

Performance of a domestic refrigerator using nanoparticles-based polyolester oil lubricant

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ABSTRACT

The performance of a domestic refrigerator with the addition of nanoparticles in the lubricant was experimentally investigated. Different sizes of nanoparticles of Al₂O₃ and TiO₂ were added to the polyolester (POE) oil in two different volume concentrations (0.05 and 0.1 vol.%). Energy consumption tests and freeze capacity tests were then performed on the refrigerator. The investigation results showed that the refrigerator worked normally and safely with the nanolubricants. The results of the experiments indicated that the refrigerator performed better with nanolubricants as compared to pure POE oil. The COP of the systems was increased by 19% and 22% when 0.05% and 0.1% Al₂O₃ nanoparticles were added to the POE oil respectively. The system with 0.1% volume concentration of Al₂O₃ and TiO₂ nanoparticles added to the POE oil consumed 27.73% and 14.19% less energy as compared to the pure POE oil system. Hence, this study showed that the addition of nanoparticles in the lubricant oil of the refrigerator is practical and it enhanced the performance of the refrigerator

Keywords: Nanoparticle; Coefficient of performance; Refrigerator; Nanolubricant.

INTRODUCTION

Modern civilization depends heavily on a huge amount of energy for its existence [1]. The primary source of this energy is fossil fuels. Fifty percent of the global energy is derived from coal alone. The use of coal creates environmental concerns of global warming and CO₂ emission [2-4]. The energy consumption by refrigeration and air conditioning systems for residential, commercial and industrial applications is increasing rapidly. In Malaysia, the energy consumed by refrigerators and air conditioners is estimated to be 26.3% of the total consumed [5]. Beside the global warming concern, another environmental concern faced by the refrigeration and air conditioning industry is the depletion of the ozone layer [6]. Ozone present in the stratospheric region absorbs ultraviolet rays from the sun and protects living things from exposure to ultraviolet radiation. Research has indicated that free chlorine radicals remove ozone from the atmosphere and that the ozone layer is therefore depleting.

A possible alternative solution to enhance the performance and improve the energy efficiency of a refrigerating system may come from nanotechnology. Nanofluids are defined as suspensions of nanometer size particles in a conventional base fluid [7-12].

The enhanced thermal conductivity of nanofluids has been a subject of intensive research for the past few decades [9, 13-18]. There are two different methods of applying nanofluids in a refrigerating system, namely nanorefrigerants and nanolubricants [19-21]. Bi et al. [22] performed an experiment on a domestic refrigerator. They used a nanolubricant made of mineral oil and TiO₂ nanoparticles in the compressor and R-134a was used as the refrigerant. Their investigation showed a reduction in energy consumption by 21.2% as compared to the original R-134a/POE oil system. Bi et al. [23] also investigated the performance of a domestic refrigerator which was originally using R-134a as refrigerant and polyolester oil as lubricant in the compressor. In the experiment, they substituted the POE oil with a mixture of TiO₂/Al₂O₃ nanoparticles added into the mineral oil [24-26]. The results showed that the energy consumption of the system with 0.1% mass concentration of TiO₂ nanolubricant was 26.1% less than the R-134a and POE oil system. Jwo et al. [27] replaced a R-134a/POE oil system with R12/MO and later added Al₂O₃ nanoparticles to the mineral oil (MO) to increase the lubricity and heat transfer performance. The results of the systems showed that the R12 system had a lower compression ratio as compared to the system with R-134a refrigerant. The system with 0.1 wt% Al₂O₃ added to mineral oil had 2.4% less power consumption and a 4.4% higher coefficient of performance as compared to the R-134a and POE oil system. Peng et al. [28] investigated the impact of nanoparticles on the heat transfer characteristics of a refrigerant-based nanofluid, CuO/R113, flowing inside a horizontal smooth tube. The experimental results showed that the heat transfer coefficient of the nanorefrigerant was greater than the pure refrigerant and the maximum enhancement was 29.7% for the coefficient of heat transfer. Henderson et al. [29] investigated the influence of SiO₂ and CuO nanoparticles on the flow boiling of R-134a and R-134a/polyolester mixtures. The direct dispersion of SiO₂ nanoparticles in R-134a resulted in a decrease of the heat transfer coefficient by as much as 55% compared to the pure R-134a. This degradation was partly due to the difficulties in obtaining a stable dispersion. But, on the other hand, excellent dispersion was achieved for a mixture of R-134a/polyolester with CuO nanoparticles and the heat transfer coefficient increased by more than 100% over the baseline R-134a/POE results. Bobbo et al. [30] investigated the tribology and solubility of R-134a in a mixture of commercial POE oil (SW32) with nanoparticles of TiO₂ and single-wall carbon nanohorns (SWCNH). They performed the tribological tests and measured the solubility of R-134a at various temperatures. The investigation revealed that a small addition of nanoparticles to the base lubricant does not affect the tribological properties of the base lubricant. The study showed that the POE/ TiO₂ mixture had the best performance compared with the pure POE and SWCNH/POE oil mixtures.

In refrigeration, air conditioning and heat pump systems, the boiling behaviour of the refrigerant and lubricant mixture is very important. The heat transfer characteristics of nucleate pool boiling of refrigerants are greatly affected by the lubricant. Generally, the addition of lubricants in the refrigerants degrades the pool boiling heat transfer. However, the amount of lubricant or oil in a refrigerating system is very small. Kedzierski [31] studied the pool boiling performance of Al₂O₃ nanoparticles with a mixture of R-134a/polyolester. Nanoparticles of Al₂O₃ in three different volume fractions were mixed with polyolester lubricant and the mixture was added to R-134a in two different mass fractions. The study showed that the pool boiling heat transfer of R-134a can be increased by approximately 13%, 10% and 9% for different mixture concentrations. Only one concentration of the mixture showed an average heat transfer degradation of approximately 14% and this was believed to be due to nanoparticle agglomeration.

The purpose of this article is to report the results obtained from experimental studies conducted on a domestic refrigerator. The experiments were conducted to show the ability of nanoparticles mixed in the POE oil to improve the power consumption of the compressor and enhance the heat transfer ability of the system. The coefficient of performance of the refrigerator with only POE oil as the lubricant in the compressor is also compared with the coefficient of performance of the system with two different nanoparticles added into the POE in different volume concentrations. In the present study, the refrigerant selected is R-134a and the nanoparticles are Al₂O₃ and TiO₂.

EXPERIMENTAL SETUP

Preparation of Nanolubricants

The nanoparticles added to the base fluid of POE oil were Al₂O₃, and TiO₂. The volume concentration (ϕ) of nanofluids can be estimated from Eq. (1) [32]. For a known volume concentration, and using the density from Table 1, Eq. (1) can be used to estimate the mass of nanoparticles. The required mass of the nanoparticles corresponding to the volume concentrations was measured accurately with the help of a precision electronic balance, as shown in Figure 1(a). The source and physical properties of the nanoparticles are given in Table 1.

$$\phi = \left(\frac{m_p}{\rho_p} \right) / \left(\frac{m_p}{\rho_p} + \frac{m_{bf}}{\rho_{bf}} \right) \times 100 \quad (1)$$

Table 1. Thermophysical properties of nanoparticles.

Nanoparticles	Size (nm)	Thermal conductivity (W/m K)	Density (kg/m ³)	Specific heat (J/kg K)
Al ₂ O ₃	40 to 80	36.0 [33]	3700	773
TiO ₂	25	8.4 [33]	3900	692
POE oil			840	

Source: Data from manufacturer [33]

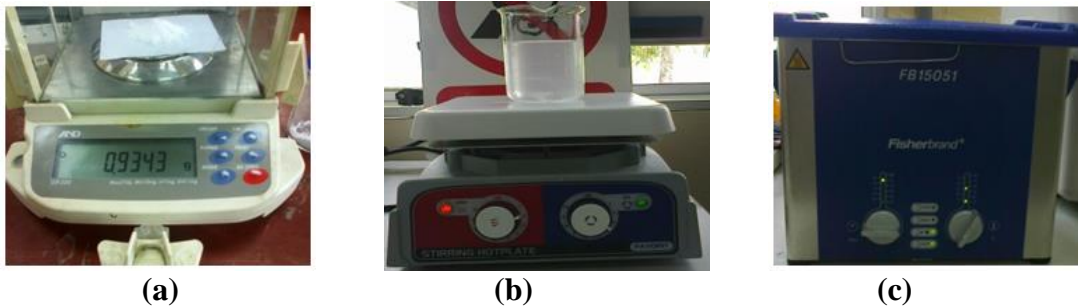


Figure 1. Equipment used in the experimental work: (a) Electronic balance, (b) stirring hotplate, (c) ultrasonic homogenizer.

The nanolubricants were prepared by a two-step method [34, 35]. The mass of nanoparticles for the 0.05% and 0.1% volume concentrations was added to the POE oil and the mixtures were stirred on a magnetic stirrer (Figure 1(b)) for two hours. The mixtures were then kept vibrating in an ultrasonic homogenizer (Figure 1(c)) for half an

hour to fully separate the nanoparticles and to prevent agglomeration and sedimentation of particles. No surfactant was added to the mixtures, as it can change the thermophysical properties of the nanolubricants. The nanolubricants were observed for sedimentation for 48 hours. Agglomeration or sedimentation did not occur and the nanolubricants were stable during the observations, which could be due to the low volume concentrations of the nanoparticles [36, 37].

System Evacuation

In order to remove incondensable substances such as air, water, moisture and inert gases from the refrigeration system, the evacuation process is used. A vacuum pump and a charging manifold is the most common equipment used for evacuation. A Robinair model 15601 vacuum pump and a three-hose charging manifold with low-side and high-side pressure gauges is used in this experiment to evacuate the system. The high-side pressure hose was kept closed all the time and the low-side hose was connected to the service port (Schrader valve) of the compressor, while the middle hose, which is also called the service hose, was attached to the vacuum pump as shown in Figure 2.

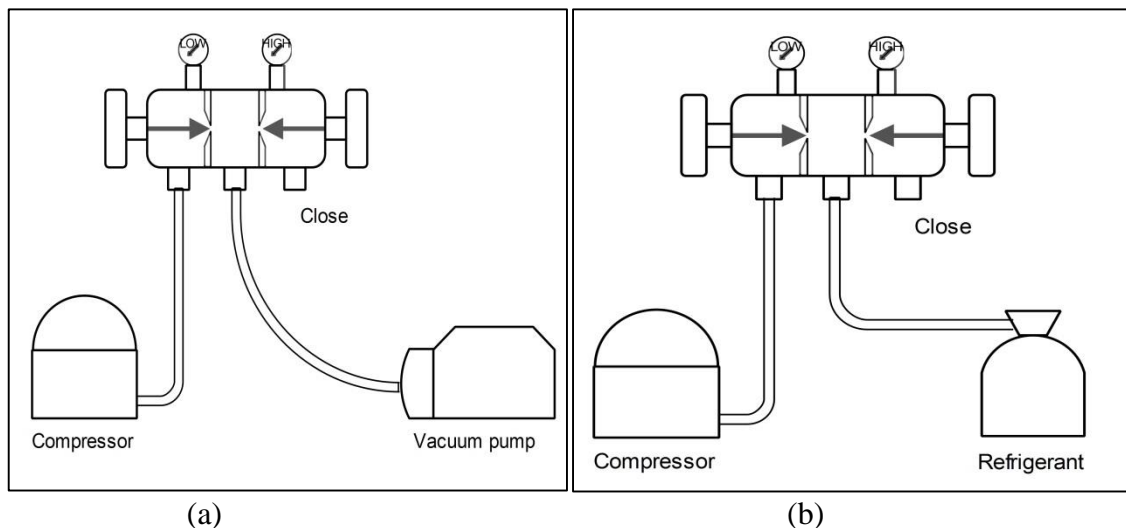


Figure 2. System evacuation and charging process.

System Charging

Table 2 shows the technical specification of the refrigerator which is used as part of the experimental rig. The refrigerator (Figure 3) can be fully charged with 120 g of refrigerant R-134a. The refrigerant can be charged into the system in either vapour or liquid form. There are different methods to accurately charge the system with the right amount of refrigerant. It can be charged by weight, by observing the sight glass and pressure and by monitoring the current load. There are also automatic digital charging systems available from different manufacturers that can charge the required amount accurately and automatically. Charging by weight is one of the most accurate and fastest methods of charging a known amount of refrigerant into the system. In this experiment, charging of refrigerant vapour is done with help of an electronic weighing machine, although observations through the pressure gauges and sight glass were also made.

Table 2. Specifications of the refrigerator (Panasonic, Model NR-BK265).

Description	Specifications
Gross capacity	234 L
Freezer compartment	75 L
Fresh food compartment	159 L
Outside dimensions (mm)	600x614x1449
Refrigerant type	HFC-134a
Charged mass	120 g
Compressor type	Recip. hermetically sealed
Compressor oil charge	195 ml
Power source	AC 240/50 Hz
Weight	43 kg



Figure 3. Refrigerator.

Experimental Apparatus

All the experiments were carried out in a room where the room temperature was 28 °C and the humidity level was above 70%. A domestic 234 litre capacity, double door, no-frost refrigerator was used. The refrigerator specifications are listed in Table 2. It was originally designed to work with R-134a refrigerant and POE oil as lubricant in the compressor. Twenty-four k-type thermocouples were used to measure the temperature of the air inside the refrigerator. The temperature of the refrigerant at suction and discharge of the compressor, and the temperature of the condenser were also recorded (Figure 4(a),(b)). The thermocouple readings were recorded by data loggers. Two pressure transducers were placed at the suction and discharge ports of the compressor with the respective data logger to record the pressure fluctuations. The power consumption of the compressor was measured by a clamp-on wattmeter (Power Analyzer, Lutron DW-6092) with 0.01 kWh resolution. Table 3 gives the detailed specifications of the test

instrumentation. An electronic balance was used to charge the exact amount of the refrigerant into the system.



Figure 4. Experimental rig: (a) freezer thermocouples, (b) refrigerator thermocouples, (c) instrumentation.

Table 3. Measurement equipment specification.

Variable	Device	Range	Accuracy
Temperature	K type thermocouples	-75 to 250 °C	$\pm(0.4\% + 1 \text{ }^\circ\text{C})$
	With 26-channel temperature recorder		
Pressure	Pressure sensor PS100-20 bar	0 to 20 bar	$\pm (0.5\% + 1d)$
	Pressure sensor PS100-5 bar with pressure meter	0 to 5 bar	
Power	3-phase power analyzer	0.000 to 9.999 kWh	$\pm (2\% + 0.008 \text{ kWh})$

Experimental Procedure

A first performance of the refrigerator was recorded with the R-134a as the refrigerant in the refrigerant circuit and POE oil as the lubricant in the compressor. The data for temperature, pressure and energy consumption were recorded twice, once for the freezer compartment and then for the refrigerator compartment. This result is used as the base data for comparison. Secondly, four different previously made nanolubricants of two different nanoparticles (Al_2O_3 , TiO_2) and two different volume concentrations (0.05% and 0.1%) were added one by one into the compressor. For each of the four samples of nanolubricant, the refrigerator was tested to investigate the effect of the nanoparticles properties on its performance. Every time, after charging of the refrigerant and lubricant, the refrigerator was allowed to stabilize for 30 minutes.

The refrigerator was placed on a 3x4 feet wooden frame with four wheels underneath it (Figure 4(c)). The compressor was pulled out from the refrigerator and fixed on the wooden frame. The refrigerant circuit was rebuilt with four T-connectors. Two T-connectors were used for the suction and discharge pressure sensors and two T-connectors were used for the suction and discharge side temperature of the refrigerant. The refrigerant and lubricant masses added during the performance tests were strictly measured and controlled. A Schrader valve was welded to the service port of the compressor to charge it with the lubricant and refrigerant. At the end of each test the compressor was disconnected from the refrigerant circuit and the lubricant was discharged through the

suction port and collected in a container. High-pressure gas was used to make sure that all the lubricant from the compressor was pushed out.

RESULTS AND DISCUSSION

Extensive experiments have been conducted on the refrigerator rig for its performance improvement. The results of the experiments are discussed below. Figure 5 shows the variation of cooling load temperature with time for pure POE oil and POE oil mixed with 0.05% and 0.1% nanoparticles of Al_2O_3 and TiO_2 . In both cases, the nanolubricant performance is better than the pure POE oil. It can be seen that the time required to reduce the cooling load temperature is the least with Al_2O_3 nanoparticles [23]. From Figure 5(b) it can be observed that the time required to reduce the cooling load temperature from -1°C to -6°C is 25 minutes for POE oil, while it takes only 10 minutes for the POE oil with 0.05% of Al_2O_3 and TiO_2 nanoparticles. In the case of a refrigerator, the lubricant used in the compressor is mixed with the refrigerant and travels through the refrigerating circuit. As compared to POE oil, which acts as an insulator in the refrigerant circuit and hinders the heat transfer, the high thermal conductivity of the nanolubricant facilitates more effective heat transfer, and therefore increases the speed of reducing the cooling load temperature [38].

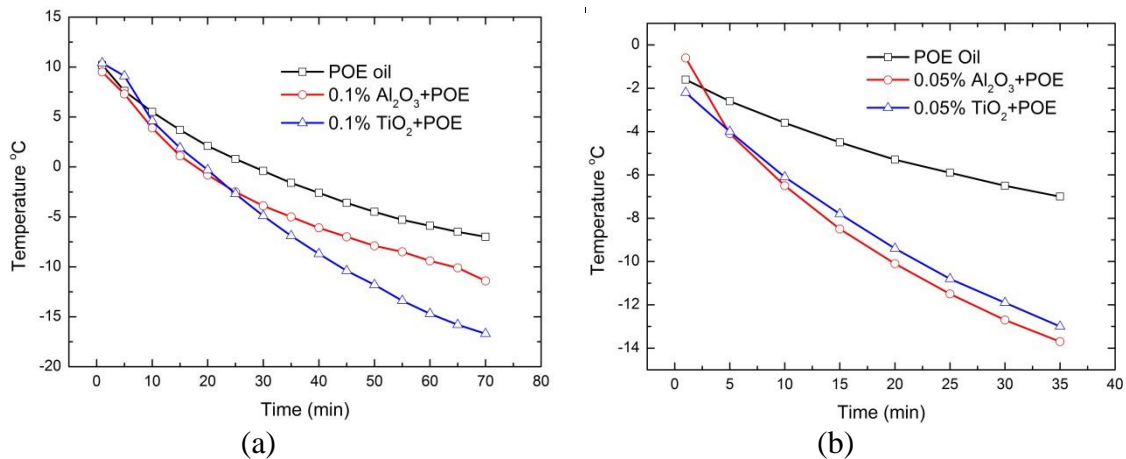


Figure 5. Temperature–time history for freezer compartment.

Freezing capacity is a standard test for refrigerators [39]. It is evaluated by the time taken to reduce the temperature in the freezer compartment from a positive temperature to a negative temperature under specified conditions. From Figure 6(a) it is evident that the freezing capacity of POE oil with 0.1% TiO_2 nanoparticles is higher than the other two systems. It takes about 35 minutes for the system with POE oil containing 0.1% TiO_2 to reduce the cooling load temperature from 10°C to -7°C , which is 50% less than the pure POE oil system. This enhancement in achieving faster cooling is due to the fact that the nanoparticles present in the refrigerant improve the heat transfer rate of the refrigerant in the evaporator. In Figure 6(b), the freezing capacity of 0.05% of Al_2O_3 is 60% less than the pure POE oil system. This improvement is due to the presence of nanoparticles in the refrigerating circuit [38]. The lubricating oil of the compressor travels with the refrigerant into the entire refrigerant circuit. The nanoparticles also reach the inside surface of the evaporator along with the oil. The presence of these nanoparticles

enhances the heat transfer of the evaporator [40] and therefore reduces the freezing capacity of the refrigerator.

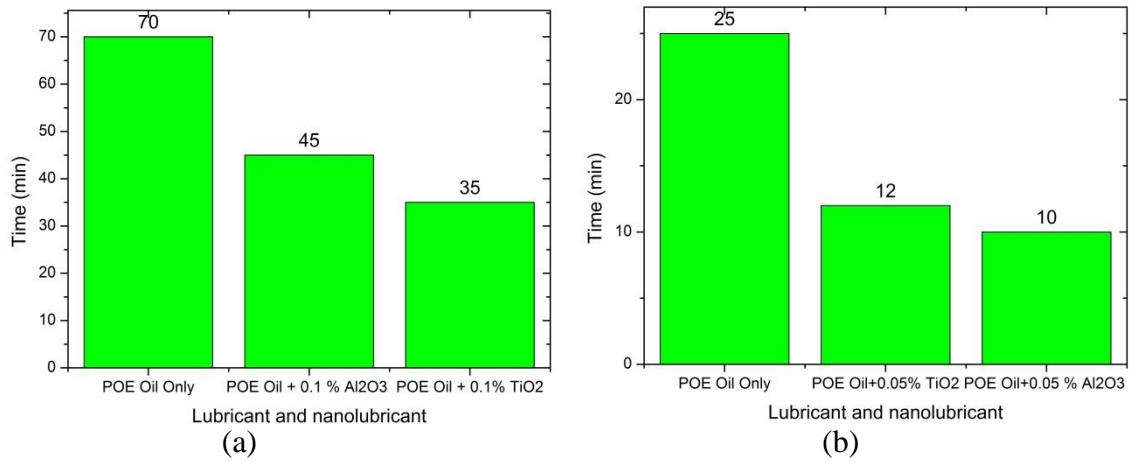


Figure 6. Nanoparticles influence on freezing capacity.

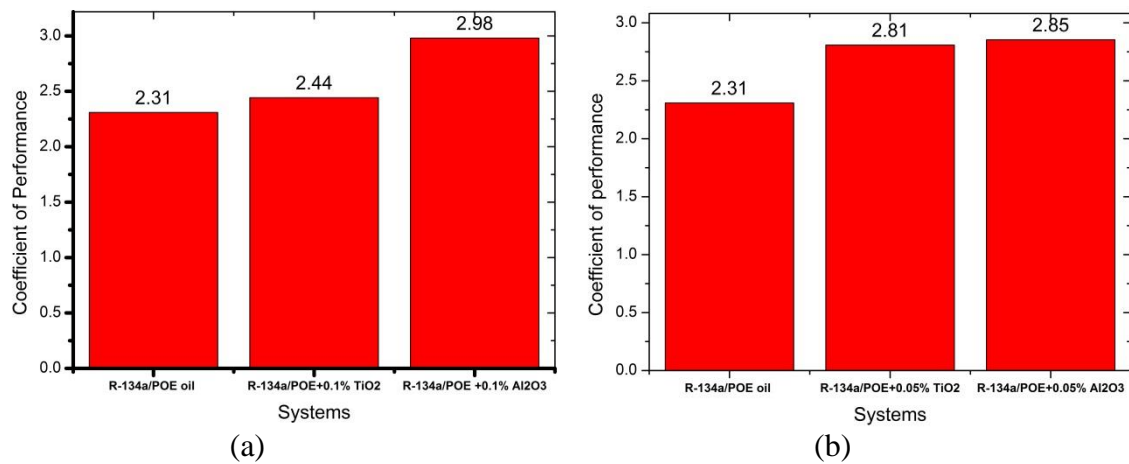


Figure 7. Comparison of coefficient of performance.

Figure 7 shows histograms for the COP of all the systems. The graphs show that all the systems with nanoparticles added to their lubricant had higher COP values. The system with the 0.05% Al₂O₃ added to the POE oil has a COP which is 19% higher than the POE oil systems. Similarly, 0.1% Al₂O₃ nanoparticles by volume when added to POE oil produce a COP which is 22% higher than the pure POE oil system. The increase in the coefficient of performance of the refrigerator with nanolubricant can be explained by considering the improved tribology and thermal conductivity caused by the nanoparticles in the lubricant oil. The investigation by [41] showed that the addition of fullerene C₆₀ nanoparticles in the mineral oil decreases the friction coefficients as compared to pure mineral oil. The friction coefficient of the lubricating oil is directly related to the power consumption of the compressor as the addition of nanoparticles decreases the friction coefficient of the lubricating oil, which results in a decrease of energy consumption by the compressor and therefore improves the COP of the refrigerator. The experiment conducted by [42] on the tribological properties of a lubricating oil with added nanoparticles showed that the nanoparticles first adsorbed on the wear scar surface, which

helped to form an amorphous film due to the shearing effect. This anti-wear film reduces the frictional power loss due to a reduction in the friction between the contact surfaces.

Increase in the thermal conductivity of the nanolubricant is one of the key reasons for the improved coefficient of performance of the refrigerator. Dispersion of nanoparticles in the lubricating oil increases the thermal conductivity of the lubricant. Although many theories have been put forward by researchers to explain the mechanism behind the increase in thermal conductivity [43], so far none can fully explain it. Brownian motion is considered to be one of the major mechanisms for enhanced thermal conductivity. The high interaction between the nanoparticles and base fluid molecules induces micro-convection. Smaller nanoparticles have a higher surface area, which increases the number of interactions and hence leads to the enhanced thermal conductivity of nanofluids.

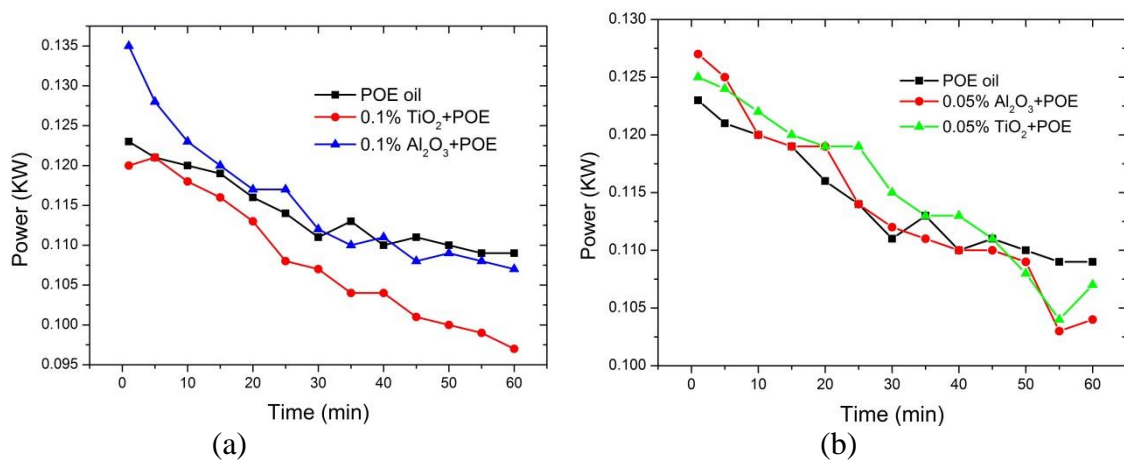


Figure 8. Power consumption of all systems.

Figure 8 shows the power consumption for all the systems. The effectiveness of the nanolubricants can be observed clearly from the power consumption of the compressor. The trend of the graph shows that the overall power consumption of the systems with nanoparticles mixed in the POE oil is better than the pure POE oil system. The decrease in compressor power consumption is due to the lower friction and better lubricity of the nanolubricants [42]. This is similar to the analysis by Bi et al. [44], who reported a 9.6% reduction in the power consumption for a refrigeration system using R-600a/mineral oil with TiO₂ nanoparticles as compared to an R-600a/POE oil system. The experimental results strongly suggest that the addition of nanoparticles in small quantities is an effective means to reduce the power consumption of the compressor.

Figure 9 shows the energy performance comparison for all systems. It can be clearly observed that the energy consumption is considerably lower when nanolubricants are used in the compressor. The reduction in energy consumption is 27.73% when 0.1% Al₂O₃ nanoparticles is mixed with POE oil and 14.19% when the same volume concentration of TiO₂ is used with POE oil. Bi et al. [23] reported that the energy of a refrigerator can be reduced by 26.1% when 0.1% TiO₂ nanoparticles are added into the mineral oil lubricant instead of the POE oil. The reduction in energy consumption is due to the tribological improvement caused by the addition of nanoparticles in the POE oil. Nanoparticles reduce the wear rate and coefficient of friction between moving surfaces, which is directly related to the energy consumption of the compressor. A comparison of the present work with that of other researchers is presented in Table 4.

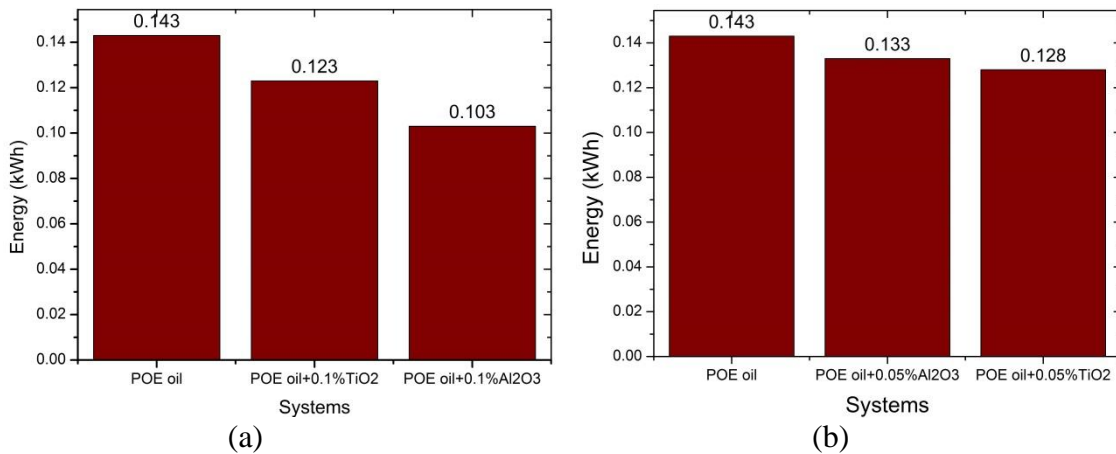


Figure 9. Energy performance of all systems.

Table 4. Comparison table for performance improvement of refrigeration systems.

Researcher	Refrigerant, lubricant and nanoparticles	Power (saving)	Energy (saving)	COP (improvement)	Freezing velocity (higher speed)
Bi et al. [22]	R-134a/POE/TiO ₂		7.43%		
Bi et al. [23]	R-134a/MO/TiO ₂		26%		
Jwo et al. [27]	R-12/MO/Al ₂ O ₃	2.4%			
Bi et al. [44]	R-600a/-/TiO ₂		5.94%		9.6%
Subramani and Prakash [45]	R-134a/POE/Al ₂ O ₃		25%		
Sabreesh et al. [36]	R-12/MO/TiO ₂			17%	
Kumar and Elansezhian [46]	R-134a/PAG/Al ₂ O ₃		10.32%	increased	
Present research	R-134a/POE/Al ₂ O ₃		27.73%	22.50%	increased
Present research	R-134a/POE/TiO ₂		14.19%	17.78%	increased

CONCLUSIONS

In this paper, the application of nanoparticles in a refrigerator has been investigated to take advantage of the anomalous increase in heat transfer caused by the suspension of nanosize particles in a fluid. A domestic refrigerator has been modified and used as a test rig to perform several tests to evaluate its performance with the nanolubricants. The temperature, pressure and energy data from the system consisting of R-134a as refrigerant and POE oil as lubricant in the compressor have been recorded as the base data. Four nanolubricants were prepared by adding 0.05% and 0.1% volume concentrations of nanoparticles of Al₂O₃ and TiO₂ into POE oil. The experimental data from the systems comprising refrigerant R-134a and POE oil with volume concentrations of nanoparticles added to it, are compared with the base data. The following conclusions can be drawn from the present study.

- i). Nanoparticles enhanced the heat transfer in the evaporator, which resulted in faster achievement of the cooling load.
- ii). The freezing capacity of the refrigerator is higher when nanolubricants are used in the compressor as compared to the POE oil system.
- iii). The power consumption of the compressor is reduced when nanolubricants are used instead of pure POE oil. As compared to the pure POE oil system, the energy consumption of the refrigerator reduces by 27.73% when 0.1% Al₂O₃ nanoparticles is mixed with the POE oil and a 14.19% reduction is achieved with TiO₂ nanolubricant.
- iv). The coefficient of performance of the refrigerator increases by 19% and 22% when two different Al₂O₃ nanolubricants are used respectively.

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