

Energy and exergy analysis of vapour compression refrigeration system using selected eco-friendly hydrocarbon refrigerants enhanced with tio₂-nanoparticle

Luke O. Ajuka ^{1*}, Moradeyo K. Odunfa ¹, Olayinka S. Ohunakin ², Miracle O. Oyewola ¹

¹ Mechanical Engineering Department, University of Ibadan, Ibadan, Oyo State, Nigeria

² Mechanical Engineering Department, Covenant University, Canaanland, Ota, Ogun State, Nigeria

*Corresponding author E-mail: ajukamario@gmail.com

Abstract

The experimental study investigated the energy and exergy performance of a domestic refrigerator using eco-friendly hydrocarbon refrigerants R600a and LPG (R290/R600a: 50%/50%) at 0, 0.05, 0.15 and 0.3wt % concentrations of 15nm particle size of TiO₂ nano-lubricant, and R134a. The effects of evaporator temperature on power consumption, coefficients of performance, exergetic efficiency and efficiency defects in the compressor, condenser, capillary tube and evaporator of the system were examined. The results showed that LPG + TiO₂ (0.15wt %) and R600a + TiO₂ (0.15wt %) had the best of performances with an average of 27.6% and 14.3% higher coefficient of Performance, 34.6% and 35.15% lower power consumption, 13.8% and 17.53% higher exergetic efficiency, a total exergetic defect of 45.8% and 64.7% lower compared to R134a. The exergetic defects in the evaporator, compressor, condenser, and capillary tube were 38.27% and 35.5%, 49.19% and 55.56%, 29.7% and 33.7%, 39.1% and 73.8% lower in the system when compared to R134a respectively. Generally, the refrigerants with nano-lubricant mixture gave better results with an appreciable reduction in the exergy defect in the compressor than the pure refrigerants, and LPG + TiO₂ (0.15wt %) gave the best result in the refrigeration system based on energy and exergy analysis.

Keywords: Eco-friendly refrigerants; Exergetic efficiency; Power Consumption; TiO₂-nanolubricant; Total exergetic defect.

1. Introduction

Energy conserved is energy profited with regards to many efforts in ensuring cooling, food product preservation, and comfort in many refrigeration applications. The dawn of industrial revolution which witnessed the conversion of heat into mechanical power used energy from burning fossil fuels, e.g. oil, coal and gas, which lead to global warming. The ever increasing utilization of new technological products from industrial revolution has led to more energy consumptions, thereby necessitating continual research for ways to provide more energy or manage available energy. Environmental impact and energy policies are as important in the production, transformation and use of energy [1]. Hence, for a safer environment and performance improvement of vapor compression systems, the indirect contribution of refrigerants to greenhouse gases emitted to the atmosphere, and inefficient energy usage remains a global concern.

[2] noted that the use of ozone depleting refrigerants such as CFCs and partially halogenated HCFCs, which became available in 1931 were due to the cost, coefficient of performance (COP), flexible applications, good thermodynamic and heat transfer properties, low maintenance and operation cost, though are not environment-friendly. However, with regards to the chemical content of CFCs and HCFCs in relation to environmental decline issues, bans to have been placed on ozone-depleting substances by the Montreal protocol. Other regulations such as the Kyoto protocol casts concern on the global warming environmental issue of HFCs as a substitute refrigerant because of their high global warming poten-

tial values. Today policies for sustainable development of refrigerants with ozone friendly potentials are being encouraged. These have led to the replacement of conventional refrigerants with environment-friendly refrigerants such as LPG, R600a, etc. The risk concern for flammability of hydrocarbon is contained as long as the volume of refrigerant charged to the system does not exceed 150g, system can be placed in any location [3].

In the near past also, the introduction of additives as a means of enhancing the base fluid properties and energy efficiency of a refrigerating system is becoming invaluable. Nanofluids have been noted as very useful alternative to conventional working fluids in refrigeration systems. Nanoparticles are used in refrigeration systems because of their notable improvement on the thermophysical, and heat transfer capabilities of working fluid in refrigeration and air-conditioning systems in relation to an enhanced efficiency and reliability.[4] reported that nanofluids had been shown to possess the following characteristics: High specific surface area and so more heat transfer surfaces between particles and fluids, high dispersion stability with predominant Brownian motion of particles, reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification, reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization, adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications.

A mickle of heat is released during the thermodynamic process of vapour compression refrigeration systems to its environment. At a finite temperature difference, this heat transferal between the system and the surrounding environment takes place, which is a ma-

major source of irreversibility in the cycle causing system performance to degrade. Hence, to assess the losses in the cycle, a comprehensive process investigation of energy and exergy balance on individual thermodynamic processes that make up the cycle must be employed.

Energy analysis based on first law is still the most commonly used method in the analysis of thermal systems and is the key to optimization as it is the basis to develop the exergy balance. However, the shortcoming of energy analysis is the inadequacy in the process and components' quality description. It does not give information on how, where, and the amount of performance degraded. [5] Noted that one major weakness in the building of energy analysis is the lack of using the second-law analysis. Exergy analysis is a thermodynamic practice based on the second law of thermodynamics, which provides a qualitative description for comparing processes and systems. An exergy analysis is usually aimed to examine the maximum performance of the system and to note the sites of exergy destruction [6] for potential improvements. There have been several studies on the exergy analysis of refrigeration systems ([7], [8], [9], and [10]). The principles and methodologies of exergy analysis are well established ([11], [12]).

[13] Reported in his study on energetic and exergetic performance of a vapour compression refrigeration system using pure hydrocarbon refrigerant (R290a, R600a, and commercial LPG). In the theoretical analysis, MATLAB and REFPROP, software was used to the coefficient of performance and exergetic efficiency. He noted that R600a had the highest COP and exergetic efficiency while LPG has the lowest when compared to R134a. The COP of R134a was higher than that of LPG by 10%. The numerical investigation by [14] showed that the addition of Al₂O₃ nanoparticles to R600a/mineral oil refrigerant in the domestic refrigerator resulted in improvements in the thermo physical properties and heat transfer characteristics of the refrigerant, hence led to an improvement in the performance of the refrigeration system. The studies showed that the refrigeration system with Al₂O₃ nano-refrigerant works without any challenge. It was reported that the freezing capacity was higher, and the reduction in power consumption was 11.5 % when POE oil is replaced by a mixture of mineral oil and Aluminum oxide nanoparticles. [15] reported from their review study of exergy analysis of vapor compression refrigeration systems that the effect of refrigerant on some exergy parameters such as evaporating temperature, condensing temperature, sub-cooling and compressor pressure. They also reported that the mixture of hydrocarbons and R134a gives a good performance and that exergy loss occurs much more in the compressor between the components within the vapor compression system. They also concluded that Nanofluid and nanolubricant causes an indirect reduction in the exergy losses in the compressor. The report by [16] in their experimental study on a domestic refrigerator using mineral oil with TiO₂ nanoparticle mixtures as lubricant and R134a as refrigerant reported that there was a 26.1% reduction in energy consumption. They also investigated the performance of a domestic refrigerator using 0.1 g/L and 0.5 g/L concentrations of TiO₂ nanoparticle with R600a as refrigerant. They reported 9.6% reduction in energy consumption with 0.5 g/L concentration of TiO₂-R600a nano-refrigerant. [17] reported that (LPG) of 60% propane, and 40% commercial butane was tested as a drop-in substitute for R134a in a single evaporator domestic refrigerator with a total volume of 10 ft³. Different capillary tube lengths of 4 to 6.0 at different charges were tested for pull-down time, volumetric cooling capacity, pressure ratio, power consumption etc. When the capillary tube lengths of 5metre and 4metre using LPG of 60g and R134a of 100 g respectively were compared, they concluded that the COP of R134a was lower than LPG by about 7.6%, and the pull-down time, pressure ratio and power consumption of LPG refrigerator were lower than those of R134a refrigerator by about 7.6%, 5.5% and 4.3%, respectively.

The studies reviewed above focused mainly on the exergy analysis of pure refrigerants and R600a with TiO₂ nanoparticle without establishing the optimal nano-lubricant concentration by volume that gives average minimal exergetic defects within the system.

Also, not too much research has been conducted on experimental evaluations with nanoparticles on LPG and other hydrocarbon mixtures with regards to exergy analysis. Therefore, this study was conducted to experimentally examine the energy and exergy performance of selected refrigerants (R134a, LPG and R600a) using TiO₂ nanoparticle in a domestic refrigerator.

2. Experimental method

The domestic refrigerator used for this study has a compartment volume of 72-liter capacity, power rating of 50HZ-110W. Four thermocouples (type-k) and two pressure gauges were set in different positions on the refrigeration system to measure temperatures of the inlet and outlet of the refrigerator components. The energy consumption of the refrigeration system was measured with a digital wattmeter. LPG (50% R290 and 50% R600a), R600a and R134a at different TiO₂-lubricant concentrations were charged using a digital weighing balance (CAMRY ACS-30-ZC41) with a measuring range of 5 to 30000g. A service port was installed in the inlet of the expansion device and compressor for charging and recovering of the refrigerant. Evacuation of refrigerant was done using a vacuum pump.

2.1. Preparation of nanoparticles / compressor oil mixture (Nano-lubricant)

The required mass of titanium nanoparticle (TiO₂) of particle size 15nm was weighed by a digital electronic balance (OHAUS Pioneer TM PA114) with measurement range of 0.0001 to 110g and a maximum error of 0.1 mg. The TiO₂ nanoparticles were added into the weighed lubricating oil to form a TiO₂ nanoparticles/oil suspension. The nanoparticles/oil suspension mixture was then vibrated and thoroughly homogenized with an ultrasonic oscillator (Branson M2800H) for three hours, until the mixture was evenly dispersed in the mixture. Table 1 below shows the characteristics of the nanoparticle used. Stability test was carried out by leaving the mixture for 24hrs to observe if there will be sedimentation. The duration of the experiment for each sample of nanoparticle/oil mixture with TiO₂ nanoparticle was less than 4hrs, which is much shorter than 24hrs for which the mixtures were observed for possible sedimentation. In the absence of sedimentation, it is safe to conclude that the nanoparticle/oil mixture with TiO₂ nanoparticles will maintain good uniformity and stability in the experiment.

Table 1: Characteristics of the Titanium (TiO₂) Nanoparticles.

Properties of TiO ₂ Nanoparticles (Anatase Nanopowder)		
Property	Unit	Value
Molecular Weight	g/mol	79.87
Average Particle Diameter	nm	15
Density	g/cm ³	0.26
Specific Surface Area	m ² /g	240
Metal basis		99.7%



Fig. 1: Experimental Set-Up: Refrigeration System.

2.2. Experimental procedures

The experimental system was first charged with 60g of pure R-134a. The temperatures at the evaporator (T_i), compressor outlet

(T₂), condenser outlet (T₃), and pressures at the suction and discharge of the compressor P_s and P_d were recorded. Power consumed was recorded for analysis. The procedure was repeated for 40g charge for pure LPG (50%:50%) and pure R-600a (Isobutane) refrigerant. Again, same procedure was repeated for 40g charge of LPG and R600a with titanium oxide (TiO₂) nano-lubricant concentrations of 0.05wt%, 0.15wt%, and 0.3wt%.

The tests were carried out in the refrigeration and air-conditioning laboratory in a tropical region (Nigeria) with an ambient air temperature range of 30 ± 2°C and relative humidity of 51%. The thermodynamic properties of the refrigerants were obtained using the [18].

2.3. Mathematical formulation for exergetic analysis of the vapour compression refrigeration system

Accurate analysis of the system was obtained by evaluating the individual components in the system. The compressor, condenser, expansion device and evaporator are the components where mass, energy and exergy balances were employed to determine the heat input, the rate of exergy destruction, and energy and exergy efficiencies.

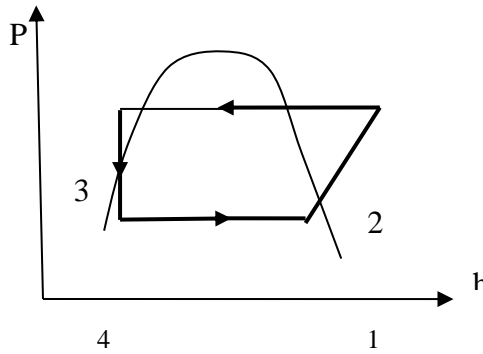


Fig. 2: Vapour Compression Refrigeration System on P-H Diagram.

2.3.1. Nano-lubricant concentration

Volume fraction of nanoparticle in the nanoparticle-oil suspension (ψ_n):

$$\psi_n = \omega_n \rho_0 / [\omega_n \rho_0 + (1 - \omega_n) \rho_n] \quad (1)$$

Mass fraction of Nanoparticle concentration in the nanoparticles/oil suspension (ω_n):

$$\omega_n = m_n / (m_n + m_o) \quad (2)$$

Where m_n, m_o, ρ_0 and ρ_n are the mass of nanoparticles, mass of lubricating oil, density of lubricating oil, and nanoparticle respectively.

A general mass, energy and exergy balances can be expressed as [19]:

$$\Sigma E_{in} = \Sigma E_{out} \quad (3)$$

$$\Sigma \dot{E}_{x,in} - \Sigma \dot{E}_{x,out} = \Sigma \dot{E}_{x,dest} \quad (4)$$

Exergy of refrigerant at any state can be measured using the reference point as follows:

$$X_{ref} = (h - h_0) - T_0(s - s_0) \quad (5)$$

2.3.2. Exergy within the evaporator

Exergies at the evaporator inlet ($X_{d, \text{evapo}, in}$) and outlet ($X_{d, \text{evapo}, out}$) are calculated using Eqs. (6) and (7).

$$X_{d, \text{evapo}, in} = \dot{m}_r (h_4 - T_0 s_4) + Q_{\text{evapo}} (1 - \frac{T_0}{T_r}) \quad (6)$$

$$X_{d, \text{evapo}, out} = \dot{m}_r (h_1 - h_4) \quad (7)$$

$$X_{d, \text{evapo}} = X_{d, \text{evapo}, in} - X_{d, \text{evapo}, out} \quad (8)$$

Substitution of Eqs. (1) and (2) into Eqn. (3) gives

$$X_{d, \text{evapo}} = \dot{m}_r [(h_4 - h_1) - T_0 (s_4 - s_1)] + Q_{\text{ev}} (1 - \frac{T_0}{T_r}) \quad (9)$$

2.3.3 Exergy within the compressor

Exergies at the compressor inlet ($X_{d, \text{comp}, in}$) and outlet ($X_{d, \text{comp}, out}$) are calculated using Eqs. (10) and (11).

$$X_{d, \text{comp}, in} = \dot{m}_r (h_1 - T_0 s_1) + W_{el} \quad (10)$$

$$X_{d, \text{comp}, out} = \dot{m}_r (h_2 - T_0 s_2) \quad (11)$$

$$X_{d, \text{comp}} = X_{d, \text{comp}, in} - X_{d, \text{comp}, out}$$

Therefore,

$$X_{d, \text{comp}} = \dot{m}_r [(h_1 - h_2) - T_0 (s_1 - s_2)] + W_{el} \quad (12)$$

2.3.4. Exergy within the condenser

Exergies at the condenser inlet ($X_{d, \text{condo}, in}$) and outlet ($X_{d, \text{condo}, out}$) are calculated using Eqs. (13) and (14).

$$X_{d, \text{condo}, in} = \dot{m}_r (h_2 - T_0 s_2) - Q_{\text{condo}} (1 - \frac{T_0}{T_r}) \quad (13)$$

$$X_{d, \text{condo}, out} = \dot{m}_r (h_3 - T_0 s_3) \quad (14)$$

$$\text{Hence, } X_{d, \text{condo}} = \dot{m}_r [(h_1 - h_2) - T_0 (s_1 - s_2)] - Q_{\text{condo}} (1 - \frac{T_0}{T_r}) \quad (15)$$

2.3.5. Exergy within the expansion device (capillary tube)

Exergic deficiencies at the capillary tube inlet ($X_{d, \text{expo}, in}$) and outlet ($X_{d, \text{expo}, out}$) are calculated using Eqs. (16) and (17).

$$X_{d, \text{expo}, in} = \dot{m}_r (h_3 - T_0 s_3) \quad (16)$$

$$X_{d, \text{expo}, out} = \dot{m}_r (h_4 - T_0 s_4) \quad (17)$$

Wherefore,

$$X_{d, \text{expo}} = X_{d, \text{expo}, in} - X_{d, \text{expo}, out} = X_{d, \text{expo}} = \dot{m}_r T_0 (s_4 - s_3) \quad (18)$$

Wherefore, the enthalpy across the capillary tube remains constant ($h_3 = h_4$), since expansion process is an isenthalpic process, therefore:

2.3.6. Total exergy destruction

The total exergy used in the system ($X_{d, \text{tot}}$) is the total sum of exergy used in each component of the system. Therefore,

$$X_{d, \text{tot}} = X_{d, \text{evapo}} + X_{d, \text{comp}} + X_{d, \text{condo}} + X_{d, \text{expo}} \quad (19)$$

2.3.7. Exergetic efficiency in the system

The overall system exergetic efficiency (η_{ex}) is the ratio of the exergy output (X_{out}) to exergy input (X_{in})

$$\eta_{\text{ex}} = \frac{X_{\text{out}}}{X_{\text{in}}} * 100\% \quad (20)$$

Exergy output (X_{out}) is the difference between exergy input (X_{in}) and the total exergy destroyed in the system (Let $X_{d, \text{tot}} = X_{d, i}$),

$$\text{Wherefore, } X_{\text{out}} = X_{\text{in}} - X_{d, i}, \text{ and } X_{\text{in}} = W_{el} \quad (21)$$

The only source of exergy input to the system is through the electrical power supplied to the compressor (W_{el}), that is, $X_{\text{in}} = W_{el}$ and Eq. (20) can be expressed as:

$$\eta_{ex} = \frac{W_{et} - X_{d,i}}{W_{et}} * 100\% \tag{22}$$

$$\eta_{ex} = 1 - \left(\frac{X_{d,i}}{W_{et}} \right) * 100\% \tag{23}$$

3. Results and discussions

Experimental results were obtained for COP, Energy consumption, Exergy Efficiencies, Exergy defects as shown and analyzed below: Table 2 and 3 shows some results obtained for LPG (Pure), R600a (Pure) and when they were both mixed with different concentrations of TiO₂ nano-lubricant respectively, while the other remaining figures below discusses the optimal charge concentra-

tion result from LPG and R600a mixed with 0.15wt % nano-lubricant and the result as compared with R134a.

In the table 2 and 3 above, pure LPG and R600a had the lowest COP, exergy efficiencies, but highest power consumption and total exergetic defect, while LPG and R600a with 0.15wt % by nano-lubricant concentration had the highest COP, exergy efficiencies, but lowest power consumption and total exergetic defect in the system. These results shows that both LPG and R600a with 0.15wt % by nano-lubricant concentration were the optimal concentrations in their category and so were further in comparison to R134a.

Table 2: Parametric Experimental Result Obtained for LPG with and Without Nanofluids

Tevapo		-3	0	3	6	9	12	15	18
OP	LPG (Pure)	1.7679	1.9571	2.1481	2.3547	2.5748	2.8602	3.1655	3.4880
	LPG (40g) + TiO ₂ (0.05wt %)	1.8549	2.0352	2.2284	2.4562	2.6463	2.9338	3.2288	3.5998
	LPG (40g) + TiO ₂ (0.15wt %)	2.1098	2.1623	2.3434	2.5645	2.7854	3.1081	3.4054	3.7576
	LPG (40g) + TiO ₂ (0.3wt %)	1.9481	2.1039	2.2430	2.4818	2.6736	2.9730	3.3270	3.7179
Nx	LPG (Pure)	0.3988	0.3987	0.3875	0.3450	0.2947	0.2505	0.2105	0.1809
	LPG (40g) + TiO ₂ (0.05wt %)	0.4158	0.4055	0.3797	0.3330	0.2923	0.2409	0.2048	0.1721
	LPG (40g) + TiO ₂ (0.15wt %)	0.4265	0.4258	0.3937	0.3433	0.2988	0.2541	0.2152	0.1802
	LPG (40g) + TiO ₂ (0.3wt %)	0.4265	0.4258	0.3937	0.3433	0.2976	0.2505	0.2152	0.1802
Power Consumption	LPG (Pure)	1.7679	1.9571	2.1481	2.3547	2.5748	2.8602	3.1655	3.4880
	LPG (40g) + TiO ₂ (0.05wt %)	68.10	68.90	69.70	71.10	73.20	74.20	75.70	76.70
	LPG (40g) + TiO ₂ (0.15wt %)	60.20	61.10	61.60	61.80	62.20	62.50	62.20	63.60
	LPG (40g) + TiO ₂ (0.3wt %)	64.50	65.10	65.50	66.30	67.00	67.20	67.50	67.90
X _{tol}	LPG (Pure)	0.4061	0.3613	0.3309	0.3741	0.3766	0.4302	0.4609	0.4876
	LPG (40g) + TiO ₂ (0.05wt %)	0.3124	0.3388	0.3444	0.3822	0.3943	0.4075	0.4349	0.4540
	LPG (40g) + TiO ₂ (0.15wt %)	0.2921	0.2950	0.3225	0.3386	0.3428	0.3572	0.3793	0.3926
	LPG (40g) + TiO ₂ (0.3wt %)	0.2981	0.2987	0.3251	0.3505	0.3702	0.3812	0.3876	0.4022

Table 3: Parametric Experimental Result Obtained for R600a with and Without Nanofluids

Tevapo		-3	0	3	6	9	12	15	18
COP	R600a (Pure)	1.4240	1.5822	1.7885	1.9977	2.2807	2.5450	2.9539	3.4731
	R600a (40g) + TiO ₂ (0.05wt %)	1.3823	1.4513	1.6838	1.9543	2.2449	2.5856	3.0235	3.5442
	R600a (40g) + TiO ₂ (0.15wt %)	1.8099	1.9711	2.1419	2.3779	2.6551	2.9189	3.3018	3.6705
	R600a (40g) + TiO ₂ (0.3wt %)	1.5801	1.7319	1.9574	2.1625	2.4731	2.7658	3.1909	3.6358
Nx	R600a (Pure)	0.3496	0.3541	0.3397	0.3000	0.2610	0.2187	0.1718	0.1298
	R600a (40g) + TiO ₂ (0.05wt %)	0.3684	0.3700	0.3563	0.3243	0.2903	0.2475	0.1923	0.1423
	R600a (40g) + TiO ₂ (0.15wt %)	0.4023	0.4027	0.3950	0.3783	0.3441	0.3001	0.2270	0.1621
	R600a (40g) + TiO ₂ (0.3wt %)	0.3789	0.3804	0.3682	0.3359	0.3078	0.2577	0.1968	0.1465
Power Consumption	R600a (Pure)	73.50	74.90	76.10	77.20	78.80	79.90	81.10	82.60
	R600a (40g) + TiO ₂ (0.05wt %)	64.30	64.90	65.70	66.60	67.30	68.30	69.10	70.80
	R600a (40g) + TiO ₂ (0.15wt %)	59.90	60.20	60.90	61.40	61.80	61.90	62.30	62.90
	R600a (40g) + TiO ₂ (0.3wt %)	62.10	62.50	63.20	63.90	64.90	65.70	66.50	67.30
X _{tol}	R600a (Pure)	0.3492	0.3699	0.3976	0.4324	0.4594	0.4900	0.5440	0.5822
	R600a (40g) + TiO ₂ (0.05wt %)	0.2962	0.3048	0.3298	0.3446	0.3663	0.3952	0.4297	0.4631
	R600a (40g) + TiO ₂ (0.15wt %)	0.1597	0.1653	0.1827	0.2220	0.2398	0.2423	0.2952	0.3193
	R600a (40g) + TiO ₂ (0.3wt %)	0.2573	0.2903	0.3183	0.3404	0.3639	0.3913	0.4247	0.4653

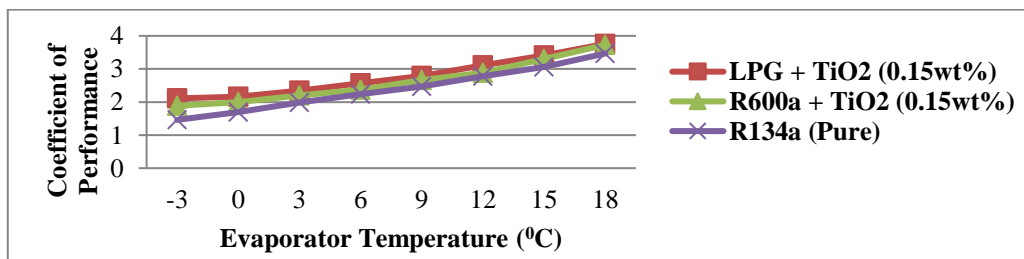


Fig. 1: Variation of Coefficient of Performance (COP) with Varying Evaporator Temperature.

The Figure 1 below shows the variation of coefficient of performance (COP) for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a with varying evaporator temperature. The figure shows that the COP increases with increase in evaporator temperature. The results obtained showed that the average percentage deviation of the COP for LPG + TiO₂ (0.15wt %), and R600a + TiO₂ (0.15wt %) were 27.6%, and 14.3% higher in comparison to R134a. Based on performance, LPG + TiO₂ (0.15wt %) and R600a + TiO₂ (0.15wt %) are better than R134a as refrigerant.

In Figure 2 below, the variation of Power consumption (W) for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a with evaporator temperature is represented. Power consumption slightly decreases with decrease in evaporator temperature. Average power consumption deviation for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a are 34.6%, and 35.15% lower in comparison to that of R134a, respectively. Power consumption values of 60.1, 59.9, and 89.9 (Watts) were obtained at an evaporator temperature of -3°C respectively. Based on power consumption, LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %)

consumed lesser amount of energy with respect to R134a as a refrigerant.

The Figure 3 below represents the variation of exergetic efficiency (η_{ex}) with evaporator temperature for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a. Exergetic efficiency decreases with increase in evaporator temperature. The average exergetic efficiencies for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a are 13.8%, and 17.53%, higher when compared to R134a, respectively. Exergetic efficiency (η_{ex}) values of 42.7, 40.2, and 37.1% were obtained at an evaporator temperature of -3°C for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a respectively.

The Figure 4 below shows the variation of exergetic efficiency defect in the evaporator with evaporator temperature for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a. This figure showed that the exergetic efficiency defect in the evaporator decreases with decrease in evaporator temperature. The results obtained showed that the average exergetic efficiency defects for LPG + TiO₂ (0.15wt %) and R600a + TiO₂ (0.15wt %) in the evaporator were 37.89 and 35.32% lower respectively when compared to the baseline (R134a) respectively.

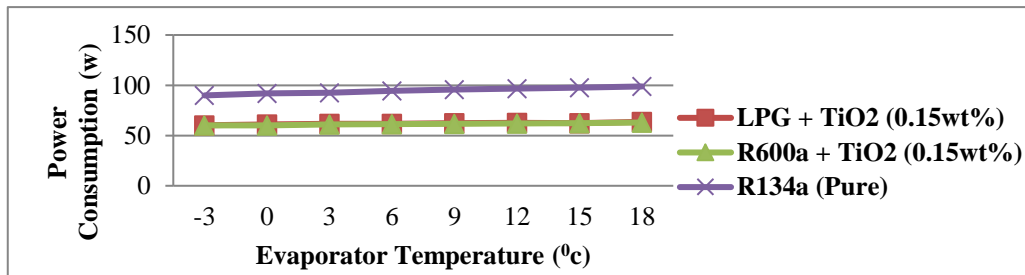


Fig. 2: Variation of Power Consumption (W) with Varying Evaporator Temperature.

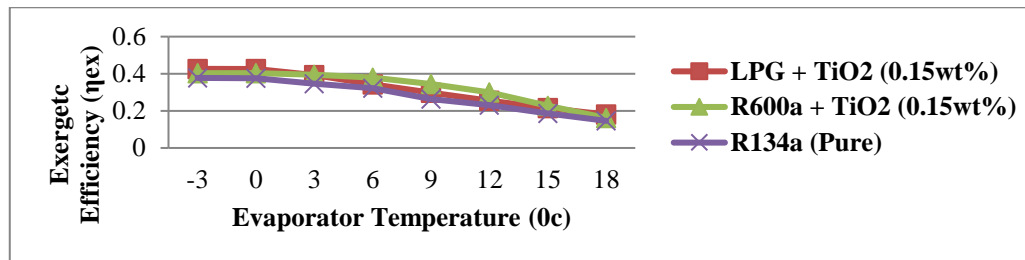


Fig. 3: Variation of Exergetic Efficiency (H_{ex}) with Evaporator Temperature.

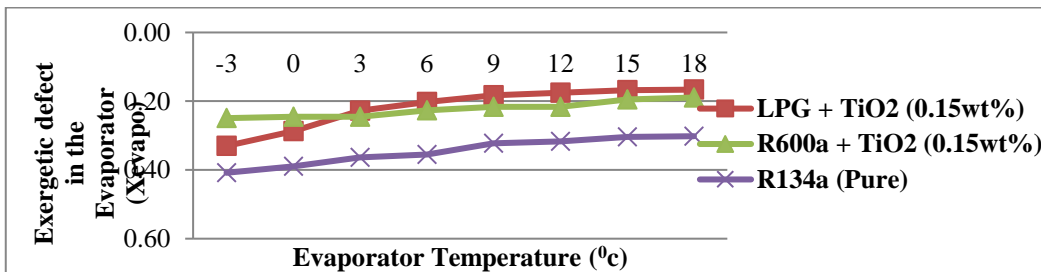


Fig. 4: Variation of Exergetic Defect in Evaporator (X_{evapo}) with Evaporator Temperature.

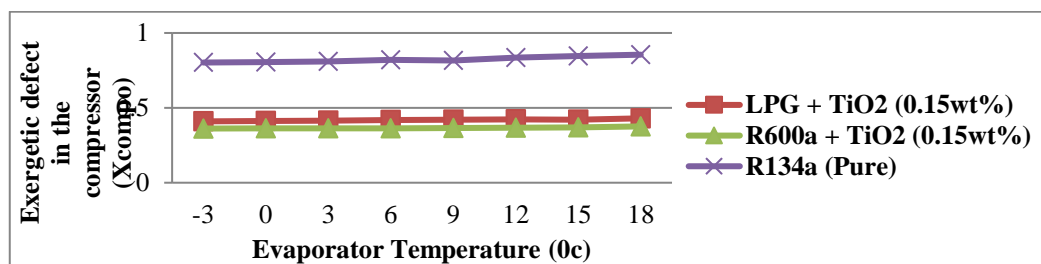


Fig. 5: Variation of Exergetic Defect in Compressor (X_{compo}) with Evaporator Temperature.

The figure 5 below shows the comparison of efficiency defect in the compressor for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a. As shown in the figure, efficiency defect in compressor decreases with decrease in evaporator temperature. The percentage exergetic efficiency defects in the compressor are 49.19% and 55.56% lower when compared to that of R134a, respectively.

Figure 6 below shows the variation of exergetic efficiency defect in the condenser (X_{condo}) with evaporator temperature for LPG +

TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a. As shown in the figure, efficiency defect in condenser decreases with decrease in evaporator temperature. The result obtained showed that the exergetic efficiency defect in the condenser for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %) were 29.7, and 33.7% lower in comparison with that of R134a respectively.

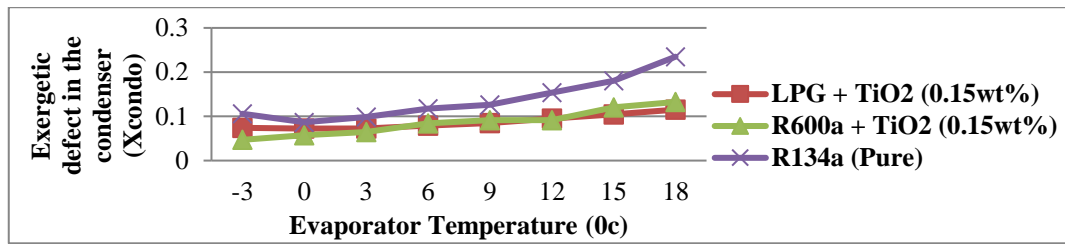


Fig. 6: Variation of Exergetic Defect in Condenser (Xcondo) with Evaporator Temperature.

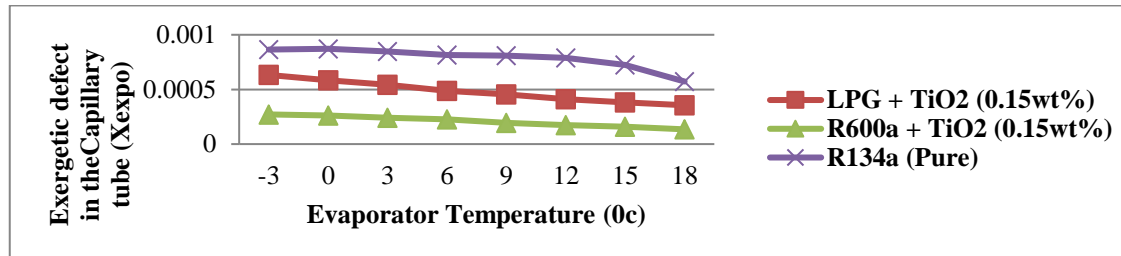


Fig. 7: Variation of Exergetic Defect in Capillary Tube (Xexpo) with Evaporator Temperature.

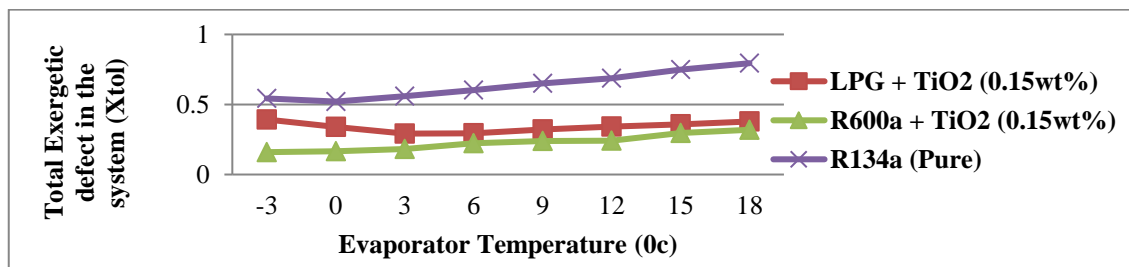


Fig. 8: Variation of Total Exergetic Defect (Xtol) in the System with Evaporator Temperature.

The variation of efficiency defect in capillary tube (Xexpo) with evaporator temperature for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a is shown in the figure 7 below, exergetic efficiency defect in the capillary tube decreases with increase in evaporator temperature. The result obtained showed that the exergetic efficiency defect in the capillary tube were 39.1, and 73.8% lower in comparison with that of R134a respectively.

Figure 8 shows the variation of total exergetic defect in the system with evaporator temperature for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %), and R134a. The result obtained showed that the average exergetic efficiency defect in the system were 45.8, and 64.7% lower for LPG + TiO₂ (0.15wt %), R600a + TiO₂ (0.15wt %) in comparison with that of R134a respectively.

4. Conclusion

The energy and exergy performance of LPG and R600a with 0.05wt%, 0.15wt%, and 0.3wt% nanoparticle concentration in the nanoparticle/Oil suspension as an alternative refrigerant to R134a in domestic refrigerators was studied, and the following conclusions were established;

The refrigerator worked satisfactorily with LPG and R600a with TiO₂ nano-lubricant without making any modification to the refrigerator. Average COP values of 2.78 and 2.63 were obtained for LPG and R600a with TiO₂ nano-lubricant (0.15wt %) which were higher when compared with 2.39 of R134a resulting to 18.63% and 11.4% higher COP than R134a. Furthermore, a reduced energy consumption percentage of 33.04 and 33.15% at an evaporator temperature of -3°C were obtained for LPG and R600a with 0.15wt% nano/lubricant mixture when compared with R134a. Exergetically, LPG and R600a with 0.15wt% nano/lubricant mixture performed better than the other experimented refrigerants such as the 60g charge of pure R134a, 40g charges of pure LPG and R600a, LPG +TiO₂ (0.05wt% and 0.3wt%), R600a +TiO₂ (0.05wt% and 0.3wt%). The nano-lubricant of 0.15wt% concentration was optimal for both LPG and R600a based on energy and exergy analysis.

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Nomenclature

T – Temperature, °C

h – Specific enthalpy, **KJ/Kg**

s – Specific entropy of refrigerator, **KJ/Kg.k**

m_r - Mass flow of refrigerant, **Kg/s**

Q_{evapo} – Refrigerated Capacity

W_{el} - Compressor work input, **W**

COP – Coefficient of Performance

X_d – Exergy destroyed

ρ – Density, kg/m³

ψ_n - nanoparticle concentration in the nanoparticles/oil suspension

T₀ – Reference Temperature

out – Outlet or Output

r - refrigerant

tol - total

1 - Outlet of Evaporator

2 - Outlet of Compressor

3 - Outlet of Condenser

4 – Inlet of Evaporator

Greek Symbol

η_{ex} - Exergetic Efficiency, %

Symbols&Subscripts

Compo – Compressor

Condo – Condenser

Expo – Expansion device or Capillary tube

Evapo - Evaporator

Abbreviations

GWP–Global warming Potential

ODP – Ozone depletion Potential

TiO₂ – Titanium IV Oxide (Nanoparticle)