Exergy analysis of refrigeration system using R600a with TiO_2 Nano lubricant

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Abstract

The irreversibility and second law efficiency of a household refrigerator using TiO_2 Nano lubricant in R600a refrigerant were evaluated using 0.2, 0.4 and 0.6g/L of Nano lubricant in R600a refrigerant. K type thermocouples were connected to the refrigerator components (compressor, condenser, evaporator, and expansion valve) at the inlet and outlet, also two pressure gauges were connected to the compressor to measure the suction and discharge pressure of the system, these values were used to determine the performance of the system using refprop version 9.1. The results showed that The total irreversibility in 0.2 and 0.4g/L TiO2 Nano lubricant with R600a reduces with 1.5 and 3% and the same with 0.6g/L TiO2 Nano lubricant when compared to the based fluid. The efficiency 0.4g/L of Nano lubricant was the highest with 45% higher than pure R600a in the system. Generally, R600a with TiO_2 Nano lubricant performed better than the based fluid in the system.

Keywords: Irreversibility, efficiency, R600a, TiO_2

1.0 Introduction

The cost of energy use for refrigeration in beverages industries and other profit-making sectors such as big and mini supermarkets and domestic users has been quite confronting. The designed parameters of the major components in a vapour compression refrigeration system are also responsible for their energy consumption, exergetic efficiency and exergy destruction (irreversibility) in the system. Exergy of a vapour compression system can be defined as the useful work obtained from the system when it is brought to the standard environmental conditions. Exergy analysis deals more with exergy loss in vapour compression system. Therefore, the application of TiO_2 Nanoparticles as additives in vapour compression system using R600a as working fluid can reduce the exergy loss in the system components. Various researchers have worked on replacement of R600a as a substitute for R134a in refrigeration system [1–8] The solutions provide adjustment of the system components such as capillary tube length and condenser. Some researchers have worked on experimental and theoretical exergy performance analysis of vapour compression refrigeration system. [9–12] Their works looked at the components responsible greatly for exergy loss and provided means of minimizing the exergy loss and improving the exergy efficiency of the refrigeration system.

Recently, the use of Nanoparticles as additives in refrigeration system has been recognized as one of the ways of improving the performance of refrigeration system. Nano lubricant and Nano refrigerant mean the dispersion of Nanoparticles in lubricant oil or refrigerant as the case may be. The heat transfer improvement brought about by Nanoparticles when dispersed in the fluid is responsible for the enhancement witness in the cooling system. Various researches had been carried out by researchers on the application of nanoparticles in a refrigeration system. Ghorbani et al. [13] performed the analysis POE/CuO Nano refrigerant in R600a and compared it to the pure POE oil in R600a in a refrigeration system. Three different various POE/CuO mass percentage samples of R600a with POE/CuO of 0.5, 1 and 1.5% were considered for the experiment and compared with pure R600a with POE oil. The result showed that presence of Nanoparticles in POE lubricant oil gave an increase in condensing heat transfer of 4.1%, 8.11%, and 13.7% respectively compared to the base fluid. Ohunakin et al. [14] carried out a study on the performance of SiO_2, TiO_2, and $Al2O_3$ Nano lubricants in domestic vapour compression refrigerator system using Liquefied Petroleum Gas (LPG). TiO_2, SiO_2 and $Al2O_3$ nanoparticles were dispersed in mineral lubricant oil. The performances such as coefficient of performance (COP), power consumption, discharge and suction viscosity and thermal conductivity at the compressor suction and discharge, the pull-down time of the experiment was also taken into consideration. The result showed that Nano lubricant with LPG had a lower temperature. Furthermore, LPG with SiO_2 and TiO_2 Nano lubricant gave 12% and 13% decrease in power consumption respectively. When compared with the pure LPG refrigerant an enhancement of 2.06% and 2.97% in the COP of SiO_2 and TiO_2 Nanoparticles in LPG respectively were recorded, while a reduction of 2.91% in Al_2O_3 Nanoparticles in LPG was at steady state. In the experiment, SiO_2 and TiO_2 Nano lubricant were more suitable than $Al2O_3$ Nano lubricant for LPG in the system. Kummar et al. [15], [16] investigated vapour compression refrigeration system using Al_2O_3 an additive in R22, R600, R600a and R134a refrigerants in polyol ester lubricant oil (POE oil) in vapour compression system. The result showed an increase in cooling capacity and substantial reduction of 11.5% in the power consumption of the system. Ajayi et al. [17], also investigated the fluid flow of Cu Nanoparticles additive in R600a and R134a refrigerant in an adiabatic capillary tube of a vapour compression refrigeration system. The result showed more isothermal region for Cu/R6000a and Cu/R134a Nano refrigerant when compared to pure R600a and R134a refrigerants. This shows a slow heat transfer that is not fast enough to give rise to the temperature of the linking region when compared to the result of Cu/R134a and Cu/R600a Nano refrigerants. Also, the coefficient of performance of the system increased. In a similar research by Adelekan et al. [8], the author performed an experiment on TiO_2 Nanoparticles of varied mass charges (40, 50, 60 and 70 g) of liquefied petroleum gas with different Nano lubricant concentration of 0.2, 0.4 and 0.6g/L in household refrigerator primarily designed to work with R134a refrigerant. The pull-down, coefficient of performance (COP), cooling capacity, time compressor power input and power consumption were investigated. The results obtained showed almost the evaporator air temperatures with a reduction in power consumption for 40, 50, 60g Nano lubricant concentration while a rise in power consumption was witnessed for a 70g charge of LPG in all Nano-lubricant concentration in the system. Bhattacharyya et al. [18] also conducted a studied on an energy saving of a geothermal Nanotechnology in the vapour compression air-conditioning system. A Nano refrigerant of $Al2O_3$/R134a was used as the working fluid in the system. The result findings obtained showed that a geothermal vapour compression air-conditioning system using $Al2O_3$/R134a Nano refrigerant consumed less energy and had a higher COP compared with conventional air conditioning refrigerant using pure R134a refrigerant. Furthermore, there are no research studies on comparative analysis studies on an irreversibly and second law efficiency on TiO_2 Nano lubricant with R600a in vapour compression system. Therefore, this paper present irreversibility performance of a household refrigerator working R600a with TiO_2 Nano lubricant as a drop-in replacement for R600a in a refrigeration system.

2.0 Experimental method and procedure

The test rig used for this experiment was a household refrigerator initially designed to work with R134a refrigerant. The system was evacuated with the aid of vacuum flusher. The TiO_2 Nanoparticles were measured using a digital scale; the TiO_2 Nanoparticles were dispersed in the mineral oil, and various samples (0.2g/L, 0.4g/L and 0.6g/L TiO_2 Nano concentration) were prepared for a 50g mass charge of R600a refrigerant. The R600a refrigerant was charged into the system with the aid of digital charging system. Each TiO_2 Nano lubricant sample was agitated using an ultrasonic oscillator. The temperatures were taken at inlet and outlet of different components (compressor, evaporator, condenser and capillary tube) of the system with four K-type thermocouples were used to measure the temperature at the inlet and outlet of each component. Also, two pressure gauges were connected to suction and discharge of the compressor to measure the suction and discharge pressure of the compressor. The measurement of the uncertainty of measuring instruments and the experimental test rig and condition are shown in Figure 1 and Table 1-2. The temperature and pressure readings were taken and repeated for five times at intervals of 30 minutes. The uncertainties of the measuring instruments used are shown in Table 1. The outputs of temperature and pressure readings were used to determine the enthalpy and entropy of the refrigerant using the Ref-prop, version 9.0l. These results were used to evaluate the coefficient of performance (COP), Irreversibility and exergy of the system. The performance evaluation for the experimental result was calculated by the following equations 1-8.

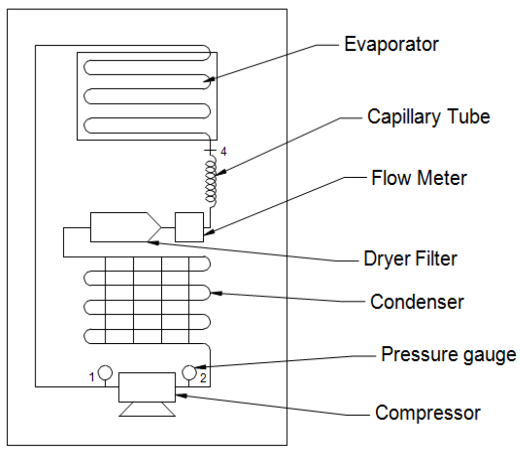

Figure 1 Schematic diagram of experimental setup

Table 1: Characteristics of the measuring instruments

S/N	Measured Data	Manufacturers Specification	Range	Uncertainty
1	Temperature	Digital Thermocouple K	-50°C - 750°C	±3°C
2	Pressure	Digital pressure gauge	5 - 5000 Pa	±1%
3	Power consumption	Digital Watt meter	1-3000W	±1%

Table 2: Range and conditions of the experiment

S/N	Parameters	Range of Experiment
1	Refrigerant mass charge	50g
2	Refrigerant	R600a
3	Compressor lubricant	Pure lubricant, $_{TiO2}$ Nano-lubricants
4	TiO2 Nanoparticles	15nm
5	Nano-lubricant concentration	0.2g/L, 0.4g/L,0.6g/L
6	Test environment temperature	27°C
7	Capillary tube length	1.5m
8	Condenser type	Air cooled
9	Evaporator size	70litres

Exergy is associated with a degree of how a particular system deviates from it given and reference state. Some Exergies are consumed in the actual process of a system. As a result of this, the total Exergy that is obtainable at the system output (Xout) is less than total Exergy at the system inlet (Xin). This amount of Exergy used up in the system is as a result of irreversibility is also called exergy destruction. The summation of irreversibility in each component of the system is called total irreversibly of the system. The following assumptions below were made to evaluate the COP and total irrepressibility of the system.

1. Steady-state operation is assumed in all the system components.
2. Pressure losses along each component are neglected.
3. There is no heat gain and heat loss from or to the system.
4. Potential and Kinetic energy are neglected.
5. There is no pressure drop along the condenser and evaporator of the system.

The exergy efficiency of the cycle is evaluated as follows:

$$I = X_{in} - X_{out} \tag{1}$$

When equation (1) is applied to each component (evaporator, compressor, condenser and expansion valve) of the system

Exergy of the evaporator

Where ṁ is the refrigerant mass flow rate (in, kg/s), h_4 is the specific enthalpy (in kJ/kg) of the refrigerant at the inlet of the evaporator and, h_1 is the specific enthalpy (in kJ/kg) of the refrigerant at the outlet to the evaporator, S_1 is the specific entropy (kJ/kg.K) of the refrigerant at the evaporator outlet, S_4 is the specific entropy (kJ/kg.K) of the refrigerant at the evaporator inlet, Q_e (kW) is heat transfer rate through the boundary at T_{evap}. Thus, Exergy efficiency of the evaporator can be written as Equation (2)

$$I_{evap} = \dot{m}(h_4 - T_O S_4) + Q_{evap}\left(1 - \frac{T_0}{T_r}\right) - \dot{m}(h_1 - T_O S_1) \tag{2}$$

Exergy of the compressor

$$I_{comp} = \dot{m}(h_1 - T_O S_1) + W_{comp} - \dot{m}(h_2 - T_O S_2) \tag{3}$$

Where S_2 is the specific entropy (kJ/kg.K) of the refrigerant at the compressor outlet W_{comp} is compressor power input (kW).

Exergy of the condenser

Exergy at the condenser are calculated from equation (9) and (10)

$$I_{cond} = \dot{m}(h_2 - T_O S_2) - \dot{m}(h_3 - T_O S_3) - Q_{cond}\left(1 - \frac{T_0}{T_{cond}}\right) \tag{4}$$

Where S_3 is the specific entropy (kJ/kg.K) of the refrigerant at the condenser outlet Q_{cond} is heat transfer rate at the condenser (kW).

Exergy of the expensing valve

Note that $h_3 = h_4$, then equation (16) becomes

$$I_{exp} = \dot{m}T_O(S_4 - S_3) \tag{5}$$

Where S_4 is the specific entropy (kJ/kg.K) of the refrigerant at the expansion valve outlet.

Total irrepressibility of the refrigerator

The total exergy of the refrigerator system is the summation of the components.

$$I_{total} = I_{evap} + I_{comp} + I_{cond} + I_{exp} \quad (6)$$

Exergetic efficiency

The second law efficiency of vapour compression system is written as follows:

The total exergy efficiency (n_X) is the ratio of exergy output (X_{out}) to exergy input

$$n_X = \left(\frac{X_{out}}{X_{in}}\right) X \ 100\% \quad (7)$$

$$X_{out} = X_{in} - X_{total} \quad (8)$$

$$n_X = \left(1 + \frac{I_{total}}{W_{comp}}\right) \quad (9)$$

3.0 Result and discussion

The irreversibility and second law efficiency of the system are discussed in in figure 2-7**.** Figure 2 shows a variation of irreversibility in the condenser with varying TiO_2 lubricant Nano concentration. The figure shows that irreversibility in compressor reduces with decrease in evaporator temperature this is because exergy consumed by the compressor is more when evaporator temperature decreases as a result of higher temperature difference. The irreversibility in compressor of pure R600a and R600a with 0.2, 0.4 and 0.6 TiO_2 Nano lubricant concentrations are 0.27, 0.28, 0.31 and 0.29 (kW) respectively. The irreversibility in the 0.2, 0.4 and 0.6g/L with R600a increases with 3.7, 14.8 and 7.4% when compared with pure R600a.

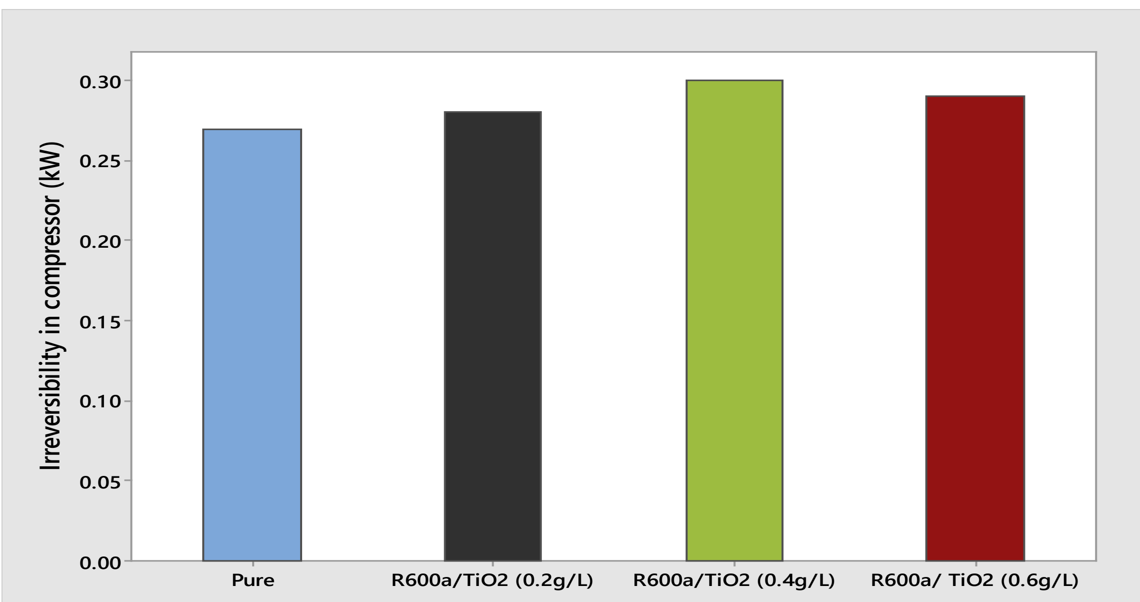

Figure 2 Variation of irreversibility in the compressor with varying TiO_2 lubricant Nano concentration

Figure 3 shows a variation of irreversibility in condenser with varying TiO_2 lubricant Nano concentration. The figure shows that irreversibility in condenser reduces with decrease in evaporator temperature this is because exergy consumed in the condenser is more when evaporator temperature decreases as a result of higher temperature difference. The irreversibility in condenser of pure R600a and R600a with 0.2, 0.4 and 0.6 TiO_2 Nano lubricant concentration are 0.26, 0.25, 0.21 and 0.24 (kW) respectively. The irreversibility in the 0.2, 0.4 and 0.6g/L with R600a increases with 3.9, 19.2 and 7.7.0 % when compared with pure R600a

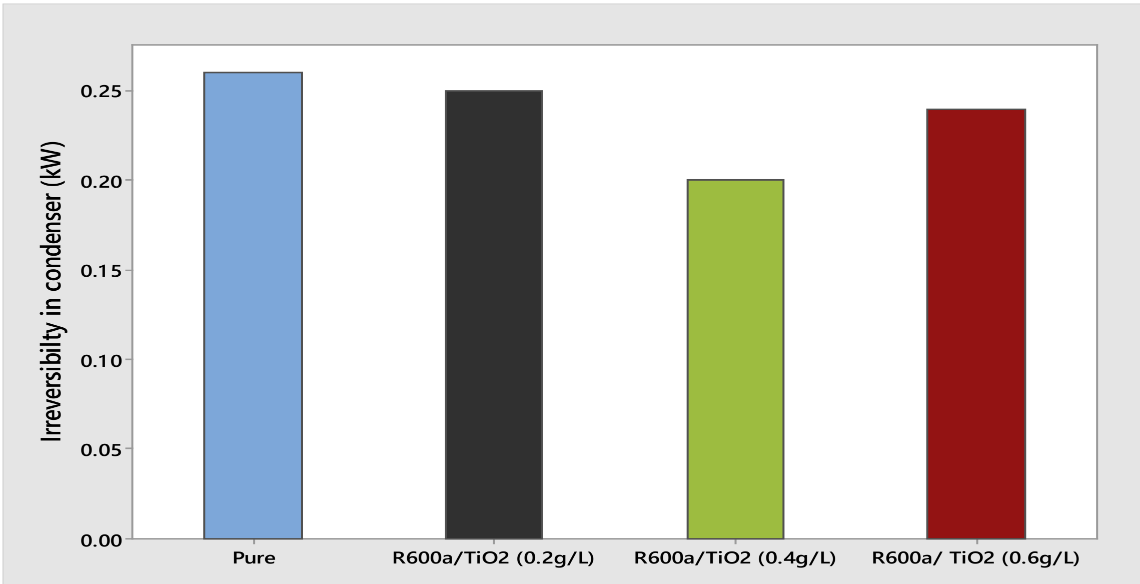

Figure 3 Variation of irreversibility in the condenser with varying TiO_2 lubricant Nano concentration

Figure 4 shows a variation of irreversibility in the evaporator with varying TiO2 lubricant Nano concentration. The figure shows that irreversibility in evaporator reduces with decrease in evaporator temperature this is due to more compressor work input. The irreversibility in evaporator of pure R600a and R600a with 0.2, 0.4 and 0.6 TiO2 Nano lubricant concentrations are 0.055, 0.035, 0.01 and 0.041 (kW) respectively. The irreversibility in the 0.2, 0.4 and 0.6g/L with R600a reduced to 36.3, 81.8. and 25.5% when compared with pure R600a. Figure 4 also shows that overall irreversibility is marginal compared to other components, this implies that transferring heat at a lower temperature is capable of decreasing the irreversibly in the evaporator.

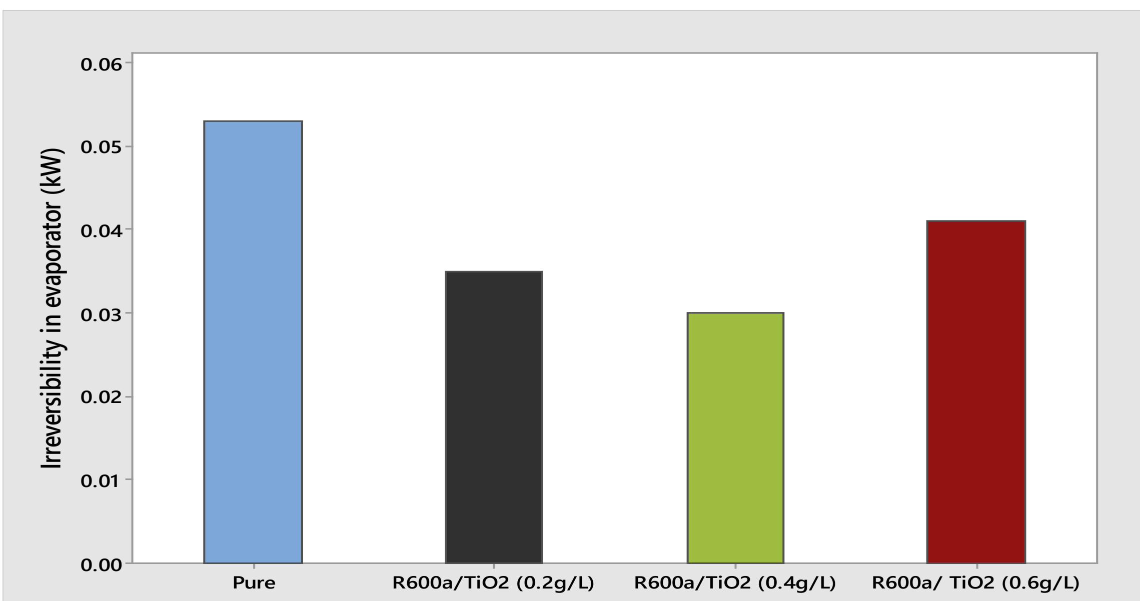

Figure 4 Variation of irreversibility in the evaporator with varying TiO_2 lubricant Nano concentration

Figure 5 shows a variation of irreversibility in the expansion valve with varying TiO_2 lubricant Nano concentration. The figure shows that irreversibility in expansion reduces with increase with the evaporator. This is because the consumption by expansion is more when evaporator temperature reduces. The result outputs showed that irreversibility in expansion valve of pure R600a and R600a with 0.2, 0.4 and 0.6 TiO_2 Nano lubricant concentrations are 0.09, 0.091, 0.1 and 0.095 (kW) respectively. The irreversibility in 0.2, 0.4 and 0.6g/L with R600a increased to 11.1, 8.9 and 5.6% when compared to the based fluid.

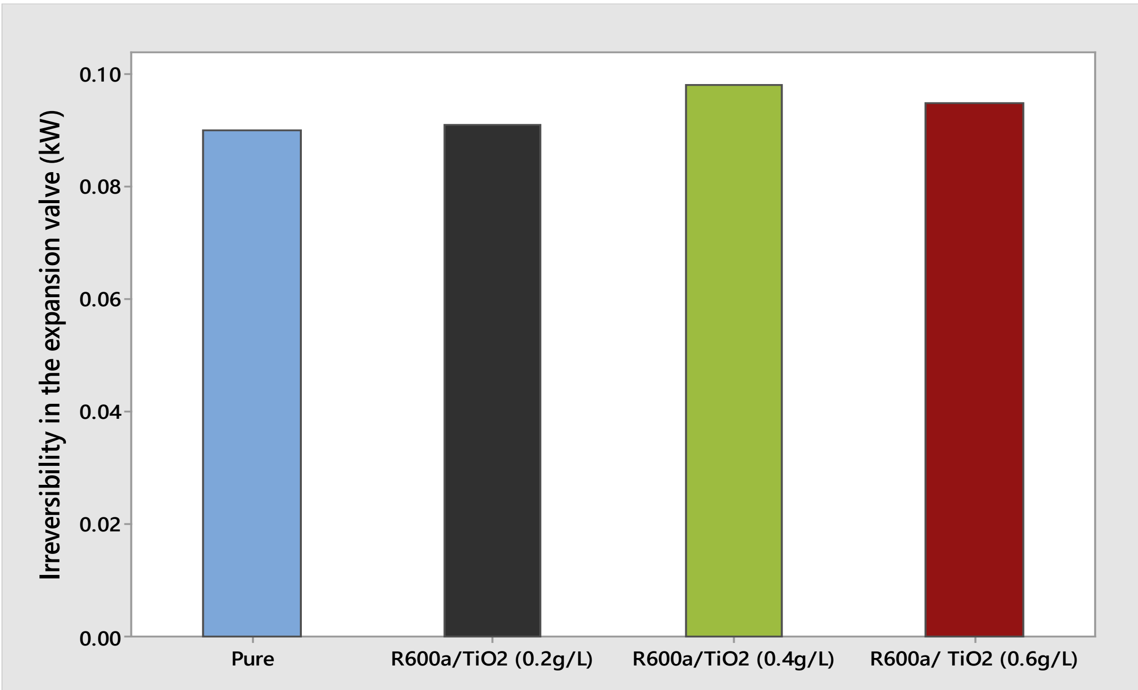

Figure 5 Variation of total irreversibility in the expansion valve with varying TiO_2 lubricant Nano concentration.

Figure 6 shows a variation of total irreversibility in the system with varying TiO2 lubricant Nano concentration. The outputs showed that total irreversibility of pure R600a and R600a with 0.2, 0.4 and 0.6 TiO2 Nano lubricant concentrations are 0.67, 0.66, 0.65 and 0.67 (kW) respectively. The total irreversibility in 0.2 and 0.4g/L TiO2 Nano lubricant with R600a reduces with 1.5 and 3% and the same with 0.6g/L TiO2 Nano lubricant when compared to the based fluid.

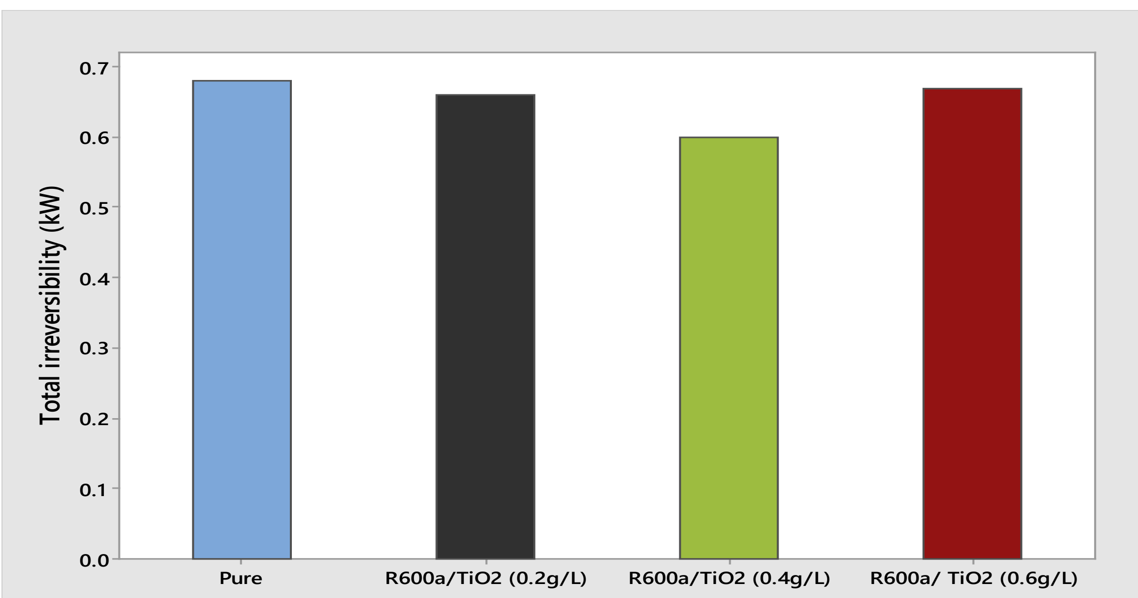

Figure 6 Variation of total irreversibility with varying TiO_2 lubricant Nano concentration

Figure 7 shows a variation of second law efficiency in the system with varying TiO 2 lubricant Nano concentration. The outputs showed that second law efficiency of pure R600a and R600a with 0.2, 0.4 and 0.6 TiO2 Nano lubricant concentration is 37, 40, 45 and 41% respectively. The second law efficiency of 0.2, 0.4 and 0.6g/L with R600a increase with 8.1, 21.6 and 10.8% when compared to the based fluid

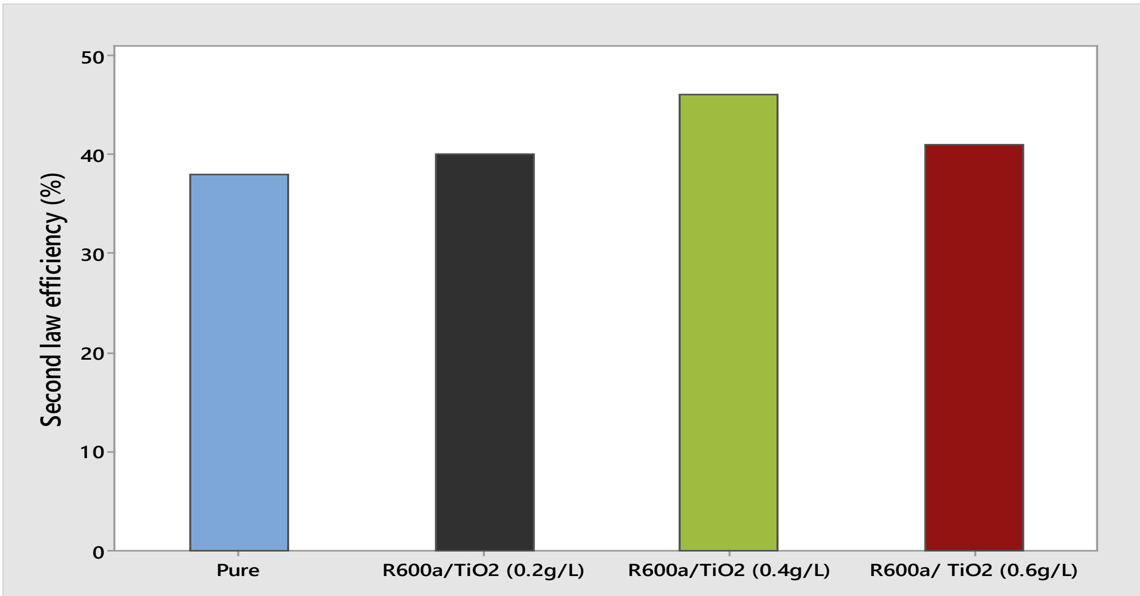

Figure 7 Variation of second law efficiency with varying TiO_2 lubricant Nano concentration

4.0 Conclusion

The second law efficiency was obtained using TiO2 lubricant Nano concentration in R600a. The result obtained showed that second law efficiency of R600a with 0.2, 0.4 and 0.6 TiO2 Nano lubricant concentrations are higher in efficiency than the based fluid. The overall irreversibility of TiO2 lubricant Nano concentration in R600a in the system is lower than pure R600a refrigerant with 04g/L TiO2 Nano lubricant offering the lower overall irreversibility. The highest irreversibility was recorded with the compressor among the four components of the system. Generally, TiO2 Nano lubricant concentrations performed better in R600a than the based fluid.

Nomenclature

COP	Coefficient of performance
h	Specific enthalpy, kJ/kg
$\dot{m}$	Mass flow rate of refrigerant, kg/s
$Qevap$	Refrigerating capacity,W
Q_{Cond}	Heat rejection by the condenser, W

R	Refrigerant
s	Specific entropy of refrigerant, kJ/kg.K
T	Temperature, K
Wcomp	Compressor work input, W
X	Exergy, W

Greek Symbols

I	Irreversibility
n_x	Exergetic efficiency (%)

Subscripts

comp	Compressor
cond	Condenser
evap	Evaporator
exp	Expansion device or capillary tube
i	Particular component in a refrigeration system
in	Inlet or input
o	Environmental state
out	output
r	Refrigerant

total	Total
1	Outlet of evaporator
2	Outlet of compressor
3	Outlet of condenser
4	Inlet of evaporator

Biographies

Taiwo O Babarinde is a PhD student at Mechanical Engineering Department, University of Johannesburg, South Africa. His area of research is alternative clean energy in refrigeration, air-conditioning and heat pump systems and also improvement of efficiency of clean energy system using Nanoparticles. He had co-supervised various undergraduate students research project in the area of alternative clean refrigerant in refrigeration and heat pump systems. Currently, he is working on experimental and numerical analysis of nano eco-friendly refrigerants in vapour compression system.

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References

[1] M. M. Joybari, M. S. Hatamipour, A. Rahimi, and F. G. Modarres, "Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator system," *Int. J. Refrig.*, vol. 36, no. 4, pp. 1233–1242, 2013.
[2] S. J. Sekhar and D. M. Lal, "HFC134a/HC600a/HC290 mixture a retrofit for CFC12 systems," *Int. J. Refrig.*, vol. 28, no. 5, pp. 735–743, 2005.
[3] T. O. Babarinde, O. S. Ohunakin, D. S. Adelekan, S. A. Aasa, and S. O. Oyedepo, "Experimental study of LPG and R134a refrigerants in vapor compression refrigeration," *Int. J. Energy a Clean Environ.*, vol. 16, no. 1–4, 2015.
[4] B. O. Bolaji, "Experimental study of R152a and R32 to replace R134a in a domestic refrigerator," *Energy*, vol. 35, no. 9, pp. 3793–3798, 2010.
[5] J. Gill and J. Singh, "Energy analysis of vapor compression refrigeration system using mixture of R134a and LPG as refrigerant Analyse énergétique d ' un système frigorifique à compression de vapeur utilisant un mélange de R134a et de GPL comme frigorigène," *Int. J. Refrig.*, vol. 84, pp. 287–299, 2017.
[6] M. Rasti, S. Aghamiri, and M. S. Hatamipour, "Energy efficiency enhancement of a domestic refrigerator using R436A and R600a as alternative refrigerants to R134a," *Int. J. Therm. Sci.*, vol. 74, pp. 86–94, 2013.
[7] S. O. Oyedepo, R. O. Fagbenle, T. Babarinde, and A. Tunde, "Effect of Capillary Tube Length and Refrigerant Charge on the Performance of Domestic Refrigerator with R12 and R600a," *Int. J. Adv. Thermofluid Res.*, vol. 2, no. 1, pp. 2–14, 2016.
[8] D. S. Adelekan *et al.*, "Experimental performance of LPG refrigerant charges with varied concentration of TiO_2 nano-lubricants in a domestic refrigerator," *Case Stud. Therm. Eng.*, vol. 9, 2017.
[9] M. El-Morsi, "Energy and exergy analysis of LPG (liquefied petroleum gas) as a drop in replacement for R134a in domestic refrigerators," *Energy*, vol. 86, pp. 344–353, 2015.
[10] P. S. Raveendran and S. J. Sekhar, "Experimental studies on domestic refrigeration system with brazed plate heat exchanger as condenser," *J. Mech. Sci. Technol.*, vol. 30, no. 6, pp. 2865–2871, 2016.
[11] T. O. Babarinde, S. A. Akinlabi, D. M. Madyira, O. S. Ohunakin, D. S. Adelekan, and S. O. Oyedepo,

"Comparative analysis of the exergetic performance of a household refrigerator using R134a and R600a," *Int. J. Energy a Clean Environ.*, vol. 19, no. 1–2, pp. 37–48, 2018.

[12] J. Gill, J. Singh, O. S. Ohunakin, and D. S. Adelekan, "Artificial neural network approach for irreversibility performance analysis of domestic refrigerator by utilizing LPG with TiO2 –lubricant as replacement of R134a," *Int. J. Refrig.*, 2018.

[13] B. Ghorbani, M. A. Akhavan-behabadi, S. Ebrahimi, and K. Vijayaraghavan, "Experimental investigation of condensation heat transfer of R600a / POE / CuO nano-refrigerant in fl attened tubes," *Int. Commun. Heat Mass Transf.*, vol. 88, no. October, pp. 236–244, 2017.

[14] O. S. Ohunakin, D. S. Adelekan, T. O. Babarinde, R. O. Leramo, F. I. Abam, and C. D. Diarra, "Experimental investigation of TiO_2, SiO_2 and $Al2O_3$ lubricants for a domestic refrigerator system using LPG as working fluid," *Appl. Therm. Eng.*, vol. 127, 2017.

[15] R. Kumar and J. Singh, "Effect of ZnO nanoparticles in R290 / R600a (50 / 50) based vapour compression refrigeration system added via lubricant oil on compressor suction and discharge characteristics," *Heat Mass Transf.*, vol. 53, no. 5, pp. 1579–1587, 2017.

[16] D. Sendil Kumar and R. Elansezhian, "ZnO nanorefrigerant in R152a refrigeration system for energy conservation and green environment," *Front. Mech. Eng.*, vol. 9, no. 1, pp. 75–80, 2014.

[17] O. O. Ajayi, P. O. Babalola, O. Kilanko, D. O. Oyegbile, and D. Lawson-jack, "A comparative experimental study on performance of domestic refrigerator using r600a and lpg with varying refrigerant cha ... authors," p. 1615.

[18] A. Bhattad, J. Sarkar, and P. Ghosh, "Exergetic analysis of plate evaporator using hybrid nanofluids as secondary refrigerant for low-temperature applications," *Int. J. Exergy*, vol. 24, no. 1, pp. 1–20, 2017.