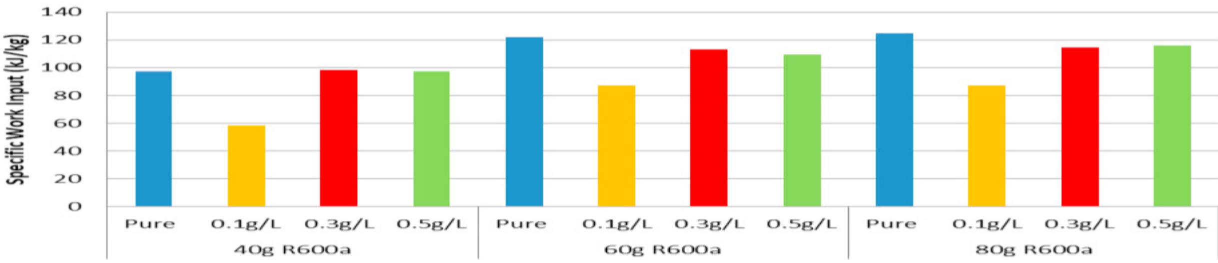

Fig. 2 Specific Compressor Work-Input Variation of the Refrigerator system

The refrigeration effect is simply the rate of heat removal for a confined space (refrigerator compartment). The effect of selected TiO_2 nanoparticle concentrations and refrigerant mass charges resulted in varied refrigeration effects performances [See Fig 3]. The highest refrigeration effect index of 290.83kJ/kg was obtained using 40g-0.1g/L R600a-TiO_2 nano-lubricant mixture while 60g-0.1g/L R600a-TiO_2 nano-lubricant mixture had the least value of 237.98kJ/kg within the rig. Inference from result showed that both nanoparticle concentration and refrigerant charge significantly affect the performance of test rig refrigeration effect index. Hence, adequate optimizations of effects are required as earlier stated in the work of Adelekan et al., [21].

Fig 4 illustrates the corresponding coefficient of performance (COP) for the varied charges of pure and nano mineral oil/R600a refrigerant mixtures. It can be observed that COP values varied with nanoparticle concentration and mass charges respectively. Furthermore, the range of COP value were 4.99 for 40g-0.1g/L R600a-TiO_2 nano-lubricant mixture and 2.08 for 80g- pure lubricant. In the work of Poggi et al. [29], either cooling capacity or COP optimization methods can be employed for selection of best operating refrigerant charge within domestic ref

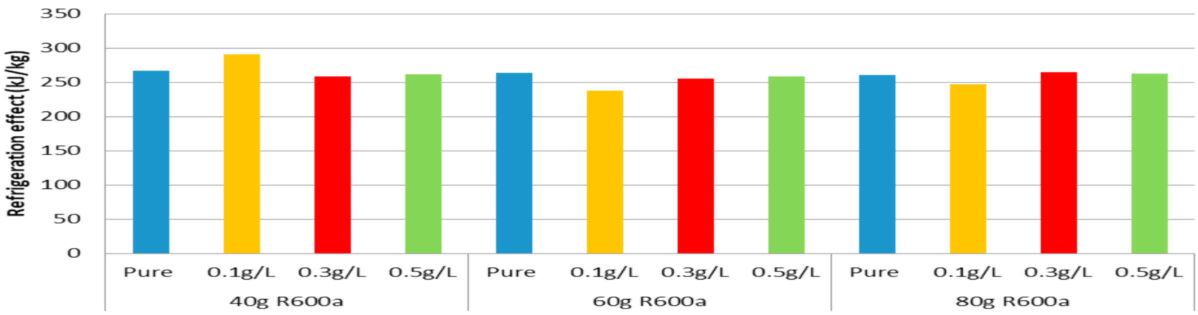

Fig. 3: Refrigeration effect Variation of the Refrigerator system

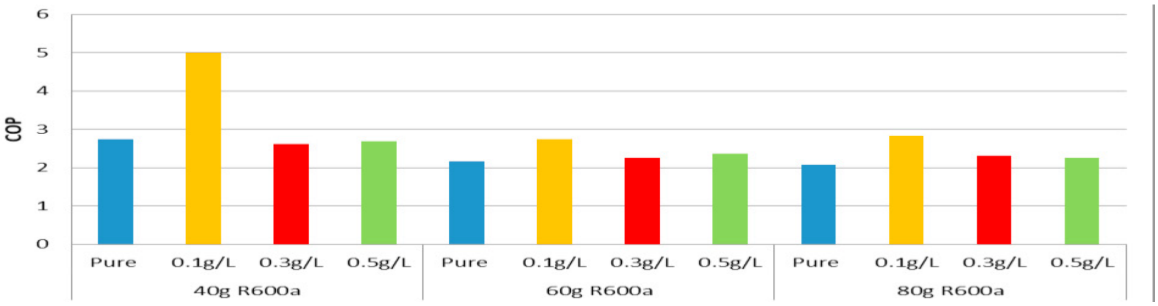

Fig. 4. Coefficient of Performance Variation of the Refrigerator system

4. Conclusion

The following deductions were concluded;

- The utilization of varied mass charges of R600a and concentration of TiO_2 nano-particle in the domestic range refrigerator worked safely.
- The least evaporator air temperature of -15°C was obtained using 60g R600a with either 0.1g/L and 0.3g/L TiO_2 nanolubricant mixture while the highest evaporator air temperature was with 80g R600a using pure mineral oil.
- 80g of R600a using pure R600a refrigerant had the highest specific compressor work input index of 124.92kJ/kg while the lowest having 58.28kJ/kg was found with 40g-0.1g/L R600a-TiO_2 mixture.
- The highest refrigeration effect value was 290.83kJ/kg for 40g-0.1g/L R600a-TiO_2 mixture which was also having the highest COP value of 4.99.

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