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Performance Evaluation of Hydrocarbon based Nano-refrigerants Subjected to Periodic Door Openings

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Abstract-

Domestic refrigerators are required to be energy efficient and environmentally safe. In this work, a slightly modified domestic refrigeration system was infused with various concentrations (0, 0.2, 0.4 and 0.6 g/L) of TiO₂ nanolubricants and R600a refrigerant with a mass charge of 40g. The average energetic characteristics of the test rig at different door openings intervals (0.5, 1, 2, 3 and 5 minutes) were evaluated. The energetic characteristics studied were coefficient of performance (COP), refrigeration capacity, power consumption and cabinet temperature recovery time. The results obtained showed that the use of nanolubricants significantly affect the energetic performance characteristics of the system. Overall, the utilization of 0.6g/L concentration of TiO₂ nanolubricant gave the best performance. The COP of the system improved by 22.39 %, while the power consumption decreased by 23.5 % when compared with pure R600a refrigerant.

Key words: R600a refrigerant, TiO₂ nanoparticle, nanolubricants, coefficient of performance

1. Introduction

The use of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) have caused environmental issues like Ozone depletion, global warming, and have lead to climate change contribution [1-4]. Addressing these concerns have justified increasing applications of natural refrigerants (like water, NH₃, HCs and CO₂) with neutral Ozone depletion reaction and insignificant global warming effect in conventional refrigeration systems [5]. The use of hydrocarbons (such as Propane, Butane, liquefied petroleum gas (LPG) and Isobutane) within refrigeration systems are the most widely adopted recently. Selection of these refrigerants are due to their zero Ozone depletion potential (ODP) and a negligible GWP [6]. However, hydrocarbon refrigerants are flammable. Hydrocarbons based refrigerants were reported in the work of Bolaji and Huan [7] to have been adopted within several experiments, and the use of mass charges not exceeding 200g were considered safe. The reduction in the energy consumption, pull down time and ON time ratio of an R134a refrigeration system retrofitted with R600a refrigerant was reported by Bi et al., [6]. R600a refrigerant was adjudged by Gill et al., [8] to have excellent COP, mass and volumetric refrigerating capacity in comparison with conventional refrigerants like R22 and R134a.



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Apart from retrofitting refrigeration systems with hydrocarbon-based refrigerant to address the above stated facts, intermittent door opening duration of domestic refrigerators increases their heat gains. Such refrigeration systems consumed more energy to attain steady state operations. Spikes in the energy consumptions of refrigerators subjected to intermittent door openings are sparsely addressed within recent literature. It was concluded that an additional 10Wh energy was consumed within a refrigerator subjected periodic door openings. Liu et al., [9] worked on improving the thermal performance of industrial freezers subjected to door openings and power cut using phase change materials. The application of phase change materials was used to address the issue. Similar approach was used to improve the performance of a domestic refrigerator subjected to periodic door openings [10].

Application of nanorefrigerants within refrigeration systems have been found to improve their performance [11]. In addition, refrigerators with nanorefrigerants works normally with improved freezing capacity and power consumption reduction. In a study by Ohunakin et al., [12], the performance of a domestic refrigerator using aluminum oxide dispersed in mineral oil lubricant at different mass charges of LPG was investigated. It was concluded that the pull down time and energy saving characteristics of the system improved [13], while Oró et al., [14], also studied the effect of nanoparticles on the performance of a domestic refrigerator using hydrocarbon based refrigerant. This work investigates the effect of vary concentration of TiO₂ (0.2g/L,0.4g/L,0.6g/L) nanolubricant and door opening time on the energetic properties of a 40g R600a domestic refrigerator subjected to periodic door openings.

2. Methodology

2.1 Experimental rig, Instrumentation and Environment

The experimental rig consists of a domestic size vapour compression refrigerator which was originally charged with HFC (R134a) refrigerant. The refrigerator was slightly modified to use 40g R600a refrigerant and fitted with type K thermocouples, pressure gauges and a wattmeter. The thermocouples were used to take the temperature readings of various sub-components of the system. The pressure gauges were used to take the pressure of the refrigerant and the wattmeter was used to measure the energy consumption. The testing took place in a controlled environment of ambient temperature of about 28 °C (See Table 1 for the technical specifications of the test rig).

Table 1: Specification of the test rig

S/N	Components	Unit
1	Evaporator Range	42 L
2	Working fluid	R600a
3	Compressor Type	R134a
4	Method of defrost	Done by hand
5	Power Rating	95W
6	Frequency Rating	50 Hz
7	Chilling Power	6kg/24hours
8	Condenser class	Air Cooled
9	Number of door present	Single

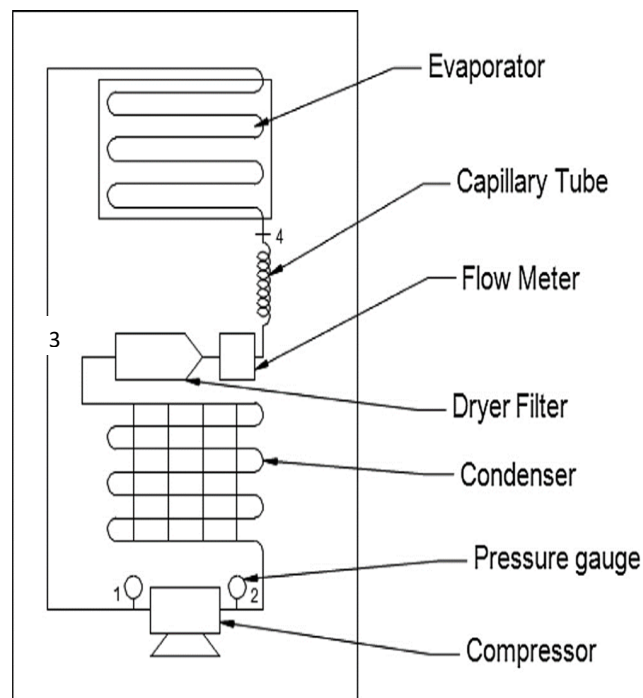


Figure 1: Schematic diagram of the test rig

2.2 Nanolubricant Preparation

Nano lubricants are formed when nano-particles (solids with 1-100nm maximum external size) are added to working fluids. Selected concentrations (0.2g/L, 0.4g/L, 0.6g/l) of the nano-particles were mixed and homogenized with mineral compressor oil lubricant to produce the various nanolubricants before introduction to the compressor. The nano-particle TiO_2 (15-21nm in size) was measured with an electronic scale (OHAUS pioneer TM PA114) and dispersed into a precisely measured amount of mineral oil (using a graduated cylinder). The mixture was then properly homogenized by making use of a Branson Ultrasonicator (Branson M2800H) and inspected for sedimentation.

2.3 Experimental Procedure

The experimental investigation was executed under a constant, no-load without alternating ON/OFF compressor operation until 240mins steady state operation of the system. The system was then subjected to periodic door opening durations (0.5, 1, 2, 3 and 5 minutes). The experimental data including temperatures, pressures and power consumption were separately collected at 5minutes interval till the system returned to steady state operation. In preparation for a new trial the system was thoroughly evacuated using clean compressor mineral oil lubricant and infused with the new concentration. (See Table 2 for the ranges and conditions of the experiment). As shown in Figure 1, the suction and discharge pressure (P_1 , P_2); cabinet, discharge and condensing temperatures (T_{air} , T_2 , T_3) and power consumption (W) were used to obtain required thermodynamic properties including h_1 (saturated vapour enthalpy at T_{air} and P_1 (KJ/kg)) h_2 (superheated vapour enthalpy at T_2 and P_2 (KJ/kg)) and

h_3 (saturated liquid enthalpy at T_3 and P_2 (KJ/kg)). The energetic characteristics investigated using the test rig are as shown in equations 1-3.

Equations

$$Q_{\text{evap}} = \dot{m} (h_1 - h_3) \text{ (kW)} \quad (1)$$

Where \dot{m} =mass flowrate (kg/s),

$$W = \dot{m} (h_2 - h_1) \text{ (kW)} \quad (2)$$

Where, W is the compressor work done per second

$$COP = \frac{Q_{\text{evap}}}{W} \quad (3)$$

Table 2: Ranges and condition of experiment.

S/N	Parameter	Range
1	Type of nano-particle used	TiO ₂
2	Size of nano-particle used	15-21 nm
3	Concentration of nanolubricant (g/L)	0, 0.2, 0.4, 0.6 g/L
4	Type of working fluid	R600a
5	Mass charge of working fluid (g)	40g

3. Results and Discussion

This section presents the results of varying the nanolubricant concentration and door opening time within the experimental test rig.

3.1 Evaporator Air Temperature Variation

Figure 1 shows the variation of evaporator air temperature with nanolubricant concentration. The introduction of nanolubricants into the system resulted in a reduction of the evaporator air temperature for 0.4g/L in comparison to the baseline (R600 with pure compressor mineral oil), however a slight increase in evaporator air temperature was seen with the 0.2g/L and 0.6g/L respectively. Similar reduction in evaporator air temperature was attributed to improvement in boiling heat transfer of the nanolubricant [15].

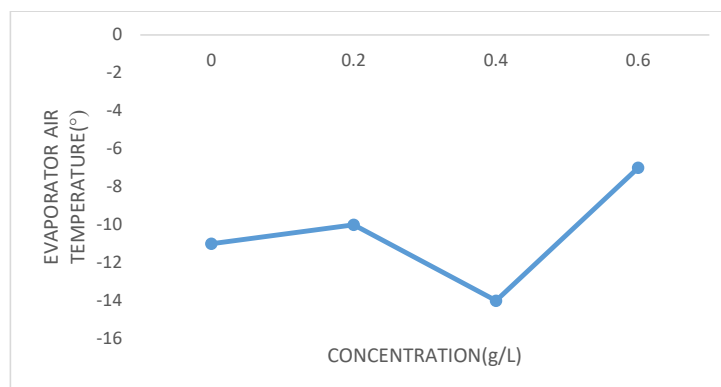


Figure 1: Variation of evaporator air temperature with nanolubricant concentration.

3.2 Cooling Capacity Variation

The instantaneous and mean cooling capacities for all the nanolubricant concentrations and the door opening interval are described in Figure 2. The inclusion of nanolubricant increased the cooling capacity for 0.2g/L and decreased it for both 0.4g/L and 0.6g/L in comparison to the pure refrigerant. The range of mean cooling capacity was estimated to be 139.8W to 168W. It was found that when the 0.4g/L and 0.6g/L concentrations were used, the cooling capacity was reduced by 15.7% and 6.3% respectively when compared with the pure refrigerant. It however increased by 1.24% when the 0.2g/L concentration was used.

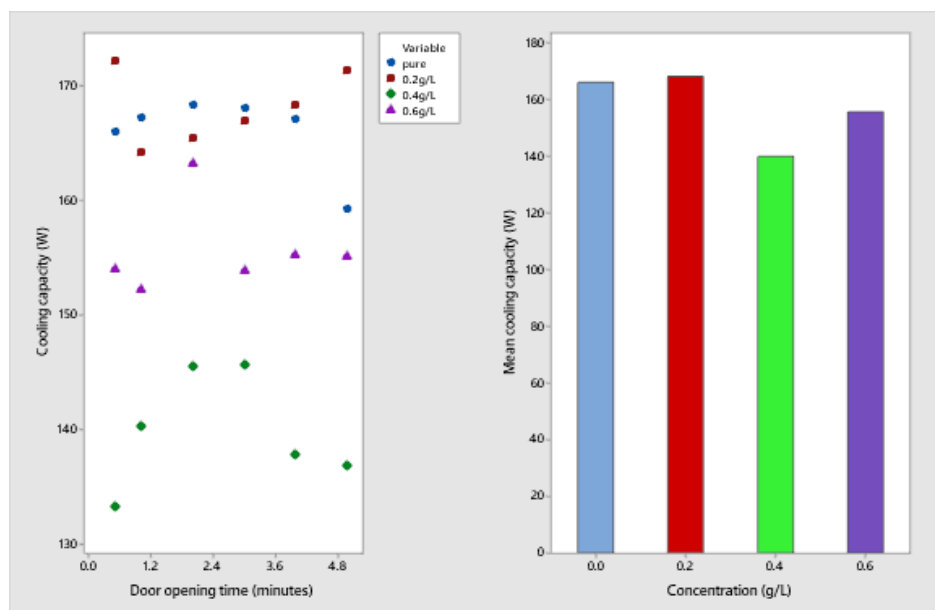


Figure 2: Instantaneous and mean cooling capacity with door opening time and nanolubricant concentration.

3.3 Recovery Time

Figure 3 shows the instantaneous and mean recovery time for all nanolubricant concentrations and door opening intervals. The results show that it took more time to recover when the door of the refrigerator was opened for a longer period of time. This can be attributed to the increased exposure to warm air. There was a recovery time range of 45-65minutes. There was a decrease in recovery time across all nanolubricant concentrations when compared to the pure refrigerant. There was a 30.7%, 16.6% and 19.2% reduction for the 0.2g/L, 0.4g/L and 0.6g/L concentrations respectively.

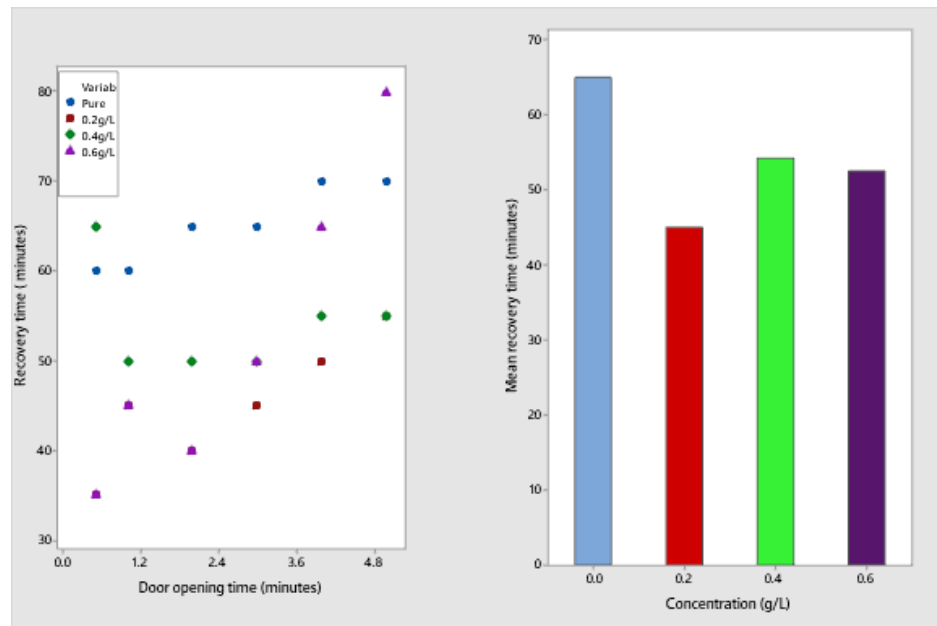


Figure 3: Instantaneous and mean recovery time with door opening time and nanolubricant concentration.

3.4 Power Consumption

The behaviour of power consumption with door opening time and inclusion of nanoparticles is shown in Figure 4. The pure refrigerant gave the highest power consumption of 87.4W. The 0.2 and 0.4g/L concentrations resulted in reduced power consumption. The lowest power consumption of 66.9W was achieved with the 0.6g/L concentration of the nanolubricant. There was a decrease in power consumption across all nanolubricant concentrations in comparison to the pure R600a. There was a 5%, 19.2% and 23.5% reduction in power consumption when the 0.2g/L, 0.4g/L and 0.6g/L concentrations of the nanolubricants were used respectively. This gave similar results to the work done by Subramani and Prakash [16] when TiO_2 – R600a refrigerant was used as a working fluid in a domestic refrigerator.

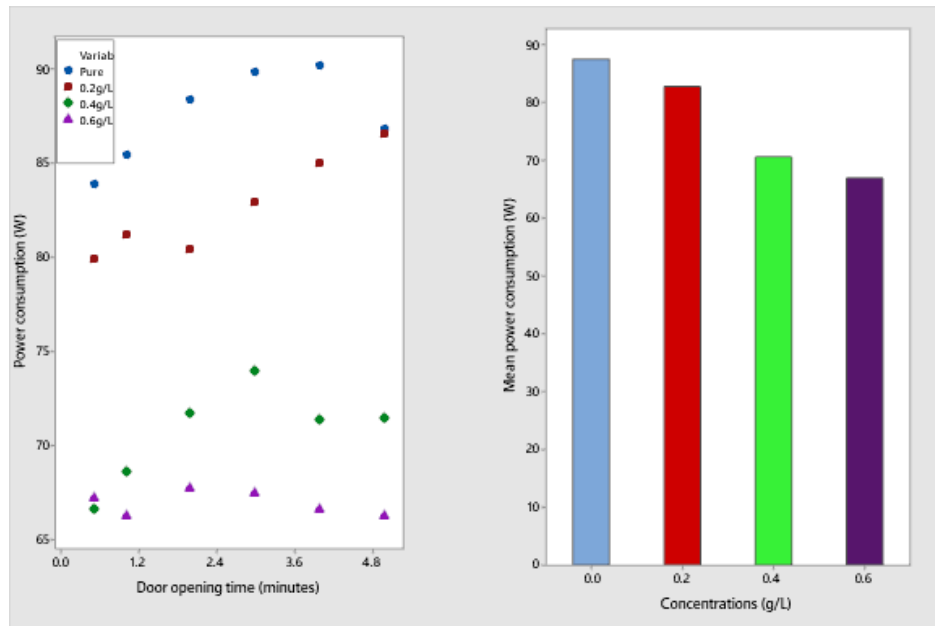


Figure 4: Instantaneous and mean power consumption with door opening time and nanolubricant concentration

3.5 Coefficient of Performance

The instantaneous and mean COP for all the nanolubricant concentration and door opening interval is shown in Figure 5. The pure refrigerant gave the lowest COP of 1.89. All the concentrations of the nanolubricants gave an improvement in COP when compared to the pure refrigerant. The highest COP of 2.31 was achieved using the 0.6g/L of the nanolubricant. The COP increased across all the nanolubricant concentrations in comparison to the pure refrigerant. There was a 7%, 3.8% and 22.4% increase in the COP when the 0.2g/L, 0.4g/L and 0.6g/L concentration of the nanolubricant were used respectively.

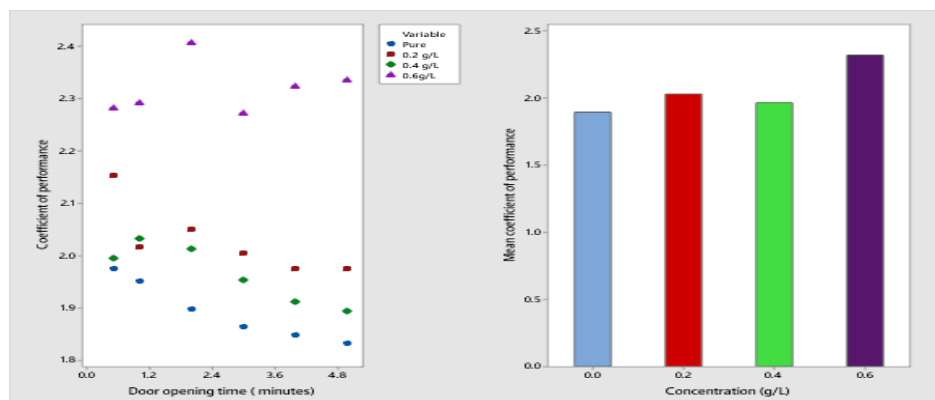


Figure 5: Instantaneous and mean COP with door opening time and nanolubricant concentration.

4. Conclusion

From this study, the following findings were concluded:

- There was an increase in evaporator air temperature when the 0.2g/L and 0.6g/L concentration of the TiO₂ nanolubricant were used compared to the pure refrigerant.
- The lowest recovery time of 45minutes was achieved with the 0.2g/L concentration of the TiO₂ nanolubricant.
- The highest cooling capacity of 168W was achieved with the 0.2g/L concentration of the nanolubricant. The highest COP of 2.31 was achieved with the 0.6g/L concentration of the nanolubricant.
- The lowest power consumption of 66.9W was achieved with the 0.6g/L concentration of the nanolubricant.

5. Recommendation

From the performance analysis carried out, the optimum concentration 0.6g/L of the TiO₂ nanolubricant can be utilized as a long-term replacement for conventional HFC refrigerant R134a. The mass charge of the refrigerant used is also lower than that used with R134a, hence, it would be cheaper to acquire.

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