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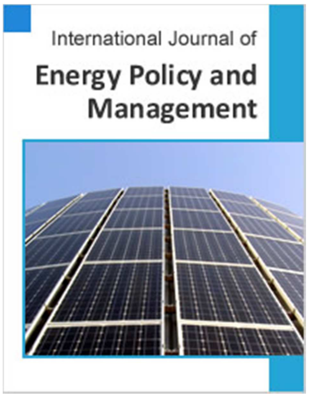

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Experimental Evaluation on Exergy Analysis of Vapour Compression Refrigeration System Using LPG with TiO_2-Nanoparticle

Luke Onyekwere Ajuka*, Kamilu Moradeyo Odunfa

Mechanical Engineering Department, University of Ibadan, Ibadan, Nigeria

Email address
ajukamario@gmail.com (L. O. Ajuka)
*Corresponding author

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Abstract
A domestic refrigerator designed to work with R-134a was used as a test unit to assess the possibility of using LPG (R290/R600a: 50% 50%), an environmental-friendly refrigerant with TiO_2 nano-lubricant. The performance of the refrigerator using various concentrations of 15nm particle size of TiO_2 nano-lubricant at 0.1, 0.2 and 0.4wt% with LPG were investigated and compared with the performance of the refrigerator when R-134a was used as refrigerant. The evaporator temperature effects on energy consumption, coefficient of performance, exergetic efficiency and exergetic defects in the compressor, condenser, capillary tube and evaporator of the refrigeration system were examined. The results show that for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), and LPG (Pure) respectively, the COP is 15.4, 22.7, 12.4, and 9.38% higher than HFC-134a, the compressor consumed 29.9, 34.6, 23.6 and 18.3% less energy for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), and LPG (Pure) respectively less energy than that of HFC-134a, and the exergetic efficiencies were LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), and LPG (Pure) respectively 7.8, 8.6, 6.5, and 6.0% higher that of HFC-134a at 29°C ambient temperature. The COP, energy consumption, exergy efficiency and other result obtained in this experiment shows that LPG mixed with TiO_2 nanoparticle particularly at 0.2 wt.% concentration can be used as refrigerant in the domestic refrigerator.

1. Introduction

The most frequently used refrigeration cycle is the vapour compression refrigeration cycle. Today, many African countries cannot do without vapour compression systems despite the fact that they are known to consume a large percentage of the available power supply. [1] reported that domestic refrigerators working with R12 consume about 12% of the total residential energy budget annually. It is therefore imminent to get a value for power consumed through additives and other structural component adjustments.

Today, due to the regulations such as Montreal and Kyoto protocols to phase out non-environment friendly refrigerants such as CFC's and HCFC's, alternative refrigerants which have low Global Warming Potential (GWP) are widely used in refrigeration and air-conditioning equipment in many sectors.

It is also important to ensure that environment friendly alternative refrigerants which have low Global Warming Potential (GWP) are widely used. Nigeria for example being the most populous in Africa is privileged to be an oil producing country, and this makes the availability and low cost of LPG a cause to consider.

Advances in nanotechnology which has led to a new type of heat transfer fluid, nanofluids (i.e., the mixture of host fluid and nanoparticles) have potential to enhance heat transfer rate thus making heat exchanger of air-conditioning and refrigeration equipment compact. This, consequently, will reduce energy consumption in these sectors along with reduction in emission, global warming potential and greenhouse-gas effects [2]. In recent years, nanofluids have been used for improving the performance of vapor compression refrigeration systems [3-5].

The first law is concerned only with the conservation of energy, and it gives no information on how, where, and how much the system performance is degraded. Exergy analysis is a powerful tool in the design, optimization, and performance evaluation of energy systems [6]. According to [7] to obtain an appreciable reduction in energy consumption of refrigeration systems it is necessary to conduct a detailed system analysis under the perspective of the first and second laws of thermodynamics. Through the principles of thermodynamics and economics, the thermo-economy evaluates a given system using concepts of products and inputs in the form of exergetic flows, i.e., considering the second law of thermodynamics [8].

Recently, several research studies conducted on refrigeration systems using different refrigerants, lubricants and nanoparticles showed significant reduction in power consumption and improvement in coefficient of performance (COP) of the system. [9] used hydrocarbon refrigerant and mineral lubricant suspended with Al_2O_3 nanoparticles and showed better lubrication and heat transfer performance. Furthermore study shows that 60% R-134a and 0.1 wt.% Al_2O_3 nanoparticles were optimal. Hence, the power consumption drops by 2.4% and COP increased by 4.4%.

[10] presents an exergetic analysis of a vapour compressor refrigeration plant when the refrigeration capacity is controlled by varying the compressor speed. The aim is performance evaluation of both the whole plant and its individual components. The analysis of the exergy flow destroyed in each device of the plant varying the compressor speed has been carried out in order to determine the relative irreversibility of the plant components. The vapour compression plant is subjected to a commercially available cold store. The compressor working with R22, R407C and R507 and designed for a revolution speed corresponding to 50 Hz supply current frequency has been used varying the frequency in the range 30-50 Hz. In this range, the most suitable working fluids proposed as substitutes of R22, as R407C (R32/R125/R134a 23/25/52% in mass), R507 (R125/R143A 50/50% in mass) and R417A (R125/R134a/R600 46.6/50/3.4% in mass), have been tested.

[11] conducted an experimental comparative energy, exergy flow and second law efficiency analysis of R22, R436b and its substitute R436b (hydrocarbon mixture of 52% of propane (R290) 48% of isobutene (R600a), vapour compression refrigeration cycles. He investigated the effects of the evaporating temperatures on the exergy flow losses, the second law efficiency, and the COP of a vapor compression refrigeration cycle. It is found that the evaporating temperatures have strong effects on the exergy flow losses is high and on the second law efficiency and COP of the cycle but little effects on the other components of the exergy losses. The second law efficiency and the COP increases, and the total exergy loss decreases with decreasing temperature difference between the evaporator and refrigerated space and between the condenser and outside air. The exergy analysis along with the energy analysis of the vapour compression refrigeration cycle is presented. The analysis indicates that the second law efficiency is very low, although the first law efficiency is within a normal range. The reasons for such low exergy efficiency are due to large exergy destructions in the compressor and the condenser.

[12] found the results of the exergy analysis of a two-stage refrigeration system operating between a constant evaporating temperature of -30°C and condensation temperatures of 30, 40, 50 and 60°C with two natural substitutes of HCFC22, namely, propane (R290) and ammonia (R717) as working fluids, are presented. It is found that the most significant losses occur in the compressors, expansion valves and condenser.

[13] developed the equations of exergy destruction and exergetic efficiency for the main system components such as heat exchangers, compressors and expansion valves. The relations for total exergy destruction in the system and the system overall exergetic efficiency are obtained. Also, an expression for minimum work requirement for the refrigeration systems of olefin plants is developed. It shows that the minimum work depends only on the properties of incoming and outgoing process streams cooled or heated with refrigeration system and the ambient temperature.

In this paper, exergy analysis is applied to the vapor compression refrigeration cycle. The expressions for the exergy analysis of the individual processes that make up the cycle as well as the coefficient of performance (COP) and exergy efficiency for the entire cycle are obtained. Effects of evaporating temperatures on the Power consumption, exergy losses, exergy efficiency and COP were investigated.

2. Methodology

2.1. System Description/Preparation of Nanoparticles / Compressor Oil Mixture (Nano-Lubricant)

A 70 litre, 110W, reciprocating type compressor, designed for R134a refrigerant.

A 15nm size mass of titanium nanoparticle (TiO_2) was weighed by using a digital weighing balance of a measurement range of 10 mg to 210 g and a maximum error of 0.1 mg. Then the certain required masses of TiO_2

nanoparticle were added into the weighed lubricating oil to form a TiO_2 nanoparticles/oil suspension (nano-lubricant) with concentrations at 0.1, 0.2 and 0.4wt.% respectively. With the aid of an ultrasonic vibrator, the nanoparticles/oil mixture thoroughly vibrated and homogenized. This process was carried out for two hours to ensure the nanoparticles were evenly dispersed. Stability test was carried out by leaving the mixture for 24hrs to observe if there will be sedimentation. Table 1 below summarizes the specific properties of the TiO_2 nanoparticle used to prepare the nano-lubricant filled into the compressor of the refrigeration system. The duration of the experiment for each sample of nanoparticle/oil mixture with TiO_2 nanoparticle was 4hours which was much shorter than the sedimentation observation period of 24hrs, so the nanoparticle/oil mixture with TiO_2 nanoparticles can maintain good uniformity in the experiment.

Table 1. *Characteristic Properties of the Titanium Oxide (TiO_2) 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%

Figure 1. *Experimental Set-up: Refrigeration system.*

Experimental Procedures:

The experimental system was first charged with pure R-134a after thorough evacuation. The corresponding temperatures at the evaporator, compressor outlet, condenser outlet, and pressures at the suction and discharge of the compressor P_s and P_d were recorded, and the Power consumed was also recorded for analysis. The procedure was repeated for (50%:50%) of pure LPG, LPG with titanium oxide (TiO_2) nano-lubricant concentrations of 0.1wt%, 0.2wt%, and 0.4wt%.

The tests were carried out in the refrigeration and air-conditioning laboratory in a tropical region (Nigeria) with an ambient air temperature range of 29 ± 1°C and a relative humidity of 51%. The thermodynamic properties of the refrigerants were obtained using the [14].

2.2. Mathematical Formulation and Exergetic Analysis of the Vapour Compression Refrigeration System

An analysis of the system was carried out by evaluating the individual components in the system i.e. the compressor, condenser, expansion device and evaporator, where mass, energy and exergy balances were employed to determine the heat input, the rate of exergy destruction, and energy and exergy efficiencies.

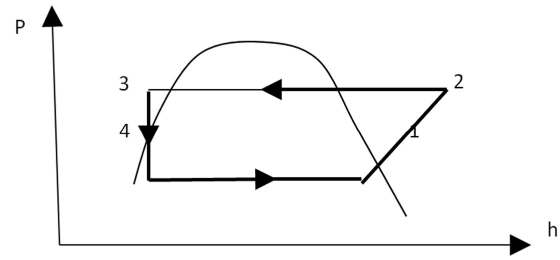

Figure 2. *Vapour Compression Refrigeration System on p-h Diagram.*

2.2.1. Nano-Lubricant Concentration Formulae

Volume fraction of nanoparticle in the nanoparticle-oil suspension ($\tilde{V}n$):

$$\tilde{V}n = \tilde{\phi}_n \rho_0 / [\tilde{\phi}_n \rho_0 + (1 - \tilde{\phi}_n)\, \rho_n] \quad (1)$$

Mass fraction of Nanoparticle concentration in the nanoparticles/oil suspension ($\tilde{\phi}n$):

$$\tilde{\phi}_n = m_n / (m_n + m_o) \quad (2)$$

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 [15]:

$$\Sigma\dot{E}_{in} = \Sigma\dot{E}_{out} \quad (3)$$

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

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

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

2.2.2. Exergy in the Evaporator

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

$$\dot{E}_{d,evapo,in} = \dot{m}_r (h_4 - T_0 S_4) + Q_{evapo} \left(1 - \frac{T_O}{T_r}\right) \quad (6)$$

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

$$\dot{E}_{d,evapo} = \dot{E}_{d,evapo,in} - \dot{E}_{d,evapo,out} \quad (8)$$

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

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

2.2.3. Exergy in the Compressor

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

$$\dot{E}_{d,compo,in} = \dot{m}_r\,(h_1 - T_0 s_1) + Wel \quad (10)$$

$$\dot{E}_{d,compo,out} = \dot{m}_r\,(h_2 - T_0 s_2) \quad (11)$$

$$\dot{E}_{d,compo} = \dot{E}_{d,comp,in} - \dot{E}_{d,comp,out}$$

Therefore,

$$\dot{E}_{d,compo} = \dot{m}_r\,[(h_1 - h_2) - T_0\,(s_1 - s_2)] + Wel \quad (12)$$

2.2.4. Exergy in the Conductor

Exergies at the conductor inlet ($\dot{E}_{d,condo,in}$) and outlet ($\dot{E}_{d,condo,out}$) are calculated using Eqs. (13) and (14)

$$\dot{E}_{d,condo,in} = \dot{m}_r\,(h_2 - T_0 S_2) - Q_{condo}\,(1 - \frac{T_0}{T_r}) \quad (13)$$

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

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

2.2.5. Exergy in the Expansion Device (Capillary Tube)

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

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

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

Wherefore,

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

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

2.2.6. Total Exergy Destruction

The total exergy used in the system ($E_{d,tol}$) is the total sum of exergy used in each component of the system. Therefore,

$$\dot{E}_{d,tol} = \dot{E}_{d,evapo} + \dot{E}_{d,compo} + \dot{E}_{d,condo} + \dot{E}_{d,expo} \quad (19)$$

2.2.7. Exergetic Efficiency in the System

The overall system exergetic efficiency (η_x) is the ratio of the exergy output ($\dot{E}_{out}$) to exergy input ($\dot{E}_{in}$)

$$\eta_x = \frac{E_{out}}{E_{in}} * 100\% \quad (20)$$

Exergy output ($\dot{E}_{out}$) is the difference between exergy input ($\dot{E}_{in}$) and the total exergy destroyed in the system (Let $\dot{E}_{d,tol} = \dot{E}_{d,i}$),

Wherefore,

$$\dot{E}_{out} = \dot{E}_{in} - \dot{E}_{d,i}, \text{ and } \dot{E}_{in} = W_{el} \quad (21)$$

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

$$\eta_x = \frac{W_{el} - E_{d,i}}{W_{el}} *100\% \quad (22)$$

$$\eta_x = 1 - (\frac{E_{d,i}}{W_{el}}) *100\% \quad (23)$$

3. Result and Discussion

The experimental results obtained for COP, Energy consumption, Exergy Efficiencies, Exergy defects are graphically shown and discussed below for the different concentrations of LPG, and R134a.

3.1. Coefficient of Performance

The variation of the system's coefficient of performance with evaporator temperature is shown in Figure 1 below. The coefficient of performance by the refrigeration system decreases with decrease in evaporator temperature. The average coefficient of performance of LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), and LPG (Pure) were 15.4, 22.7, 12.4, and 9.38% higher than R134a respectively. The refrigerant LPG + TiO_2 (0.2wt%) had the highest coefficient of performance of 2.58 average value.

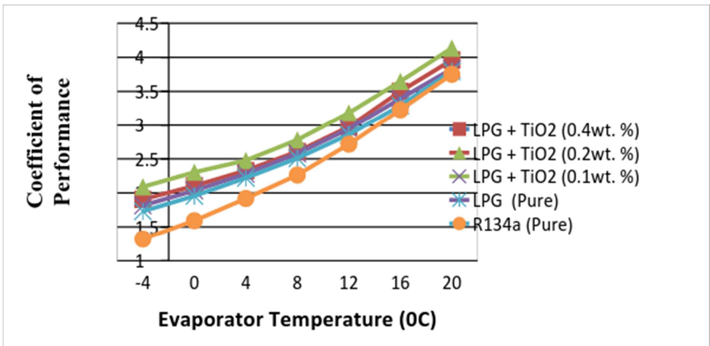

Figure 3. *Variation of COP with Evaporator Temperature.*

3.2. Power Consumption

The variation of Power Consumption (Watts) with evaporator temperature is shown in Figure 2 below. The Power consumed by the refrigeration system decreases with decrease in evaporator temperature. The average power consumed by the refrigerant R134a is 29.9, 34.6, 23.6 and 18.3% higher than LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), and LPG (Pure) respectively. The refrigerant LPG + TiO_2 (0.2wt%) consumed the least energy among the tested set with an average value of 62.03 Watts.

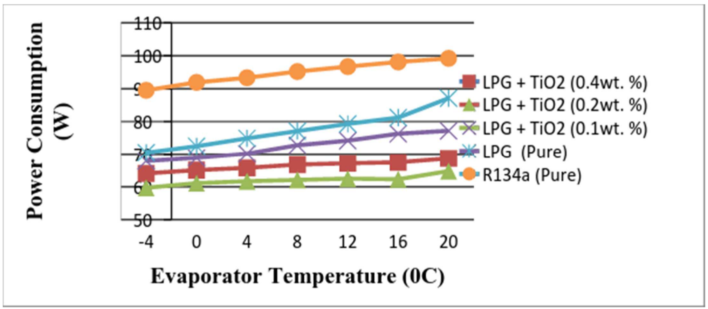

Figure 4. *Variation of Power Consumption with Evaporator Temperature.*

3.3. Exergy Destruction in the Evaporator

The variation of exergy destruction in the evaporator with evaporator temperature is shown in figure 3 below. The average exergy deficiency in the evaporator (E_{evapo}) using LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), and LPG (Pure) were 31.7, 31.1, 29.6, and 27.8% lower than pure R134a respectively.

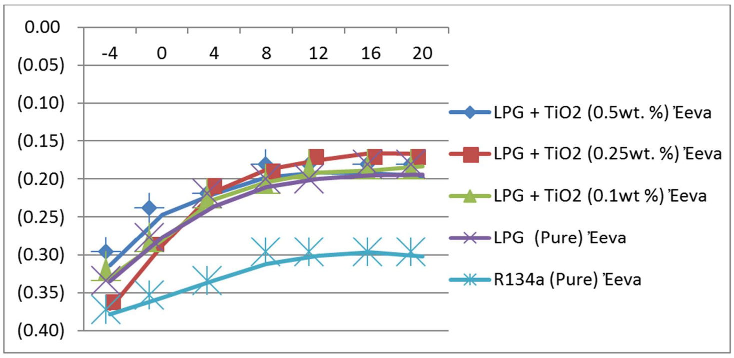

Figure 5. *Variation of Exergy destruction in the Evaporator with Evaporator Temperature.*

3.4. Exergy Destruction in the Compressor

The Figure 4 below shows the variation of exergetic deficiency in the compressor (E_{compo}) with evaporator temperature. The result showed that exergetic deficiency in the compressor decreases with decrease in evaporator temperature. The average exergetic deficiencies for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%) and LPG (Pure) are 35.5, 39.8, 29.4, and 25.04% lower when compared to R134a, respectively.

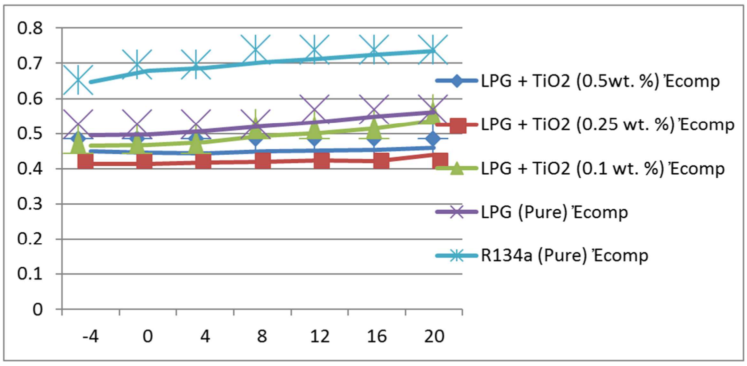

Figure 6. *Variation of Exergy destruction in the Compressor with Evaporator Temperature.*

3.5. Exergy Destruction in the Condenser

The Figure 5 below shows the variation of exergetic deficiency in the condenser (E_{condo}) with evaporator temperature. The result showed that exergetic deficiency in the condenser decreases with decrease in evaporator temperature. The average exergetic deficiencies for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%) and LPG (Pure) were 19.4, 26.4, 24.86, and 20.5% lower when compared to R134a, respectively.

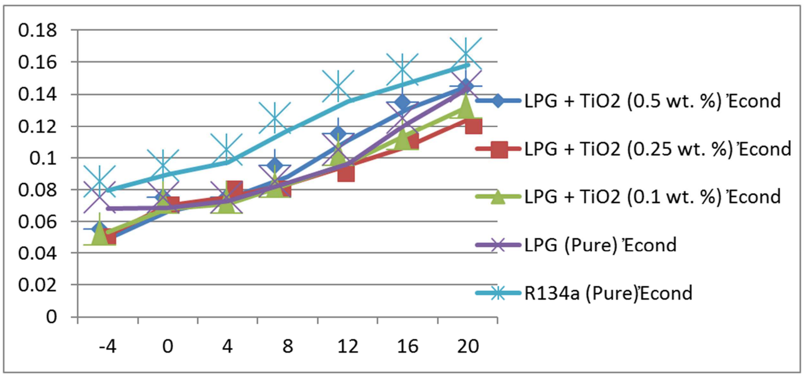

Figure 7. *Variation of Exergy Destruction in the Condenser with Evaporator Temperature.*

3.6. Exergy Destruction in the Capillary Tube

The Figure 6 below shows the variation of exergetic deficiency in the Capillary Tube (E_{cappo}) with evaporator temperature. The result showed that exergetic deficiency in the Capillary Tube decreases with decrease in evaporator temperature. The average exergetic deficiencies for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%) and LPG (Pure) were higher than R134a with a percentage value of 1.76, 1.65, 1.82, 1.93% respectively.

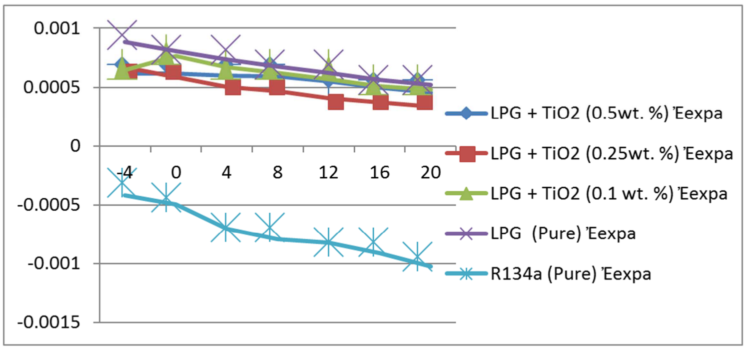

Figure 8. *Variation of Exergy Destruction in the Capillary Tube with Evaporator Temperature.*

3.7. Total Exergy Destruction in the System

The total exergetic deficiency in the system (E_{tol}) with evaporator temperature is shown in Figure 7 below. The average exergetic deficiencies for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%) and LPG (Pure) are 14.2, 19.8, 30.9, and 26.4% lower when compared to R134a, respectively.

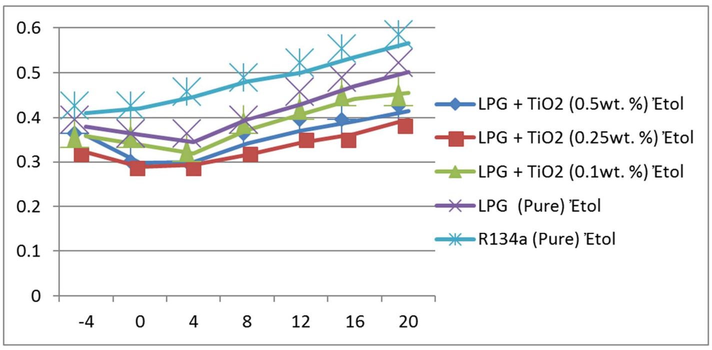

Figure 9. *Variation of Total Exergy Destruction in the System with Evaporator Temperature.*

3.8. Exergy Efficiency in the System

The Figure 8 below shows the variation of exergetic efficiency (η_x) with evaporator temperature. Exergetic efficiency decreases with increase in evaporator temperature. The average exergetic efficiencies for LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.2wt%), LPG + TiO_2 (0.1wt%), LPG (Pure) are 7.8, 8.6, 6.5, and 6.0% higher when compared to R134a, respectively. Exergetic efficiency (η_x) values of 43.2 and 40.1% were obtained at an evaporator temperature of -4°C for LPG + TiO_2 (0.2wt%) and R134a respectively.

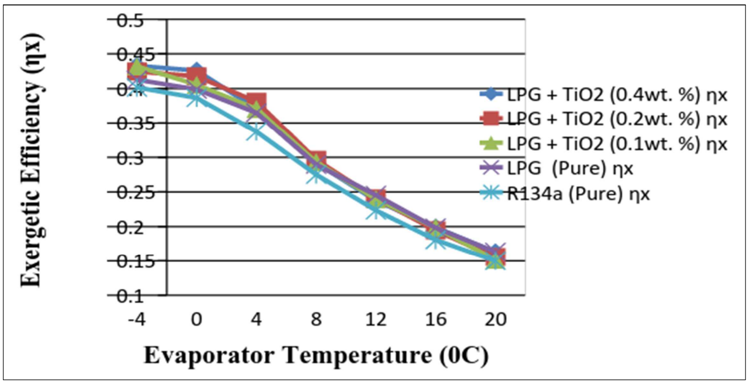

Figure 10. *Variation of Exergy Efficiency in the Vapour Compression System with Evaporator Temperature.*

4. Conclusion

In this study, the first and second law analysis of vapor compression refrigeration cycle with different concentrations of TiO_2 nano-lubricant were carried out on LPG (50% 50%). The power consumption, coefficient of performance (COP) and exergetic efficiency (η_x) of the system in the different operating conditions were investigated.

The performance of the refrigerant test series energetically for LPG with 0.1wt%, 0.2wt%, and 0.4wt% nanoparticle concentration in the nanoparticle/Oil suspension as an alternative refrigerant to R134a in domestic refrigerators were concluded were thus;

The refrigerator worked satisfactorily with LPG purely and with TiO_2 nano-lubricant without making any modification to the refrigerator.

Power consumption savings is higher using LPG particularly with TiO_2 (0.2wt%) nanoparticle concentration in the nanoparticle/Oil suspension compared with R134a, LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.1wt%), LPG (Pure). LPG generally consumed less energy compared to R134a.

The coefficient of performance of LPG with TiO_2 (0.2wt%) was the best of the refrigerant test series. The performance of LPG with TiO_2 (0.4wt%) was lower compared to LPG with TiO_2 (0.2wt%) which indicates that the coefficient of performance does not necessarily increase with increase in nanoparticle concentration, rather there must exist a concentration point before performance starts to decline i.e Figure 1 showed that Performance increased with addition of 0.1wt%, 0.2wt% of TiO_2 to LPG (pure) but declined at 0.4wt% TiO_2 addition to LPG.

In terms of exergy, the efficiency of the refrigerator when LPG is used with 0.2wt% of TiO_2 nanolubricant was used is the best among the test set of R134a, LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.1wt%), LPG (Pure) refrigerants, while R134a has the least exergetic efficiency. It can be concluded that LPG with 0.2wt% of TiO_2 nano-lubricant performs better than R134a, LPG + TiO_2 (0.4wt%), LPG + TiO_2 (0.1wt%), LPG (Pure) both energetically and exergetically.

Acknowledgements

The authors would like to appreciate Mr. Taiwo and Damola for their technical assistance in the Refrigeration and Air-conditioning Laboratory.

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
$\dot{E}_{,d}$ – Exergy destroyed
T_0 – 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

ρ – Density, kg/m^{-3}

Greek Symbol

η_x - Exergetic Efficiency,%

Symbols & Subsripts

Compo – Compressor

Condo – Condenser

Ṽn - nanoparticle concentration in the nanoparticles/oil suspension

ῷn - Mass fraction of Nanoparticle concentration in the nanoparticles/oil suspension.

Abbreviations

Capo – Capillary tube

GWP–Global warming Potential

ODP – Ozone depletion Potential

TiO_2 – Titanium IV Oxide (Nanoparticle)

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