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EXERGY ANALYSIS OF TITANIUM DIOXIDE (TiO_2) SUSPENDED WITH R290/R600 AS A SUBSTITUTE FOR R134A

Synthetic refrigerants are being phased out gradually in accordance with international environmental protection protocols because of global warming and ozone layer depletion. Adopting R290/R600 refrigerant, an environmentally friendly refrigerant, to replace R134a, a high global warming potential refrigerant, provides one of the solutions. In this study, exergy analysis of R134a and TiO_2 suspended with lubricant and R290/R600 with a composition of 60% R290 and 40% R600 (60:40) was investigated in vapour compression system (VCRS) using R290/ R600 in TiO_2 nanomixture lubricant and compared with R134a and R290/ R600 in pure lubricant. At the inlets and outlets, the main components of the VCRS are connected to temperature and pressure sensors to measure the inlet and outlet temperatures and pressures. The results obtained were used to analyses the exergy losses at various VCRS components (compressor, condenser, evaporator, expansion valve) were investigated to determine the refrigerator's total exergy destruction ($\dot{E}x_{dest.Total}$) and efficiency (η_{ex}). The $\dot{E}x_{dest.Total}$ of R290/R600 in pure lubricant and R290/R600 TiO_2 nanomixture lubricant was reduced by 26.9% and 42.3%, respectively, and system η_{ex} increased by 27.7% and 38.9% respectively when compared to R134a in the system. Hence, TiO_2 suspended with R290/R600 is potential a substitute for R134a.

Keywords: COP; Exergy; R134a; R290; R600

1. Introduction

Emissions of greenhouse gases produced by the use of halogenated refrigerants in vapour compression refrigeration systems (VCRS), considerably cause global warming [1]. Natural refrigerants are eco-friendlier than synthetic refrigerants, making them more appealing for use in air conditioning, heat pumps, and refrigeration systems today [1,2]. Since they have outstanding thermodynamic properties and can be used in system equipment, hydrocarbons like propane (R290) and isobutane (R600a) have emerged as alternative natural refrigerants and are primarily used in simple refrigeration and heat pump systems [3,4]. Apart from environmental challenges chlorine based refrigerants such as Hydrofluorocarbons (HFC), hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs) are associated with higher energy demand [5]. The energy and efficiency of refrigeration systems are influenced by a variety of factors such as mass charge, working fluid density, and the design of its parts.

Some researchers in the field of refrigeration energy have come up with replacement for R134a refrigerant in the VCRS with hydrocarbon. However, this has always required modifying VCRS parts like the condenser and capillary. Righetti [6] experimented R1234ze(E), R1234yf, and R600a. The outcome showed that R1234ze(E), R1234yf, and R600a all outperformed R134a in refrigerator. In a VCRS, Koshy and Prabha [7] tested the exergy of R134a and R290/R600a. Their outcome showed that when R134a refrigerant was used in the system, the COP and efficiency were better by 28.5 and 42.1% respectively. Park et al. [8] evaluated the use of R290/R600a to repalce R12 in a home refrigerator. Analysis indicated R290/R600a outperformed R12. In a VRCS, Yan and Yu [9] assessed by comparing the exergy of R600a and R290/R600a to that of a modified VCRS. The refrigeration capacity of R290/R600a in adjusted VCRS was increased with the COP when compared to conventional VRCS with R600a.

Finding an R134a replacement, Gaurav and Raj Kumar [10] conducted an analysis of a VCRS. Among the factors calculated are COP, cooling capacity, exergetic efficiency (η_{ex}) and exergy destruction ($\dot{E}x_{dest.}$). various refrigerants were tested, with R134a as the baseline. Their results show that R290 witnessed the highest COP and exergy efficiency across tested refrigerants with the lowest efficiency defect. In subtitling R134a, Sun et al. [11] worked on the performance of R513a. They discovered that a system with drop-in R513a exhibits improvements of up to 9%

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in COP and 14% in η_{ex}. Additionally, R1513a provided less irreversibility of 5% to 13% and improved η_{ex} of 3%. They came to the conclusion that the compressor needed to be redesigned or modified in order to increase the energy and η_{ex} of an R513a system. Under various operating conditions, R152a and R134a were tested by Xinwen et al. [12] in a domestic refrigerator without oil. The oil-free VCRS consisted of two oil-free compressors. The findings indicated that the average η_{ex} ratio for R152a is 26% higher than that of R134a. Additionally, because of its higher vapour density, R134a exergy destruction is 9% more than R152a. The VCRS with R152a achieved an η_{ex} that is 7% higher than R134a due to the lower overall exergy destruction. Belman-Flores et al. [13] used a computational model to determine the thermodynamic parameters, such as COP, exergy destruction, and η_{ex} for both refrigerants, for R1234yf and R134a in VCRS. According to the findings, R134a destroys less energy than R1234yf. They came to the conclusion that redesigning the capillary tube, the mass charge, and the piping could be a recommended course of action to improve the system's thermodynamic performance when using R1234yf. Other researchers [14-16] investigated R600a to replace R134a by modifying a VCRS components, and they all concluded that R600a outperforms R134a in terms of COP.

The use of nanotechnology to improve refrigeration system performance is becoming more popular. The efficiency of a refrigerator can further be enhanced by adding nanoparticles to the lubricating oil before charging the refrigerant into the system compressor [5,17-20]. There are studies available to assess the performance of the VCRS with different nano oil mixture and nanorefrigerant. The term "nanorefrigerant" describes a nanofluid in which a typical refrigerant serves as the base fluid. According to experimental research, nanorefrigerants are more thermally conductive than conventional refrigerants [21], [22].

VCRS exergy is the useful work produced by a system under typical environmental conditions. To reduce exergy loss in system components, TiO_2 nanoparticles are selected in VCRS with R290/R600 as an alternative working fluid to R134a. Moreover, there aren't many studies comparing R134a, a refrigerant with no ozone depleting potential (ODP) but a high global warming potential (GWP), with TiO_2 nanoparticles suspended in lubricant and R290/R600 as a direct replacement in the system and also without the system's components modification. This study aims to enhance the η_{ex} of a VCRS using R290/R600-TiO_2 nano oil mixture. In light of this, R290/R600-TiO_2 nanomixture is proposed in this paper as a replacement for R134a in VCRS.

2. Methods and materials of the experimental

2.1. Procedures of the experiment

A VCRS refrigerator that was initially developed to operate with R134a refrigerant that used a polyether oil served as the experiment's test rig. The experiment starts with the R134a refrigerant as a baseline. With the help of a vacuum flusher, the system was properly flushed. In this experiment, TiO_2 nanoparticles were selected as an additive in the lubricant oil for the R290/R600. Due to its properties, and with its large surface area, good thermal conductivity, and anti-wear capabilities, TiO_2 nanoparticles (Anatase) with spherical shape were chosen. According to specification provided by the producer (Sigma Aldrich), the nanoparticles' size was 15-21 nm. Fig. 1 displays the TiO_2 nanoparticles' XRD pattern, which was used in the experiment.

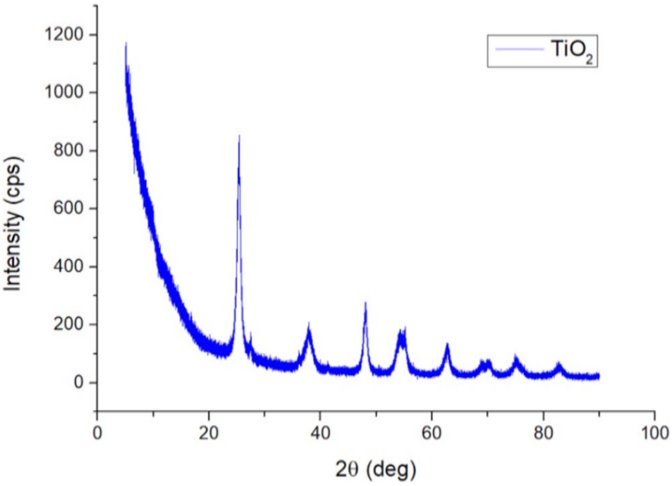

Fig. 1. XRD analysis of TiO_2's structural integrity

A refrigerator compressor lubricant was used to produce the nanomixture for R290/R600 refrigerants. The TiO_2 nanoparticles were made using an ultrasonicator for five hours and a magnetic-stirrer for even dispersion in the lubricant. TiO_2 nanomixture samples in the concentrations of 0.2 g/L, 0.4 g/L, and 0.6 g/L were prepared. Because hydrocarbon refrigerants have a much lower GWP than R134a and have zero ODP, a mixture of R290 and R600 was chosen. The TiO_2 nanoparticles nanomixture was made with 45 g of R290/R600 since the refrigerator system was originally designed to function with a 110g of R134a. This is also because hydrocarbon refrigerants have a lower density than R134a does [1]. The characteristic properties of the refrigerants selected for the experiment in presented in TABLE 1.

TABLE 1

Characteristics of the refrigerants R134a, R290, and R600

Refrigerant	**Molar mass (Kg/kmol)**	**Critical temperature (°C)**	**GWP**	**ODP**	**Safety group**
R134a	102.03	101.06	1300	0	A1
R290	44.10	96.74	3	0	A3
R600	58.12	151.98	3	0	A3

Using a digital charging scale, the refrigerant was introduced into the system. Various system components' inlets and outlets on the refrigerator were instrumented. Temperatures at various component's inlet and outlet was measured using K-type thermocouples (°C). Additionally, to measure the suction and discharge pressures, Bourdon type pressure gauges (kPa) were coupled to the compressor's suction and discharge. The experimental test setup and conditions are shown in Fig. 2. Five measurements of the temperature and pressure were made at intervals of 30 minutes.

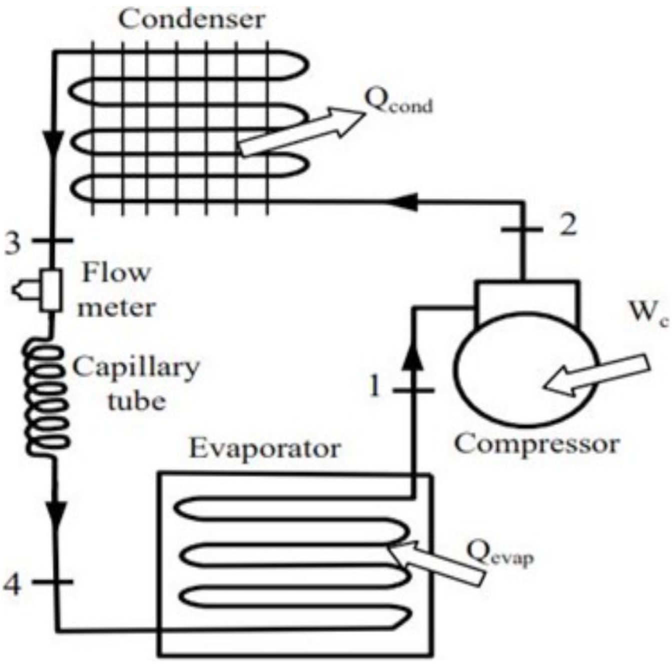

Fig. 2. The experimental test rig's diagram

The version 9.0 refprop was made use of to calculate the enthalpies and entropies of the refrigerant using pressure and temperature measurement outputs. These outputs were used to assess the system's COP, exergy destruction ($\dot{E}x_{dest.}$), and exergetic efficiency η_{ex}. Equations (1)-(10) [15] were used to calculate the analysis for the experimental result.

The degree to which a refrigerator system deviates from its given and reference state is referred to as its exergy. Exergies are typically consumed in a system's actual process. The total Exergy gained at the system's output (*out*) is less than the total Exergy obtained at the system's inlet (*in*). Exergy destruction consumes exergy in the refrigeration system. Total exergy destruction (total irreversible) of the refrigerator system is defined as the sum of exergy destruction in each component of the refrigerator system.

In this experimental research, it is assumed that there is no pressure drop in the heat exchanger (Evaporator and Condenser). The experiment was conducted at an ambient temperature of 30°C. It was also assumed that the kinetic and potential energy are negligible. The experimental condition is considered at steady-state operations.

Equation (1) represents the exergy balance for a control volume in a steady state process.

$$\begin{aligned}\dot{E}x_{dest} &= \sum\dot{E}x_{in} - \sum\dot{E}x_{out} + \\ &+ \sum\left[Q\left(1-\frac{T_o}{T}\right)\right]_{in} - \sum\left[Q\left(1-\frac{T_o}{T}\right)\right]_{out} + \\ &+ \sum\dot{W}_{in} - \sum\dot{W}_{out}\end{aligned} \quad (1)$$

Stream exergy flows are the first two terms, heat transfer exergy flows are the next two, and work exergy flows are the last two, $\dot{E}x_{dest}$ is the exergy flow destruction.

Compressor, condenser, capillary tube, and evaporator comprise the domestic refrigerator, as shown in Fig. 2. The destruction rate contributing to each component's exergy is listed below in equations (2) to (7).

Compressor:

$$\dot{E}x_{dest.comp} = \dot{W}_{comp} + \dot{E}x_1 - \dot{E}x_2 \quad (2)$$

Condenser:

$$\dot{E}x_{dest.cond} = \dot{E}x_2 - , \quad (3)$$

Capillary tube:

$$\dot{E}x_{dest.cap} = \dot{E}x_3 - \dot{E}x_4 \quad (4)$$

Evaporator:

$$Q_{evap} = \dot{m}(h_1 - h_4) \quad (5)$$

$$\dot{E}x_{dest.evap} = (\dot{E}x_4 - \dot{E}x_1) - \dot{E}x_{Qevap} \quad (6)$$

$$\dot{E}x_{dest.evap} = \left(\dot{E}x_4 - \dot{E}x_1\right) - \left[\left(Q\left(1-\frac{T_o}{T}\right)\right)\right] \quad (7)$$

In the equations, heat has a positive (+) sign when it flows within the system. Heat that escapes the system, on the other hand, has a negative (–) sign. Exergy destruction for each component can now be calculated, where $\dot{E}x_1, \dot{E}x_2, \dot{E}x_3, \dot{E}x_4$ represent the exergy destruction at the evaporator outlet, compressor outlet, condenser outlet and evaporator inlet respectively The sum of all exergy destruction ($\dot{E}x_{dest}$) is equal to the total exergy destruction ($\dot{E}x_{dest.Total}$) as expressed in equation (8).

$$\begin{aligned}\dot{E}x_{dest.Total} &= \dot{E}x_{dest.comp} + \dot{E}x_{dest.cond} + \\ &+ \dot{E}x_{dest.cap} + \dot{E}x_{dest.evap}\end{aligned} \quad (8)$$

Calculating the COP of a vapour compression refrigeration cycle involves dividing the heat gained in the evaporator by the work done by the compressor as expressed in equation (9):

$$COP = \frac{Q_{evap}}{\dot{W}_{comp}} \quad (9)$$

The ratio of a refrigerator's COP to the corresponding Carnot cycle is known as exergetic efficiency (η_{ex}) in equation (10):

$$\eta_{ex} = \frac{COP}{COP_{Carnot}} \quad (10)$$

3. Results and discussion

The performances of the refrigerator system in terms of pull downtime, COP, exergy destruction ($\dot{E}x_{dest}$) and exergy efficiency (η_{ex}) are described in TABLE 2 and Figs. 3-9.

The effects of TiO_2 nanoparticles suspended in the lubricant (TiO_2 nanomixture) with R290/R600 refrigerant on system components are shown in TABLE 2 and Figs. 3-9. As can be seen in Fig. 3 and TABLE 2, the pull down times are 150, 210, 180, 120, and 180 minutes for R134a, pure R290/R600, 0.2 g/L, 0.4 g/L, and 0.6 g/L of TiO_2 nanomixture, respectively, at an evaporator temperature of –15, –14, –16, –17 and –14°C. Due to an increase in the boiling-heat transfer and critical-heat flux, the evaporator's heat transfer rate increased using TiO_2/nano oil-mixtures [23,24]. The result agrees with the work of Nair et al. when R134a/ Al_2O_3/nano oil-mixture was tested against R134a in a VCRS [25].

TABLE 2

The evaporator pull-down time of the experiment

Time (min)	R134a Temp. (°C)	R290/R600 (Pure) Temp. (°C)	R290/R600 (0.2 g/L) Temp. (°C)	R290/R600 (0.4 g/L) Temp. (°C)	R290/R600 (0.6 g/L) Temp. (°C)
0	30	30	30	30	30
30	–5	–3	–5	–8	–1
60	–11	–9	–12	–15	–8
90	–13	–12	–14	–16	–11
120	–14	–12	–14	–17	–12
150	–15	–13	–15	–17	–13
180	–15	–13	–16	–17	–14
210	–15	–14	–16	–17	–14
240	–15	–14	–16	–17	–14
270	–15	–14	–16	–17	–14

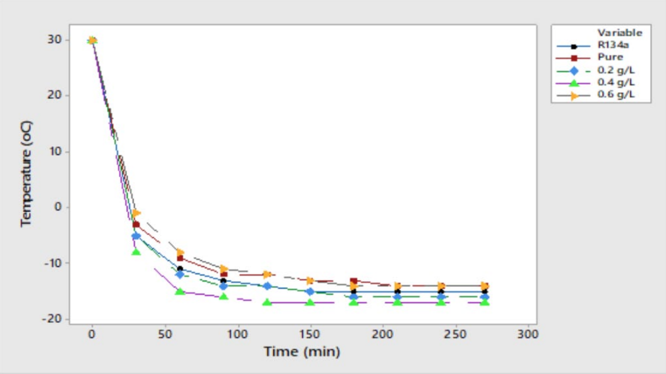

Fig. 3. Effect of the nanomixture on the pull down time of the system

Fig. 4 depicts the VCRS compressor's $\dot{E}x_{dest.comp}$. With a drop in evaporator temperature, the $\dot{E}x_{dest.comp}$ of the compressor decreases. The $\dot{E}x_{dest.comp}$ decreases as evaporator temperature decreases. The $\dot{E}x_{dest.comp}$ of R134a, pure R290/R600, and R290/R600 with 0.2 g/L, 0.4 g/L, and 0.6 g/L TiO_2 nanomixture are 0.0126, 0.0088, 0.0082, 0.0066, and 0.0120 kW, respectively, with R290/R600 in 0.4g/L TiO_2 nanomixture having the lowest $\dot{E}x_{dest.comp}$ of 47.6%. The improved performance in the use of TiO_2 nanomixture may be attributable to less friction and compressor wear [26]. As a result, the compressor needs to put in less effort to achieve the same result and the evaporator temperature is lower when using TiO_2 nanomixture than when using the R134a and R290/R600 in the based lubricant in the system. This is consistent with research by Kumar et al. [27], which discovered that using ZnO nanoparticles with LPG increased cooling capacity by increasing thermal conductivity.

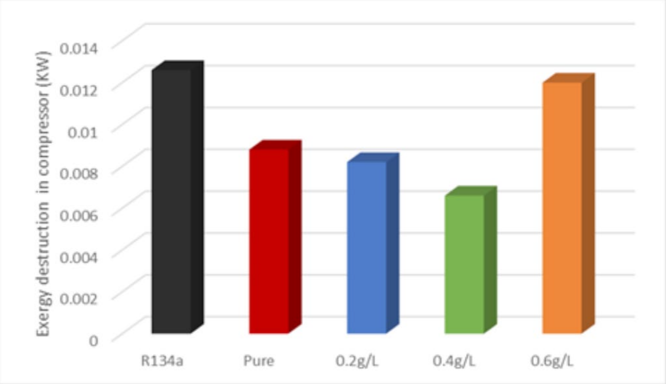

Fig. 4. Effect of the nanomixture on the exergy destruction of the compressor ($\dot{E}x_{dest.comp}$)

The $\dot{E}x_{dest.cond}$ in the VCRS condenser is shown in Fig. 5. Compared to R134a, the $\dot{E}x_{dest.cond}$ of TiO_2 nanoparticles suspended with R290/R600a in the condenser is reduced with a decrease in evaporator temperature. This is because the condenser consumes more exergy when the evaporator temperature drops due to a higher difference in temperature. R134a, pure R290/R600a, and concentrations of 0.2 g/L, 0.4 g/L, and 0.6 g/L of TiO_2 nanomixture all have $\dot{E}x_{dest.cond}$ values of 0.0068, 0.0060, 0.0034, 0.0039, and 0.0042, respectively (kW). With an $\dot{E}x_{dest.cond}$ of 0.0034 kW, or 42.6% less than R134a, the R290/R600 with 0.2g/L TiO_2 nanomixture exhibits the lowest $\dot{E}x_{dest.cond}$ in the system. Because the based lubricant consists of TiO_2 nanoparticles, the system's thermal conductivity increases [28,29], which improves the rate rejection rate to the surroundings. This correlates with the outcomes of Khairat et al. [30] who used $CuAlO_2$ nanofluid to increase the thermal conductivity of the turbulent convention within a pipe with a cavity.

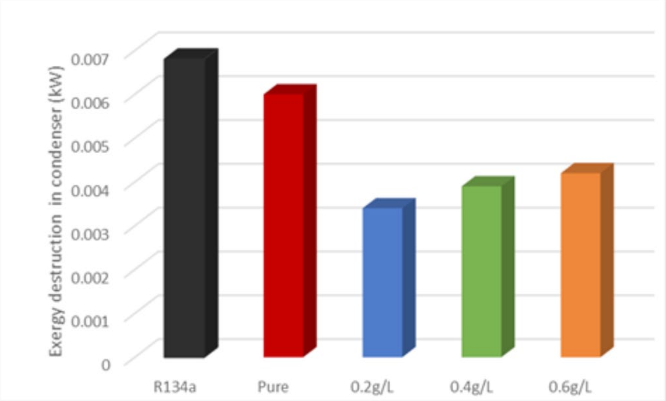

Fig. 5. Effect of the nanomixture on the exergy destruction of the condenser ($\dot{E}x_{dest.cond}$)

The exergy destruction in the $\dot{E}x_{dest.cap}$ is presented in Fig. 6. The $\dot{E}x_{dest.cap}$ for R134a in the system is higher than that of pure R290/R600 and R290/R600 in the TiO_2 nanomixture. The R290/R600 refrigerant in 0.2 g/L presents the lowest $\dot{E}x_{dest.cap}$ of 0.0026 kW in the system which is 49% and 3.7% lower than R134a-POE oil and pure R290/R600.

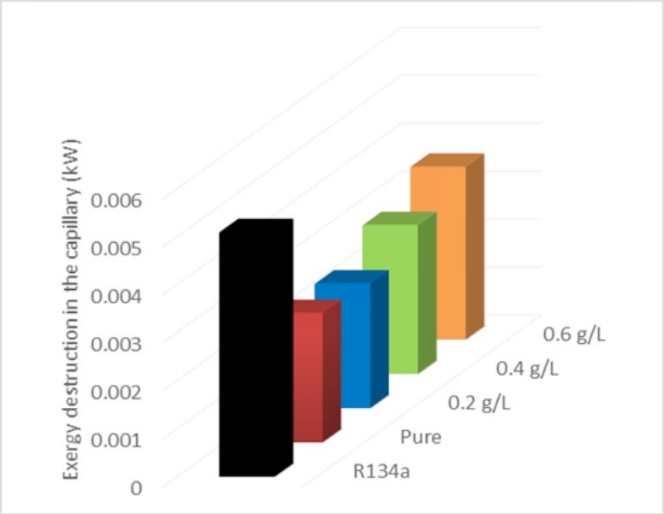

Fig. 6. Effect of the nanomixture on the exergy destruction of the capillary tube ($\dot{E}x_{dest.cap}$)

Fig. 7 shows the $\dot{E}x_{dest.evap}$ of the refrigerator system at the evaporator. It is shown that Fig. 7 that the R134a has the highest $\dot{E}x_{dest.evap}$ at the evaporator. Although, $\dot{E}x_{dest.evap}$ of R290/R600 in TiO_2 nanomixture is slightly higher than pure R290/R600. However, R290/R600 TiO_2 nanomixture still possess lower total exergy destruction compared to R134a and pure R290/R600 in the system. The total exergy destruction for R134a, pure R290/R600, and R290/R600 in 0.2 g/L, 0.4 g/L and 0.6g/L/TiO_2 nanomixture are 0.0026, 0.0019, 0.0016, 0.0015 and 0.0021 kW respectively. The R290/R600 in 0.4g/L TiO_2 nanomixture offers the lowest total exergy destruction ($\dot{E}x_{dest.Total}$) in the system which is 42.3% and 21.1% lower than R134a, pure R290/R600 respectively in the system as shown in Fig. 8. The result obtained conforms with the research of Mahmood et al. and Babarinde et al. [31,32] when compared the performance of R134a with R600a.

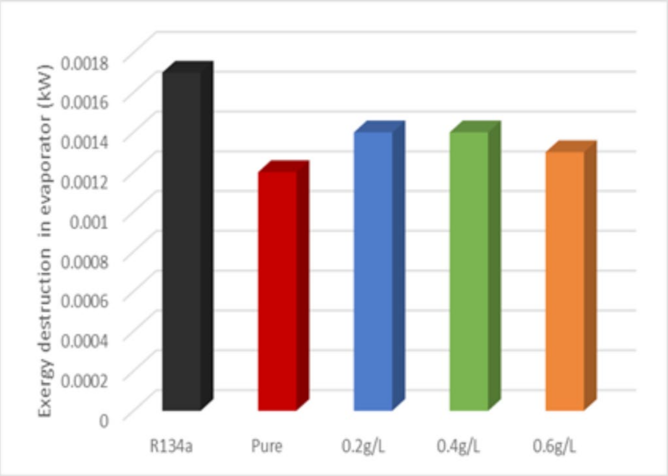

Fig. 7. Effect of the nanomixture on the exergy destruction of the evaporator ($\dot{E}x_{dest.evap}$)

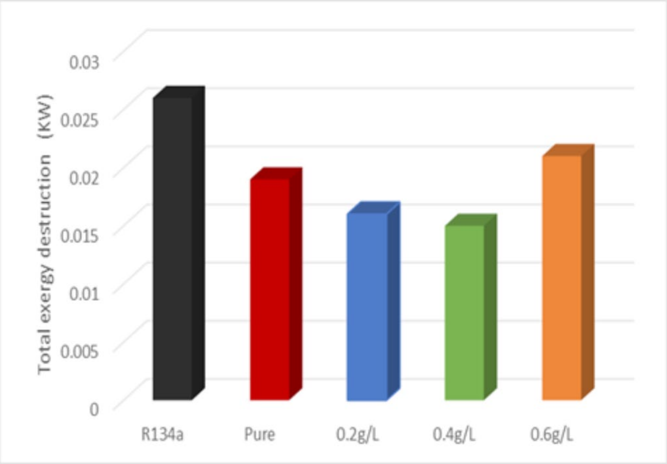

Fig. 8. Effect of the nanomixture on the total exergy destruction ($\dot{E}x_{dest.Total}$)

Fig. 9 shows the exergetic efficiency (η_{ex}) of the system. The R290/R600 TiO_2 nanomixture has the highest efficiency in the system. The exergy efficiency of 36, 46, 49, 50 and 45% were obtained for R134a, pure R290/R600, and R290/R600 in 0.2 g/L, 0.4 g/L and 0.6 g/L TiO_2 nanomixture respectively with R290/R600 in 0.4 g/L of TiO_2 nanomixture showing the highest efficiency in the system. Furthermore, reduction in the discharge pressure was experienced with use R290/R600 TiO_2 nanomixture in the system compared to R134a and pure R290/R600 in the mineral oil. This indicates a longer working life of the refrigerator compressor.

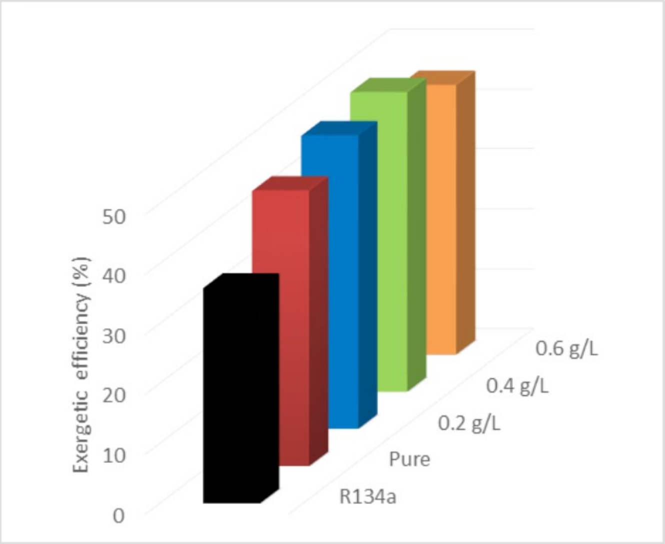

Fig. 9. Effect of the nanomixture on the exergetic efficiency (η_{ex}) of the system

TABLE 3 illustrates a summary of the experiment.

TABLE 3

Summary of the experiment

Refrigerants	Evaporator	Evaporator	Compressor	Condenser	Capillary	COP	Total	Exergetic
Nanomixture	Temperature	Exergy destruction	Exergy destruction	Exergy destruction	Exergy destruction		Exergy destruction	Efficiency
	°C	(kW)	(kW)	(kW)	(kW)		(kW)	(%)
R134a	–15	0.0017	0.0126	0.0068	0.0051	2.1	0.026	36
Pure	–14	0.0012	0.0088	0.006	0.0027	2.3	0.019	46
0.2g/ L	–16	0.0014	0.0082	0.0034	0.0026	2.4	0.016	49
0.4g L$^{/}$	–17	0.0014	0.0066	0.0039	0.0031	2.5	0.015	50
0.6g/ L	–14	0.0013	0.012	0.0042	0.0036	2.2	0.021	45

4. Conclusion

In a VCRS system, exergy analysis of Titanium dioxide (TiO_2) suspended with R290/R600 as a substitute for R134a was carried out. After a thorough experimental investigation of the experiment, the following conclusions were made:

- A lower pull downtime was achieved at the evaporator with R290/R600 TiO_2 nanomixture compare to R134a and pure R290/R600 in the system.
- The exergy destruction at the compressor accounts for the highest exergy destruction obtained in the refrigerator components throughout the experiment for both refrigerant tested in the system
- However, a decline in the total exergy destruction was experienced with the introduction of TiO_2 nanoparticles into the mineral oil with R290/R600 until the optimal concentration is achieved in the system.
- A decline in the exergy efficiency was obtained with R290/R600 in 0.6 g/L/TiO_2 TiO_2 nanomixture which indicates the optimal TiO_2 nanomixture is 0.4 g/L in the system. Therefore, R290/R600/TiO_2 nano oil mixture is potential replacement for R134a in a domestic refrigerator system.

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