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ORIGINAL ARTICLE

Effect of TiO_2/MO Nano-lubricant on Energy and Exergy Savings of an Air Conditioner using Blends of R22/R600a

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ABSTRACT – This experimental study determines the energetic and exergetic performances of an air conditioner using blend of R22/R600a (60:40 by mass) for different volume fractions (0.1%, 0.2%, 0.3%, and, 0.4%) of TiO_2 nanoparticles dispersed into mineral oil (MO). Energetic and exergetic parameters investigated in this experiment including power consumption, cooling effect, discharge pressure and temperature, coefficient of performance (COP), exergy destruction (irreversibility), irreversibility in the component, sustainability index (SI) and exergy efficiency at different operating conditions. The k-type thermocouples and pressure gauge were used to measure the temperature and pressure at different locations of the air conditioner. Thermodynamic characteristics of the refrigerant were collected using REFPROP 7. Results showed that the lowest power consumption and total exergy destruction were observed in the system with 0.4% volume fraction of TiO_2 nanoparticles charge in the TiO_2/MO lubricant with refrigerant blend; these values of energy consumption and total exergy destruction were 12.76 % and 7.5 % respectively, which is lower than R22/Polyol ester (POE) lubricant. The COP for the blend was increased by 6.5% to 8.3% compared to R22 and with nano-lubricant COP for the blend was increased by 17.9% to 19.9% compared to R22/POE. The air conditioner using blend charge with 0.4% TiO_2/MO lubricant has the maximum COP and exergy efficiency among the selected nano-lubricants. These values of COP and exergy efficiency were 19.9% and 35.07% respectively, greater than that of R22/POE. Again, compressor discharge temperature was found to be decreased with the introduction of nano-lubricants compared to the original system, and the expectancy of compressor life may be extended with TiO_2/MO nano-lubricant. Among the components, the compressor was found to be maximum exergy destroyer (at 60%), followed by the condenser (at 25.4%) and evaporator (at 13.3%). Overall, the study found that refrigerant blend with nano-lubricant minimised the energy consumption and exergy destruction and the system operated safely with nano-lubricant without any system modification.

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Coefficient of performance (COP); Nano lubricant; Exergy destruction; Exergy efficiency

INTRODUCTION

The R22 is commonly applied in many cooling and air-conditioning technologies. However, R22 is very detrimental to the environment as it is a member of the hydrochlorofluorocarbon (HCFC) coolant family that offered a large GWP (global warming potential) of 1790 than that of CO_2 and it has small ODP (ozone depletion potential) of 0.04 than that of R11. The looming danger associates with refrigerant in the HCFC family is inclined to phased out by 2030 in the developed countries and by 2040 in the developing country according to Montreal Protocol [1]. In September 2007, developed nations had shifted the calendar to 2020 and developing nations to 2030 that drives many scientists to work on searching a retrofit to R22. Any refrigerant that can be served as an alternative or retrofit to R22 should have similar or improved physical and chemical properties of R22 [2]. The effort was then directed to produce a refrigerant blend by mixing compounds without the deficiencies of the individual components, which showed improved thermal performance of the refrigerator. The alternatives of R-22 can be categorised into five families for air conditioning applications namely natural coolants [3], HCFC/HFC mixtures, HFC/hydrocarbon blends, hydrofluro-olefins (HFOs), and HFC/HFO blends [4-5].

Energy analysis used in the system considers only the quantity of the energy rather than the quality of the energy. Due to the irreversibility in the system and system environment, energy analysis is found to be insufficient. To overcome the insufficiency, the concept of exergy was an application of the second law of thermodynamics has become popular among the researchers. Exergy is regarded as the highest work potential of energy when the system is operated between ambient and system temperature [6]. It was a useful indicator of the quality of energy as it determines the location of exergy destruction, amount of exergy destruction (ED), and irreversibility in the process. The system with the highest and lowest exergy destroyed within a system and can be used to improve system performance, was also investigated [7]. However,

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energy analysis is not enough in the case of a vapour compression system as it involves continued thermodynamic phase change process, which eventually requires exergy analysis[8].

Numerous researches [9–12] have performed experimentally to investigate the alternative to R22 using energy and exergy analysis. The search for alternative refrigerant to R22 still is in a very early stage. However, a lot of research works have initiated to discover a suitable drop-in replacement to R-22. Stegou-Sagia and Paignigiannis [13] used R404A, R410A, R410B, and R507, to replace R-22 in a refrigerating unit. They reported that these refrigerants exergy behaviour was largely lower than R22. Apera et al. [14] investigated the exergy behaviour of R22, R407C, and R507 for a fluctuating speed compressor refrigerator. They found that R-22 shows better overall performance and that R407C is the alternate option. Li and Groll [15] executed an exergy investigation of a cascade refrigeration system using carbon dioxide/ammonia and showed that the highest temperature of the condenser was -15 ºC to minimise exergy loss. The influence of HC refrigerants on a vapour compression cooling system based on exergetic performance was analysed experimentally by Ahamed et al. [16]. They concluded that exergy destruction for butane and isobutene was lesser compared to R134a. Exergy efficiency was also greater for R600a and R134a related to R600 as coolants. The exergy destruction was higher in the compressor than in other components of the air conditioner, i.e. the compressor accounts for 69% of the total exergy loss. Razzaq et al. [17] studied in a review article to utilise hydrocarbon (HC) as an alternative refrigerant-based on a thermodynamic and environmental approach. The author summarised that HCs and their blends offer better thermal and environmental performance compared to R22 and R134a coolant. Arcaklioğlu et al. [18] studied thermal performance and elemental exergy loss of a refrigeration system employing R32, R125, R134a, R143a, R152a, R290, R600a and blends with R12, R22, and R502 (i.e. CFCs) standing on the SLTD. The authors concluded that R290, R600a, and their blends have higher thermal and second law performance compared to others. They also found that exergy loss was maximum in the condenser. Said and Ismail [19] measured the analytical performance of the refrigerants R123, R134a, R11, and R12. The author entrenched that a higher compression energy needed for R123 and R134a compared to R11 and R12 for a definite portion of the expected exergy. Aprea and Renno [20] reported the performance of a commercial refrigeration unit, utilising R22 and its suitable alternative (R417A) as operating coolants. The proclaimed result showed that the alternative coolant (R417A) might deliver as a long-term reinstatement for R22; it can be applied to advanced and current systems using traditional R22 lubricants. Kumar and Selladurai [21] studied an experimental exergy measurement of the HC and the blend of R290/R600a as a replacement of R134a. The author concluded that the COP for the blend enhanced by 28.5% compared to R134a. The maximum average second law efficiency of the process (42.1%) was found for HC mixture and they decided that the blend was persistently superior to the R134a. Bayrakci and Ozgu [22] conferred a comparative work for various pure HCs such as R290, R600, R600a, R1270 along with R22 and R134a with the analytical work. They summarised that the energetic and exergetic efficiencies reach to the optimum for R1270 at all working processes.

Teng et al. [23] undertaken laboratory research for an air conditioner operating with R290 at different mass fractions of 25-70%. They investigated the performance of the AC at different ambient temperatures. Their results found that at a different temperature, the maximum mass ratio is about 50-55%. Jabaraj et al. [24] assessed the thermal features of an air conditioner redesigned with R407C/R290/R600a refrigerant mixtures without altering the lubricant (mineral oil). In their experiment, the author found that COP and refrigerating effect for the new refrigerant blend increased by 12.57% and 11.15% respectively compared to R22. Oruç et al. [25] determined the energy and exergy performance of an air conditioner system running with R424A and R417A. The COP for R22 was found to be larger compared to R417A and R424A (17-23% and 4-18%). Devotta et al. [26] studied the effect of R290 in window air conditioner retrofitting R22. Their outcomes revealed, the COP of R22 was lower than that of R290 by 2.8-7.9%, and energy consumption for R290 reduced by 12.4-13.5%.

Nowadays, nanofluids have become an emerging technology in the arena of heat transfer, and it is the colloid of nanoparticles (1-100nm) and a base fluid. The commonly used base fluids are water, different organic liquids, lubricants, oils, different polymer solutions, and other familiar fluids. Nanofluids are used to improve the thermodynamic and hydraulic performance of the systems. Also, nanoparticles used in the base fluid tend to improve the thermo-physical properties (thermal conductivity, viscosity, etc.) of the base fluid significantly [27]. Commonly, it is acknowledged that due to the existence of solid particles, thermo-physical properties of the traditional coolant enhanced. The prominent thermo-physical properties that are greatly influenced by nanofluid is the thermal conductivity followed by viscosity and capacity of heat [28]. Nazari et al. [29] investigated the thermal performance of a heat pipe utilising graphene oxides nanoparticle to prepare the water-based nanofluid for four mass concentrations (0.25, 0.5, 1, and 1.5 g/l) of graphene oxides. The authors found that the thermal conductivity of water enhanced, while the thermal performance of the heat pipe decreased by 42% when graphene oxide is used. The thermal efficiency of the device decreased at the maximum graphene oxide concentration (of 1.5 g/l) due to the increase in friction forces and the increase in nanofluid viscosity. Experiments on thermal efficiency in a boiling pool of alumina and copper oxide nanofluids have been developed by Sarafraz et al. [29-30]. They showed that the heat transfer from the pool boiling process would deteriorate over a prolonged period, as nanoparticles would form a fouling layer on the surface, causing substantial thermal resistance. A novel cooling strategy for photovoltaic solar cell systems, which uses a broad microchannel heat sink operating with different nanofluids, was introduced by Radwan et al. [32]. It was found that compared with aqueous alumina and pure water, the aqueous SiC nanofluids were found to be able to increase the cooling thermal efficiency of the cells. It was also found that the system's thermal efficiency is highly dependent on the nanofluid volumetric concentration and Reynolds number.

In the vapour compression system, nanoparticles are used as additives into the refrigerant and lubricant, which is known as ‘nano refrigerant’ and ‘nano lubricant’ respectively. The application of nano lubricant in the compressor of the air-conditioner reduced the friction coefficient and wear rate, improved heat transfer characteristics, and enhanced the energy efficiency of the system [32–34]. In the study of Adelekan et al. [36], a varied concentration of TiO_2 nanoparticles was used to assess the performance of a domestic freezer using LPG as a lubricant. Their result found that COP and energy consumption improved for LPG. Bi et al. [37] experimentally measured the influence of TiO_2 (0.1, 0.3, and 0.5 g/L) nanolubricant in a domestic refrigerator using R600a refrigerant. They reported that R600a with nanolubricant worked safely and energy consumption for 0.5g/L TiO_2 –R600a refrigerant was lessened by 9.6% compared to pure R600a. A detailed review to determine the possibility of using nano refrigerant and nano lubricant in a vapour compression system was reported in [38-40]

Also, a few articles addressed the exergetic performance evaluation of AC which is an important attribute for an energy-efficient system design. Considering this purpose, in this work, the energetic and exergetic performance of a split type air conditioner containing TiO_2 nanoparticles/mineral oil lubricant mixture and blend of R22/R600a (60:40 by mass charged as refrigerant) was examined to extend the current frontier of knowledge and to minimise the research gap. An R22 split type air conditioner was modified to work with the refrigerant blend (R22/R600a). Four different volume fractions of TiO_2 nanoparticles (0.1-0.4 %) were added to the mineral oil to form the respective blend of TiO_2/MO nanolubricant. The selected volume fractions of TiO_2 were mixed to the lubricant using a two-step method to form the combination of nanolubricant, and the lubricant was then injected into the compressor of the experimental facility as nanolubricant replacing existing polyol ester oil (POE). The experimental investigation includes energy consumption, compressor work, discharge temperature, coefficient of performance (COP), exergy destruction, exergy destruction in the components, exergy efficiency, and sustainability index (SI); to determine the parametric performance. The parameters obtained using nanolubricant, and refrigerant blend were compared with the parameters obtained using R22 with POE under the same operating conditions. The experimental study was performed considering the importance of alternative refrigerant as well as environmental friendliness and low energy consumption.

Properties of the Selected Refrigerant

Originally, the air conditioner was engineered for refrigerant R22 that can be retrofitted by HCs and its blends. The most widely used and available HCs refrigerants are R600a and R290. The main concern of using HCs is the flammability of the refrigerant. The selection of refrigerant depends on certain parameters like vapour pressure, critical pressure and temperature, latent heat of vaporisation, boiling point, and molecular weight. Furthermore, consideration of the environmental footprints of the chosen refrigerant is crucial. According to the Air conditioning and Refrigeration Industry Board (ACRIB) of the UK, the hydrocarbon charge in a system is limited to 40-45% by total mass [41]. Physical and thermos-physical properties of the refrigerant are determined using REFPROP 7 package software, and the global warming potential (GWP) of the blend determined according to Eq. (1). The physical characteristics of the chosen refrigerant are shown in Table 1. The properties of the selected refrigerant were collected from REFPROP7 software. This software has been widely used in the researches as a reliable and accurate source of refrigerant properties. The table shows that the mixture offers a higher critical temperature compared to R22 and the molecular weight of the blend is 80% of the molecular weight of R22. The variation of saturation pressure and latent heat of vaporisation with saturation temperature for the selected refrigerant is demonstrated in Figure 1 and 2. The figure shows that the vapour pressure for the blend is very close to the vapour pressure of R22, whereas latent heat is much higher for the blend compared to R22.

$$GWP_X(TH) = \frac{\int_0^{TH} \Delta F_X dt}{\int_0^{TH} \Delta F dt} \tag{1}$$

Table 1. Physical properties of the selected refrigerant

Properties	Refrigerant	
	R22	R22/R600a (60:40)
Critical temperature (ºC)	96.145	115.53
Critical pressure (MPa)	4.99	4.86
Molar mass (kg/kmol)	86.468	72.35
GWP	1810	1087

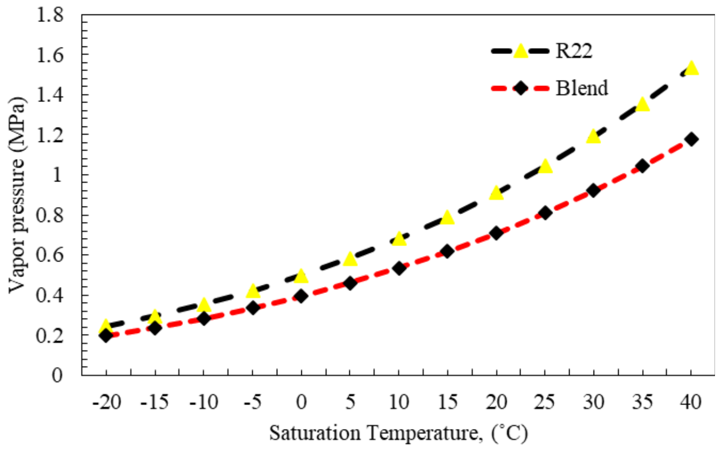


Figure 1. Comparison of vapour pressure with saturation temperature.

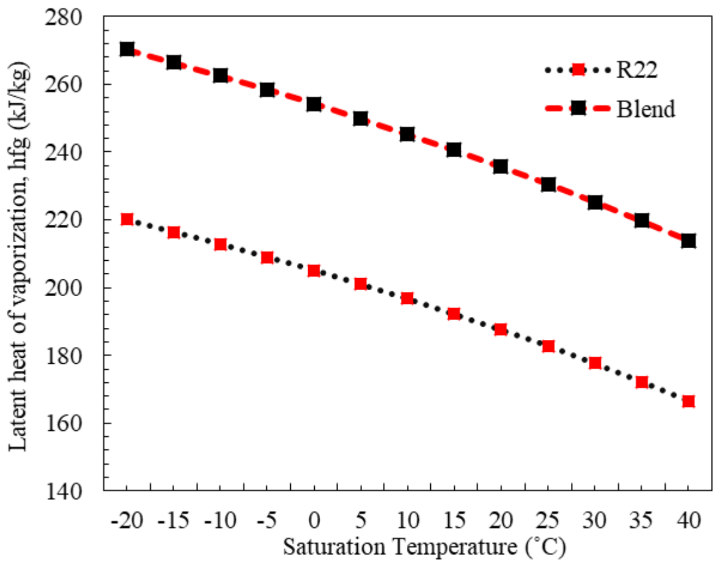


Figure 2. Comparison of latent heat of vapourisation with saturation temperature.

Nanolubricant Preparation

The compound used in the lubricant based on pure mineral oil wasTiO_2 in the shape of the nanoparticle. The average size of the nanoparticle was 25 nm and was supplied by Taj Scientific Ltd. Suniso 4GS mineral oil (MO) with a viscosity grade of 68 was selected as base lubricant oil based on its compatibility with hydrocarbon refrigerants. The characteristics of the lubricant oil are presented in Table 2. For TiO_2, four distinct concentrations were considered, namely 0.1-0.4 %, and the mass of nanoparticles was determined with a digital precision electronic balance of ±0.00001 gm resolution and distributed in the base fluid. Mineral oil and TiO_2 nanofluid samples of various TiO_2 volume fractions were prepared with the help of a magnetic stirrer (400 rpm), to achieve a good dispersion of the particles in the mineral oil (Gil et. [2]).

Table 2. Characteristics of lubricant oil [44].

S/N	Characteristics	Units
01	Lubricant type	Suniso 4GS
02	Viscosity Grade	68
03	Flashpoint, ASTM D92	179 ˚C
04	Pour Point, ASTM D 97	-36 ˚C
05	Viscosity, ASTM D 445 at 40 ˚C	55 cSt
06	Viscosity, ASTM D 445 at 100 ˚C	5.9 cSt

The blend was sonicated for 72 hours for complete dispersion of TiO_2 in the mineral oil. To confirm the perfect dispersion of TiO_2 and stability of the nanolubricant, the sonication process was carried on. For the stabilisation of the lubricant, a conventional surfactant was added to the lubricant so that the agglomeration does not appear. The stability test of the nanolubricant was performed using a time settlement experiment [42] and the nanolubricant was stable without any settlement for two months after preparation. The prepared samples were injected in the compressor through the compressor service port replacing POE.

Viscosity Measurement

The viscosity of mineral oil is indirectly related to the load-carrying capacity and the compressor power consumption rate used in the refrigeration unit. Adding foreign substances to mineral oil affects the viscosity of the mineral oil. Lee et al. [43] indicate that the incorporation of nanoparticles improved mineral oil viscosity and was proportional to the volume fraction of the nanoparticles. In this experiment, the pure mineral oil and modified mineral oil kinematic viscosity properties were measured using a Saybolt Universal viscometer. Figure 3 shows the effect of nanoparticles on the mineral oil kinematic viscosity (lubrication) as a function of temperature. The temperature dependence is as anticipated, and the viscosity of the nanolubricant is higher than the pure oil, as is clear from the figure. The findings also show that the rise in viscosity due to the introduction of nanoparticles in the low-temperature region is more noticeable. The viscosity of the nanolubricant increases with the increase of volume concentration of nanoparticles in the mineral oil. Viscosity was found to be 77.7% higher for 0.4% TiO_2/MO at 40 ºC compared to R22/POE.

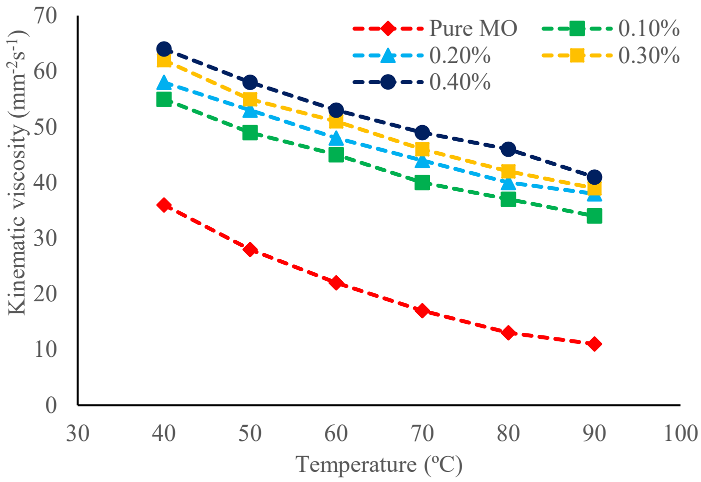
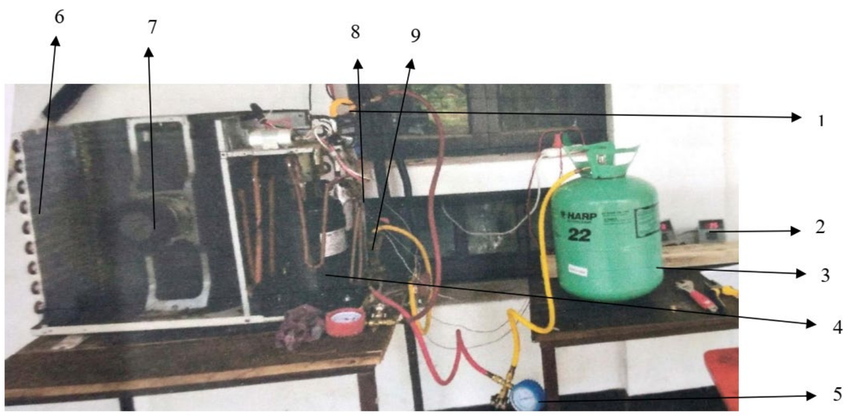


Figure 3. Effect of nanoparticles on the kinematic viscosity of mineral oil with temperature.

Experimental Facility

A split type wall mounted air-conditioner of General AOG12ASMC type of 3.45 kW capacity was used for the experimental work. This experimental facility consists of a hermetically sealed rotary compressor, an air-cooled condenser, a capillary, and an evaporator. Figure 4 shows the outdoor and indoor unit of the experimental section. Figure 5 displays the schematic line diagram of the experimented test section. The specifications of the air conditioner are shown in Table 3.



1. kWh meter, 2. Temperature controller, 3. refrigerant cylinder, 4. compressor, 5. pressure gauge, 6. condenser coil, 7. condenser fan, 8. K type thermocouple, 9. expansion valve

(a)

(b)

Figure 4. Experimental test section: (a) outdoor unit and (b) indoor unit.

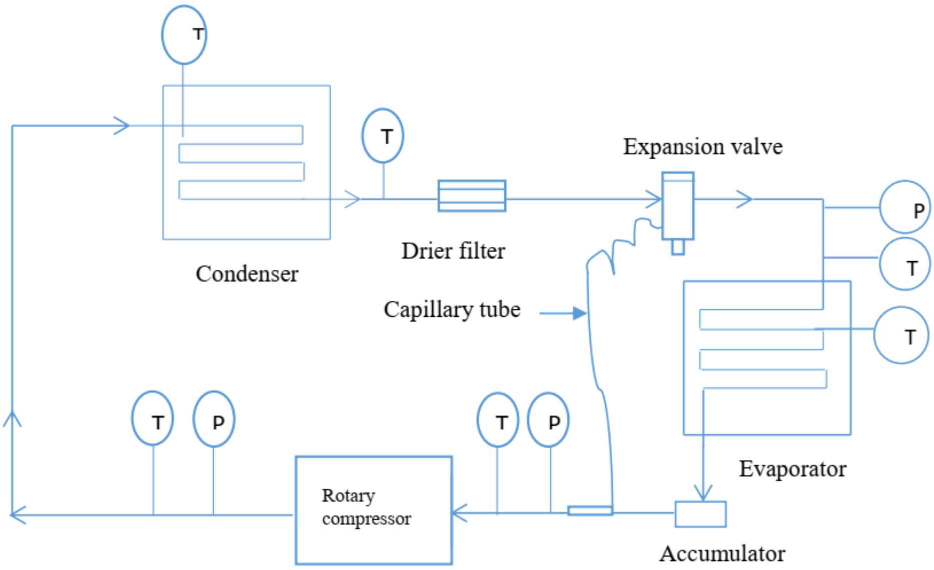


Figure 5. Experimental line diagram.

Table 3. Specifications of air conditioner.

Specifications	Value
Model	AOG12ASMC
Capacity	3.40-3.45 KW (11600-11800 BTU/hr.)
Type	Split type air conditioner
Power type	220-240V, 50Hz
High pressure (max)	390 psi
Low pressure (max)	115 psi
Refrigerant	R-22
Lubricant	POE
Charge amount (kg)	0.75 Kg
Current	6.10-6.20 amp

To evacuate the system, the test section was integrated with a vacuum pump and a charging manifold to charge and discharge the refrigerant from the system. At the suction and discharge side of the compressor, two pressure gauges (resolution 1 kPa) were employed to indicate the suction and discharge pressure. A single-phase kWh meter was equipped to evaluate air conditioners unit power consumption. A digital electronic balance (wih resolution of 1g) was utilised to estimate the amount of refrigerant charge to the system. Six calibrated k type thermocouples with temperature controllers were installed at separate air conditioner locations to measure temperature. A digital hygrometer was installed to monitor room temperature and moisture content. REFPROP 7 software was used to determine the specific enthalpy and entropy at different pressure and temperature.

In the beginning, the air conditioner was flushed by nitrogen gas to remove moisture content, refrigerant particles, metal impurities from the system. The vacuum pump was used to evacuate the refrigerant, and new refrigerants have been discharged through the inlet manifold at a pressure of 4.26 bar and current reading of 5.8 A. The temperature and pressure at different locations are stored at an interval of 15 min. To minimise experimental uncertainty, the test was repeated five times, and the average data is considered. All of the experimental data was collected at the steady-state condition and desired thermostat temperature. The system was charged with refrigerant blends, and nanolubricant and data were measured for every volume concentration of nanoparticles. The refrigerant used in this experiment was collected from the local market.

MATHEMATICAL FORMULATIONS

To determine the energy and exergy matrices like COP, cooling effect, compression work, exergy destruction, total irreversibility, and second law efficiency with the implementation of mass balance, energy balance, and exergy balance in different components are essential.

Energy Analysis

The energy analysis of an air conditioner includes energy consumption by the compressor, cooling capacity, coefficient of performance (COP), and energy efficiency ratio (EER). In the compressor, work of compression for per kg refrigerant flow:

$$w_{in} = (h_2 - h_1) \tag{2}$$

For unit kg of refrigerant flow, heat absorbed in the evaporator is known as the cooling effect or refrigerating capacity. The cooling effect can be written as:

$$q_e = (h_1 - h_4) \tag{3}$$

The effectiveness of the cooling system is governed by the COP and is determined by the ratio of cooling effect to the compression work.

$$COP = \frac{q_e}{w_{in}} \tag{4}$$

$$COP = \frac{h_1 - h_4}{h_2 - h_1} \tag{5}$$

Second Law Analysis

The second law analysis includes the irreversibility in the individual components, total exergy destruction, exergy efficiency, efficiency defects, and sustainability index. For exergy analysis, the following mathematical formula can be considered. At any given state, specific exergy is:

$$\psi_i = (h_i - h_0) - T_0 (s_i - s_0) \tag{6}$$

Exergy balance for evaporator can be written as:

$$I_{des,eva} = (h_4 - h_1) - T_0(s_4 - s_1) + \left(1 - \frac{T_0}{T_{eva}}\right) q_e \tag{7}$$

Exergy destroyed in the compressor:

$$I_{des,\ comp} = [(h_1 - h_2) - T_0 (s_1 - s_2)] + w_{in} \tag{8}$$

Exergy destroyed in the condenser:

$$I_{des,\ cond} = (h_2 - h_3) - T_0 (s_2 - s_3) - q_c \left(1 - \frac{T_0}{T_{cond}}\right) \tag{9}$$

Exergy balance for expansion device:

$$I_{des,\ exp} = T_0(s_4 - s_3) \tag{10}$$

Total exergy loss:

$$I_{total} = I_{des,\ eva} + I_{des,\ comp} + I_{des,\ cond} + I_{des,\ exp} \tag{11}$$

Exergetic efficiency:

$$\eta_{exergy} = \frac{\psi_1 - \psi_4}{W_{el}} = \frac{(h_1 - h_4) - T_0 (s_1 - s_4)}{w_n} \tag{12}$$

Exergy defects can also be determined for all of the components. Exergy defect is the ratio of exergy consumed in each element to the exergy needed.

$$Exd = \frac{\psi_i}{w_n} \tag{13}$$

Exergetic sustainability index:

$$SI = \frac{1}{1 - \eta_{exergy}} \tag{14}$$

Uncertainty Analysis

In this research, it is important to quantify the uncertainty associated with the outcomes from the primary measured value. This process of calculating the uncertainty in the result is known as 'propagation of uncertainty'. From the analysis of Moffat [45], total uncertainty, U comes from the primary uncertainties, P_1, P_2, P_3, P_4 ……. can be determined as follows:

$$W^2 = [(\frac{\delta R}{\delta P_1} w_{p1})^2 + (\frac{\delta R}{\delta P_2} w_{p2})^2 + (\frac{\delta R}{\delta P_3} w_{p3})^2 + \cdots + (\frac{\delta R}{\delta P_m} w_{pm})^2] \tag{15}$$

$$W_U = W^{1/2} \tag{16}$$

where, wp_1, wp_2, wp_3 ………………… are the primary uncertainties of the measured variable P_1, P_2, P_3, P_4 ……. The uncertainties in the primary measured value are shown in Table 4.

The total uncertainty in the primary measured data is given by the root sum square of the uncertainties of the bias error, B and precession error, P. The bias error is the average difference between the measured value and the actual value. The bias error was measured using standard calibration method for the instruments used in this experiment. The precision error is the standard deviation of the measured values.

$$U = \sqrt{B^2 + P^2} \tag{17}$$

Table 4: Uncertainties in primary measurement parameters.

Primary measured item	Bias error, B	Precision error, P	Total uncertainty (%)
Pressure, P	0.5	0	0.5
Temperature, T	0.5	0	0.5
Energy consumption	0.0035	0.01	0.0106
Enthalpy, h	0.0625	0	0.0625
Entropy, s	0.0625	0	0.0625

RESULTS AND DISCUSSION

Temperature and pressure data were collected from the experimental section, and thermophysical properties of R22 and a blended mixture of R22/R600a (60/40 by mass) were determined using REFPROP 7.0 package software. The energetic and exergetic parameters using different volume fractions of TiO_2 nanoparticles with MO lubricant was determined using Eq. (2) to (13) and compared with R22/POE system.

Discharge Temperature

The variation of compressor delivery temperature with the evaporating temperature is reported in Figure 6. The compressor delivery temperature for the blend was lower than that of R22 at every evaporating temperature. The discharge temperature was decreased with the increase of the evaporating temperature. As the compressor discharge temperature decreases in this study, it can be concluded that the life expectancy of the compressor can be enhanced with the application of nanolubricant as well as refrigerant blend. For reduced discharge temperature, the compressor was required to consume less amount of energy.

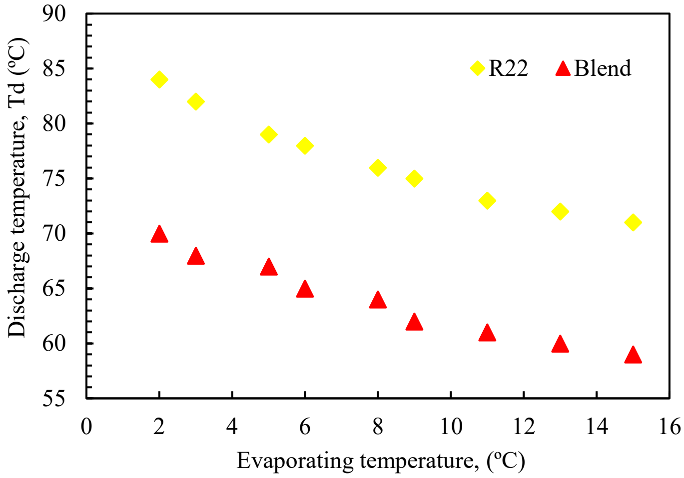


Figure 6. Variation in compressor discharge temperature.

Coefficient of Performance (COP)

The relationship of COP and evaporator temperature for R22 and its blend is described in Figure 7 at an atmospheric temperature of 27 ºC. The outcomes show that COP for the blend is always higher compared to R22 at every evaporator temperature due to the increased latent heat. COP was increased by 6.5-8.3% for the blend compared to R22. The influence of ambient temperature on COP is shown in Figure 8. The COP decreased with the increment of the local temperature. As the local temperature rises, the gap between local and system temperatures rise. For higher temperatures, the degradation of energy increases as the destruction of exergy increases. Hence, the general air conditioner performance reduces. The effect of nanolubricant on COP is shown in Figure 9. COP was found to be maximum for 0.4% TiO_2/MO lubricant. COP was found to be increased by 17.9-19.9% for nano-lubricant compared to R22/POE and 8.7-9.9% compared to the pure blend. COP with nanolubricant was higher as the compressor energy consumption with nanolubricant was lower. Bi et al. [37], Krishna Sabareesh et al. [44] showed the improvement in COP using TiO_2/MO lubricant for various systems.

Energy Consumption

The experiment was conducted for 8 hours in a day from 9.00 a.m. to 5.00 p.m. The daily energy consumption for this experiment is shown in Table 5 in kWh. The result shows that energy consumption was declined with the increase of volume fractions of the nanoparticle. Compressor running time also was reduced while using nano-lubricant. Gill et al [2] showed that TiO_2/MO lubricant minimised the compressor work as well as energy consumption. Energy consumption was reduced by 12.76% for a blend with 0.4% TiO_2/MO lubricant than that of R22 and POE lubricant.

Figure 10 represents the work of compression for the selected refrigerant and lubricants. The figure shows that compression work was maximum for R22 and work of compression reduced with the increment of volume fraction of the nanoparticles. As the discharge temperature of the compressor was reduced due to the application of nanoparticles, and the compressor required less energy to operate.

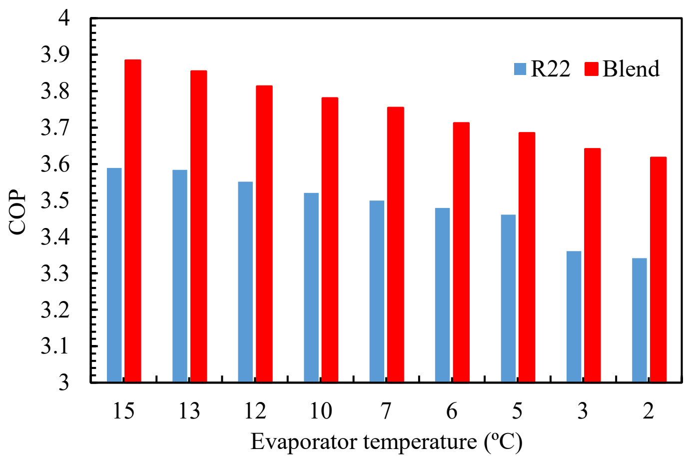


Figure 7. Variation of COP with an evaporator temperature.

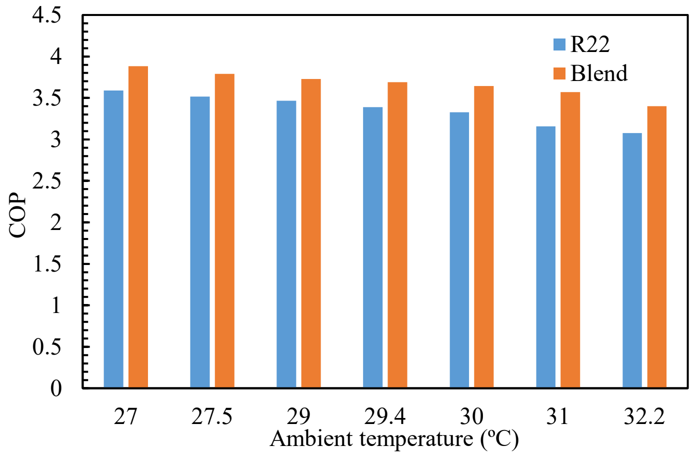


Figure 8. Effect of ambient temperature on COP.

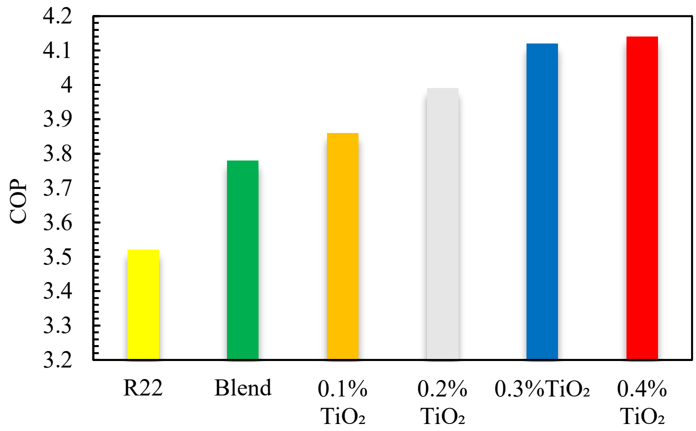


Figure 9. Comparison of COP for selected nanolubricant.

Table 5. Comparison of energy consumption.

Refrigerant	Lubricant	Energy consumption (kWh)	Energy savings (%)
R22	MO	5.633	----
Blend	MO	5.208	7.55
Blend	0.1%TiO_2 + MO	5.083	9.76
Blend	0.2%TiO_2 + MO	5.001	11.22
Blend	0.3%TiO_2 + MO	4.928	12.52
Blend	0.4%TiO_2 + MO	4.914	12.76

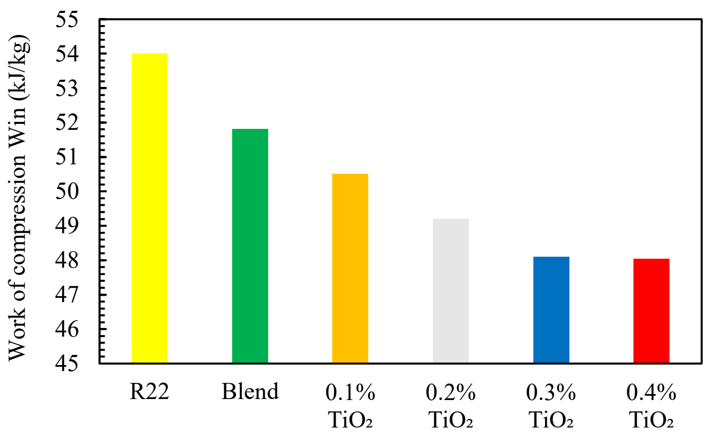


Figure 10. Variation of work of compression.

Refrigerating Effect

Figure 11 depicts the variation of the refrigerating effect of R22, blend, and nano lubricants. The refrigerating effect shows a great difference while using the blend instead of R22 with pure mineral oil. The figure also indicates that nanolubricant offered a minor improvement in the refrigerating effect. It was observed that the blend had a higher latent heat of vapour compared to R22; hence a higher amount of heat was absorbed in the evaporator by the blend.

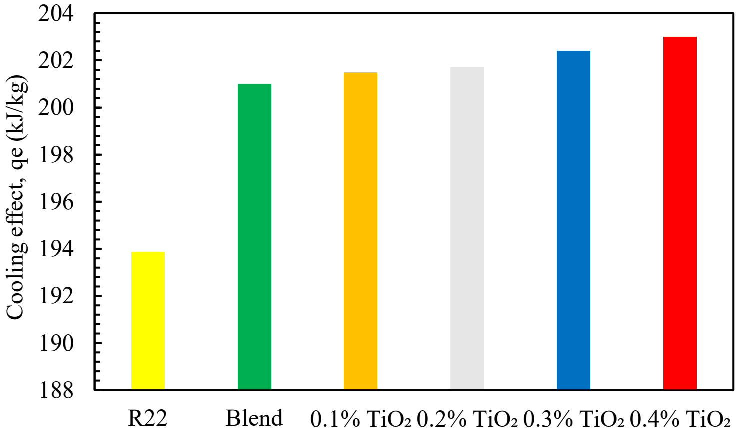


Figure 11. Variation of cooling capacity.

Exergetic Performance Analysis

Exergy assessments of a system involve total irreversibility, exergy efficiency, and component exergy destruction. Figure 12 shows the variation in exergy destruction of the air conditioner with evaporator temperature for R22 and blend. Exergy destruction was observed to decrease with the rise of evaporative temperature. The following illustration reveals that the blend was much more effective than R22 according to total irreversibility. Exergy destruction was reduced by 10-18 % for the blend compared to R22. The figure also clarifies that the irreversibility was lower for the selected nano-lubricants and further decreased with the increment of volume fraction of nanoparticles. Exergy destruction was reduced by 7.5 % to 8.4 % for the blend with 0.4% TiO_2/MO compared with R22. The irreversibility of the system reduced with the addition of nanoparticles in the lubricant was attributed by the compressor energy consumption. As the compressor energy consumption and discharge temperature were low for nano-lubricant, the system exergy destruction was observed to be minimum.

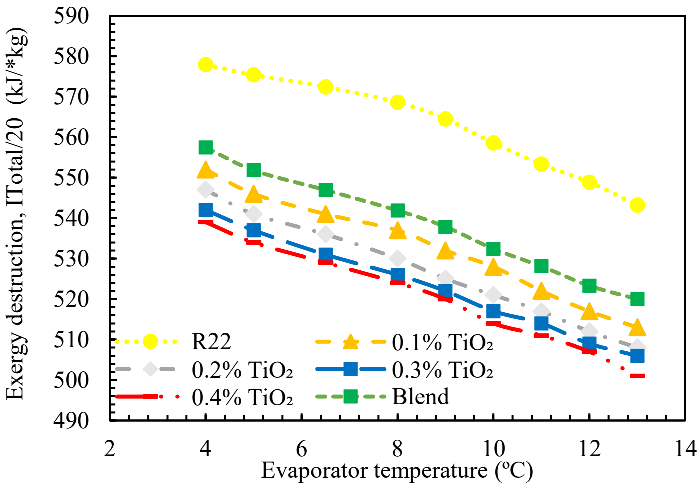


Figure 12. Exergy destruction.

The change of exergy efficiency with the evaporative temperature for R22 and the blend with nanolubricant is displayed in Figure 13. Exergy efficiency for refrigerant blends was always greater than R22 for each evaporative temperature. Exergy efficiency was improved by 9-11.2% for the blend than that of R22. With the addition of nano-lubricant, exergy destruction reduced for the air conditioner and improved energy efficiency and COP of the air conditioner; hence exergy efficiency also increased consequently.

Exergy destruction at different components (in percentage) is shown in Figure 14. The figure shows that maximum exergy was destroyed at the compressor (almost 60%) followed by the condenser (at 25.4 %). The compressor possesses a greater temperature relative to other system parts. The variance between the local and compressor temperature was higher, which eventually increases the irreversibility in the compressor. Figure 14 shows the Grasman diagram for exergy flow in a different component of the system.

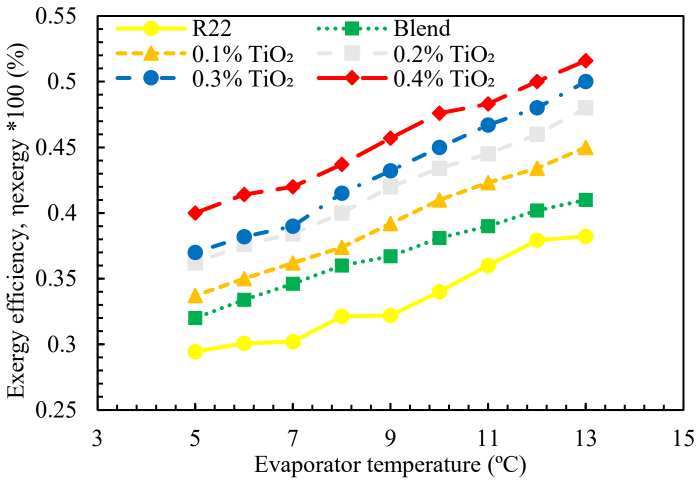


Figure 13. Variation of second law efficiency.

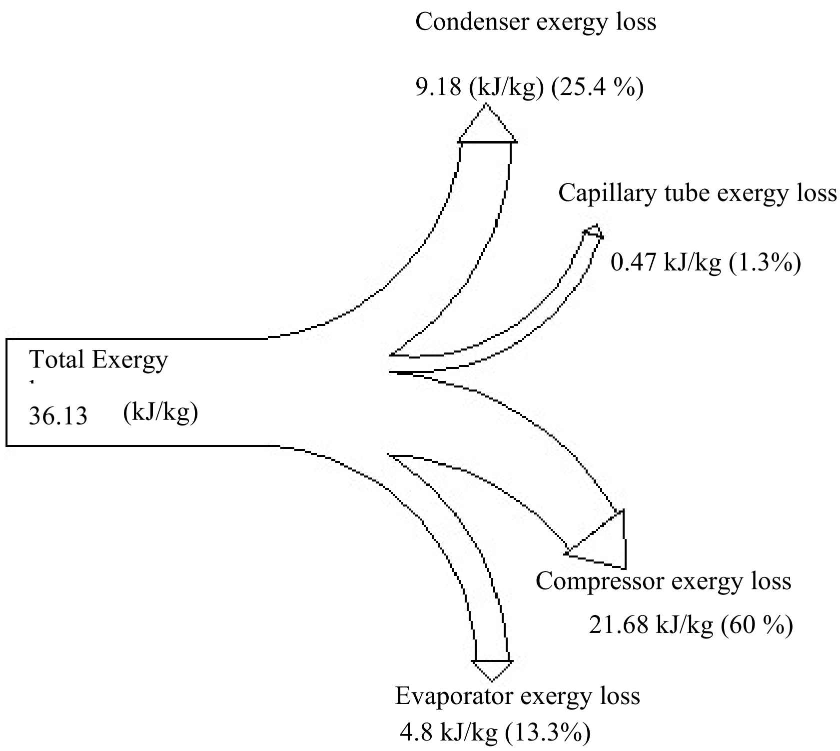


Figure 14: Grasmman diagram for exergy flow in the components.

The sustainability index (SI) of the system is different at different evaporator temperatures is shown in Figure 15. The figure illustrates that the sustainability index increased with the rise of evaporative temperature. The sustainability index was higher for refrigerant blend compared to pure R22 refrigerant. The sustainability index was also increased with the increase of nanoparticles volume concentration.

Uncertainty

Table 5 shows the uncertainty in the calculated value. The uncertainty was higher for total exergy destruction. Total exergy was the summation of the exergy destruction in individual components. The propagation of error in the calculation of total exergy destruction was high compared to other calculated parameters.

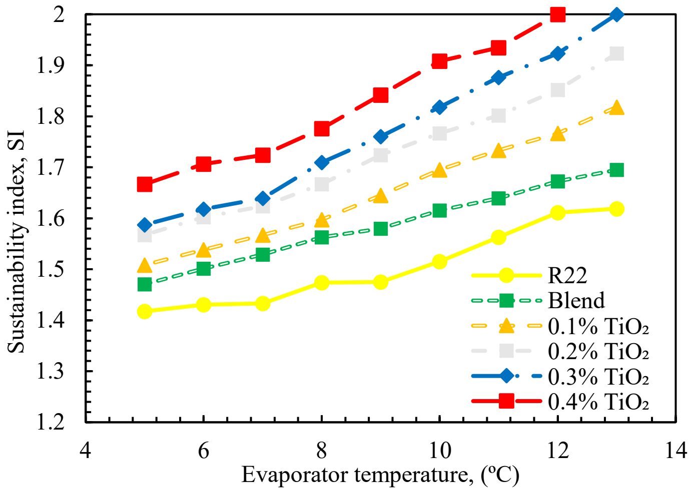


Figure 15. Variation of the sustainability index.

Table 5. Uncertainty in calculated values.

Quantity	Uncertainty (%)
R.E	0.175-0.19
W_c	1.10-1.11
C.O.P	2.5-2.64
I_{Total}	2.7-2.86
η_{exergy}	2.4-2.55

CONCLUSION

In this work, the first and second law of thermodynamics were combinedly used to report energetic and exergetic performance parameters of a split type residential air conditioner using R22/R600a (60:40) refrigerant to retrofit R22. The lubricant oil (POE) was replaced with TiO_2/MO nano-lubricant for four-volume fractions of TiO_2 nanoparticles. An improvement in the energetic and exergetic performance was observed with the addition of nanoparticles in the base lubricant. Based on the experimental findings and the above argument, the following conclusions are summarised:

i. The viscosity of the lubricant was found to be increased with the increase of volume fractions of nanoparticles in the mineral oil and viscosity was maximum for 0.4% TiO_2/MO lubricant (64 $mm^{-2}s^{-1}$).

ii. The compressor discharge temperature of the system using a blend with the selected nano-lubricants was smaller than that of R22/POE.

iii. COP increased by 6.5-8.3% for blend compared to R22 and COP increased with the increase of volume fraction of nanolubricant. An increase of about 19.9 % was recorded for 0.4% TiO_2/MO lubricant when compared with R22/POE.

iv. Energy consumption for the blend was lower compared to R22. Energy consumption was reduced by 7.55% for the blend compared to R22. Energy savings was maximum (12.76%) when 0.4% TiO_2/MO lubricant was used by replacing the original lubricant.

v. Exergetic performance analysis with the selected blend and nano-lubricants showed lower exergy destruction was recorded for the lubricant with nanoparticles compared with normal lubricant. Exergy destruction was found to be decreased with the increase in the volume fraction of TiO_2, and the lowest exergy was found for 0.4% TiO_2/MO lubricant that was 7.5% lower compared to R22/POE.

vi. Second law efficiency increased with the increase of evaporator temperature and the second law efficiency was maximum for the blend with 0.4% TiO_2/MO lubricant (51.6%).

vii. The maximum amount of exergy is destroyed at the compressor (60%) followed by the condenser (25.4%).

In this study, TiO_2/MO lubricant was found to be an excellent candidate for lubricant due to the positive effect on the performance of the air conditioner. Considering the environmental impact of R22 refrigerant, the proposed system can be an alternative to the existing system. More experimental work with nano-lubricant and hydrocarbon refrigerants should be conducted for energy-efficient and environmentally friendly air conditioner design.

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