Energy Performance Evaluation of a Refrigeration System Under Synthesized Biodegradable Material Enhancement

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Abstract:
This study investigates the impact of optimizing refrigeration systems using an environmentally friendly refrigerant, isobutane (R600a), which has a low global warming potential (GWP) and zero ozone depletion potential (ODP), coupled with bio-nanofluid. The utilization of this natural refrigerant, combined with a bio-nanofluid developed from agricultural produce, introduces the innovative concept of this study and has the potential to enhance the global market. The incorporation of synthesized biodegradable waste significantly enhances the performance characteristics, including the coefficient of performance (COP), reduced compressor energy consumption, and improved refrigerating effect (RE). Bio-nanoparticles from mango peels (MP) and mango leaves (ML) were extracted using aluminium sulphate ($Al_2(SO_4)_3$) as the inorganic salt, and experimental examination was achieved with 0.1, 0.5, and 1.0% volume concentrations of the bio-nanofluid. The vapour compression refrigeration system (VCRS) performance was evaluated under an ambient temperature value of 26 °C. The results indicate that the system's performance operating with a 0.5% volume concentration of aluminium oxide (Al_2O_3) nanoparticles from MP improved significantly compared to the base fluid, with 62% COP enhancement and 17.6% reduction in energy consumption. The lowest evaporator temperature of -23 °C was attained in 120 min.

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1. INTRODUCTION

The refrigeration system is considered one of the major devices among household appliances. The VCRS is critical worldwide today due to its flexibility and multiple applications, such as grocery refrigeration for the refreshment and preservation of perishable items such as beverages, foods, evaporated milk, and vaccines in the medical sector [1, 2]. Every refrigeration system has four essential components, which include the compressor, condenser, evaporator, and expansion valve. Each component enables the refrigerant to transition from one phase to another, that is, from liquid to vapour, due to a change in specific temperature and pressure [3].

However, research shows that refrigeration systems that use 1,1,1,2-tetrafluoroethane (R134a) consume high energy; therefore, there is a need to substitute it with an energy-saving refrigerant, and R600a is considered a prominent replacement among hydrocarbon refrigerants in refrigeration systems [4, 5]. Meanwhile, R600a maintains the same level of efficiency as R134a and now serves as a drop-in replacement due to excellent thermodynamic properties, a high critical temperature that improves system performance, and miscibility with the base fluid (mineral oil), which enhances compressor efficiency. Moreover, it has zero ODP and negligible GWP, which prevents environmental depletion [6, 7].

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The use of R600a as a refrigerant subdues the fast-growing energy consumption rate in refrigeration systems. The main practical limitation of hydrocarbon refrigerants is their flammability, requiring restrictions on refrigerant charge and system design, typically to ≤150 g, as well as appropriate safety measures [8, 9]. Additionally, R600a has a relatively low operating pressure compared with other synthetic refrigerants, which reduces the stress imposed on operational compressors and other system components. Invariably produces lower compressor discharge temperatures, which decreases thermal degradation of lubricating oil and minimizes compressor wear [10]. These characteristics enhance compressor reliability and extend the service life.

The adoption of R600a has increased worldwide because it offers an effective balance between system performance and environmental sustainability. The application of additives in a refrigeration system seems more enabling compared to a base fluid substance [11].

Nanotechnology continues to have practical applications in refrigeration systems, as it tends to enhance the heat transfer properties of the nanolubricant. Chemical and physical methods were the two prominent approaches for synthesizing nanoparticles. However, the chemical method is used to produce metal nanoparticles, which require the use of non-eco-friendly chemicals [12, 13]. Hence, the biological approach for synthesizing nanoparticles using plant extracts was found to be a possible alternative to conventional chemical and physical approaches due to the availability of nanomaterials that allows for large-scale synthesis, environmental friendliness, and economic value [14]. The nanoparticle synthesized with plant extracts is preferred over other biological means such as enzymes and microorganisms. Although this has remained in the medical sector, it has started to gain a footprint in engineering, particularly in the refrigeration sector [15, 16].

The novelty of this study is the performance enhancement of the VCRS using two synthesized biodegradable materials derived from ML and MP. Subsequently, during experimental analysis, it was observed that the energy consumption of the VCRS was significantly reduced, thereby mitigating the indirect carbon dioxide (CO_2) emissions associated with power generated from the national grid, hence reducing the effect on climate change.

2. LITERATURE REVIEW

Nanotechnology offers promising approaches to enhance the thermodynamic performance of VCRS by improving heat transfer during the condensation (2–3) and evaporation (4–1) processes and influencing compressor work during compression (1–2), while the expansion process (3–4) reduces the refrigerant pressure and temperature, consequently increasing the RE and reducing the energy consumption by the compressor, as shown in the pressure-enthalpy (P-h) chart in Fig. 1 [17].

In recent times, researchers have conducted experimental investigations on refrigeration systems with nanolubricant additives prepared by physical and chemical methods, using various refrigerants based on their environmental properties, including safety group (SG), as shown in Table 1.

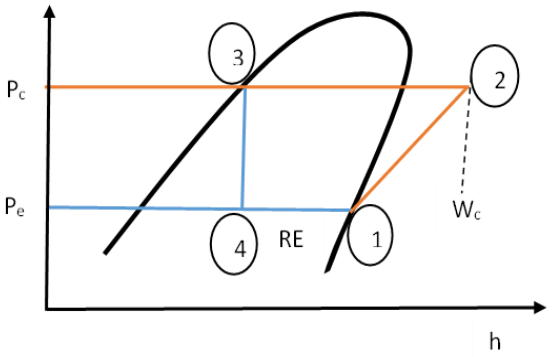

Fig. 1. P-h diagram of a VCRS

Table 1. Refrigerant characteristics [18]

Refrigerant type - Hydrocarbon refrigerants	Composition	GWP	ODP	SG
R290	C_3H_8	3	0	A3
R600a	C_4H_{10}	3	0	A3
R1270	C_3H_6	2	0	A3
R170	C_2H_6	6	0	A3
R600	C_4H_{10}	4	0	A3

In 2009, Jwo et al. [19] conducted an experimental investigation using an Al_2O_3-polyol ester (CO_2) oil-based nanofluid with hydrocarbon refrigerant as a replacement for R134a at various nanoparticle concentrations, and the results show a COP improvement of 2.4% and an energy reduction of 4.4%. Kumar and Elansezhian [20] performed an experiment comparing the base fluid with nanorefrigerant in a VCRS that operates with R134a and Al_2O_3-polyalkylene glycol (PAG) oil at a volume

fraction of 0.2%; the result indicates the system performed better when operating with nanofluid compared to the conventional fluid, with an energy reduction of 10.32%.

Yusof et al. [21] evaluated the performance of a VCRS with Al_2O_3 nanoparticles and R134a refrigerant. The system showed a 7% performance enhancement and a 2.1% power saving at a nanoparticle concentration of 0.2%. Bondre et al. [22] analyzed a comparison of the performance of a refrigeration system test rig using various nanoparticle concentrations that worked on pure POE oil and Al_2O_3/R134a. The COP was improved by 17.27% when 0.1% nanofluid was dispersed into the system. Soliman et al. [23] carried out an experiment on a VCRS using R134a as the refrigerant and 0.1% Al_2O_3-based nanoparticles. The COP increased by 10.5% and energy savings by 13.5%.

Bibin et al. [24] conducted an experiment on a refrigeration system with Al_2O_3, CuO, and TiO_2 nano-refrigerants. The research showed that for TiO_2 nanoparticle applications with R134a, the maximum COP improvement is 18.75%, while Al_2O_3/R134a provides a 27% energy reduction compared to conventional fluids. Senthilkumar et al. [25] investigated the performance of R-600a on a VCRS using CuO/Al_2O_3 as a hybrid nanolubricant. The results revealed that the hybrid nanoparticle additive increased the system COP by 27% with 24% energy reduction and enhanced cooling capacity by 20% compared to the base lubricant.

Nair et al. [26] experimentally investigated a VCRS using R134a/PAG and R134a/PAG/Al_2O_3 mixtures. The addition of 0.5 wt.% Al_2O_3 nanoparticles to the PAG oil increased the COP of the system by up to 6.5% compared with the R134a/PAG system.

The application of bionanofluid in a refrigeration system provides possible future visibility with the intention to enhance the system performance.

3. MATERIALS AND METHODS

Nanoparticles and subsequent nano-lubricant formulation were processed before system performance evaluation. Nanoparticles were synthesized from MP and ML, which are locally sourced due to their availability. The nanomaterials were obtained from a farm, and they were thoroughly washed with distilled water to prevent any interference from contaminants such as dirt and dust during the processing.

3.1 Nanoparticle Preparation Process

A biological approach is a green synthesis method used in preparing the nanoparticles, which requires grinding the organic nanomaterials into nanoparticles. The nanosized powder obtained is dispersed into the base fluid and mixed thoroughly to form a homogenized nanofluid [27, 28]. This biosynthesis method is comparatively simple and can be scaled up for large production for industrial purposes.

3.2 Operating Conditions for Synthesizing Nanoparticles

The rinsed organic nanomaterials were shade-dried for 30 days through a steady drying process, allowing them to retain the heat-sensitive nutrient and resulting in a higher-quality product compared to direct sunlight. After complete dryness, as shown in Fig. 2, they were milled into fine powder using a mechanical blender to increase surface area and enhance extraction and dispersion of the nanoparticle, as displayed in Fig. 3. Then, a 1 L of distilled water was evenly added to 20 g of each milled sample, MP and ML, and the mixtures were boiled for 1 h 30 min on the hot plate to extract phytochemicals from the plant, which enables it to act as a reducing agent that changes metal ions into nanoparticles, thereby making bionanoparticle synthesis biocompatible, as shown in Fig. 4 [29, 30]. The mixtures were sieved in order to separate the boiled nanomaterials from the aqueous solution.

Fig. 2. Dried nanomaterial

Subsequently, 250 mL of the $Al_2(SO_4)_3$ solution was poured into the extracts, and it was stirred at an interval of 1 h to allow proper reaction with the organic matter.

Fig. 3. Nanomaterial particulate

Fig. 4. Leave particulate and distilled water on the hot plate

The reaction mixture was poured into centrifuge tubes and inserted into the centrifuge machine, and the speed was set to 3500 rpm for 40 min to enhance the separation of nanoparticles from the supernatant faster, as shown in Fig. 5.

Fig. 5. Centrifuge machine

The nanoparticles were poured into ceramic crucibles and dried using a muffle furnace at 150°C for 12 h to remove moisture [31]. After calcination, the nanoparticles were kept inside a desiccator to make it airtight and cooled to room temperature to prevent atmospheric moisture, as shown in Figs. 6 and 7.

Fig. 6. Set of nanoparticles in the muffle furnace

Fig. 7. Nanoparticles in the desiccator

The biologically prepared nanoparticles were collected into centrifuge tubes, as represented in Fig. 8.

Fig. 8. Prepared bio-nanoparticles

3.3 Nanofluid Preparation

A two-step approach was adopted, which requires that the nanomaterials be first synthesized into nanoparticles through thermal decomposition of metal compounds. The nanosized powder obtained after production is dispersed into the base fluid and mixed thoroughly to form a nanofluid using a magnetic stirrer and ultrasonic agitation. In this study, a two-step approach was used to synthesize the nanoparticles [32, 33].

The prepared bio-nanofluid was dispersed in compressor oil at a volume of 220 mL, and the mixtures were agitated using an ultrasonic probe sonicator to achieve the desired homogeneous bionanolubricant and reduce agglomeration. In addition, the nanofluids were dispersed into the compressor oil at three different volume concentrations of 0.1%, 0.5%, and 1.0%. A measured volume of the base fluid corresponding to the required nanofluid volume concentration was extracted and replaced with an equal volume of nanofluid to maintain a constant total volume of the lubricating oil, as represented in Table 2. The mixed bionanolubricant was subjected to a stability test by monitoring the mixture for a period of 25 days, and it was discovered that the mixture was homogenized without any particle settlement [34]. Since the mixture was homogeneously mixed after the stability test was conducted, it was dispersed into the compressor successively through the suction port.

Table 2. Nano-lubricant Mixture Composition

Volume fraction (%)	Nanofluid (mL)	Base fluid (mL)	Total volume (mL)
0.1	0.22	219.78	220.00
0.5	1.10	218.90	220.00
1.0	2.20	217.80	220.00

3.4 Experimental Setup

The application of the bionaolubricant was utilized in a VCRS that was developed from locally sourced materials ML and MP. The prepared bionanolubricant was dispersed into the single hermetic reciprocating compressor, and after a while all components were fixed on a VCRS, as shown in Fig. 9. The mechanical devices were connected to the test rig, which included a pair of type-K data loggers (DL) with the model number UT325F, which have four channels each, and their probes were attached to the condenser, evaporator, expansion valve (capillary tube), and compressor to measure the refrigerant temperatures at various test points. A digital manifold pressure gauge (DMPG) with the model number DY523 was used to determine the suction and discharge pressures of the single hermetic compressor, and the wattmeter examined the power consumed by the compressor. The selection of these measuring devices with a maximum range is to mitigate risk and provide opportunity for future experimental application. The range and accuracy of the measuring devices were represented in Table 3.

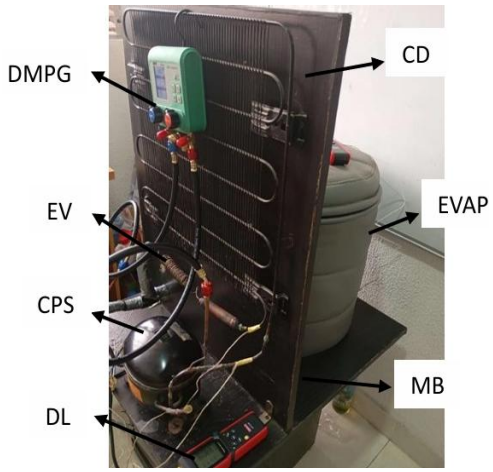

Fig. 9. Experimental test rig

Table 3. Specification of the measuring device

Measuring instrument	Range	Accuracy
Digital Thermocouple	-200 to 1372 °C	±(0.2%+0.5°C)
Manifold Pressure gauge	0 to 6000 kPa	±0.5% FS
Wattmeter	0-2900 W	±1%

A refrigerant can that contains 390 g of R600a was connected to the system using a pressure hose. A quantity of 30 g of R600a was charged into the system through the service port, and the required refrigerant charge was monitored by observing the display unit on the digital weighing balance. Immediately after the charge, the remaining refrigerant was weighed to ensure the actual 30 g were charged into the system.

Each of the experiments was set to operate for 5 h under a controlled environmental condition, and subsequently, each experiment was repeated three times, and the mean of the computed data was utilized to determine the performance metrics of the VCRS. However, after completing three series of tests for each lubricant, the system was allowed to cool to enable the mixture of refrigerant and lubricant to separate and return to their housing before vacuum pumping the refrigerant using a vacuum pumping machine.

3.4.1 Data Acquisition

The probes of the digital DL were fixed to the test rig, and the refrigerant temperatures at various points were measured as T1, T2, T3, T4, and T5. The Reference Fluid Thermodynamic and Transport

Properties (REFPROP), version 9.1, was used to determine the corresponding enthalpy values from the measured temperature and pressure data, as shown in Table 4.

Table 4. Enthalpy description and analysis

Temperature	Description	
T1	Evaporator outlet temperature	Enthalpy (h_1)
T2	Compressor outlet temperature	Enthalpy (h_2)
T3	Condenser outlet temperature	Enthalpy (h_3)
T4	Capillary tube outlet temperature	Enthalpy (h_4)
T5	Refrigerating chamber temperature	

3.5 Using an Equation in an Experiment

The VCRS was evaluated using the thermodynamic fluid equations 1 to 4 [35, 36].

The COP is the ratio of total heat content change in the evaporator to the work done by the compressor, Eq. 1:

$$COP = \frac{Q_e}{W_c} \quad (1)$$

where: Q_e is the total heat content change in the evaporator, W_c is the compressor work input.

The RE is the change in enthalpy of the evaporator inlet and outlet, Eq.2:

$$RE = he_1 - he_4 \quad (2)$$

where: he_1 is the outlet heat content of the evaporator, and he_4 is the inlet heat content of the evaporator.

Compressor work input (W_{comp}) is the product of the refrigerant mass flow rate (RMFR) and the change in total heat content of the compressor, Eq.3:

$$W_{comp} = \dot{m}(h_{2comp} - h_{1comp}) \quad (3)$$

where: h_{2comp} is the outlet heat content of the compressor, h_{1comp} is the inlet heat content of the compressor, and $\dot{m}$ is the RMFR.

The RMFR is the ratio of the total heat load in the evaporator to the total heat content of the evaporator, Eq.4:

$$\dot{m} = \frac{Q_e}{h_{1evap} - h_{4evap}} \quad (4)$$

where: Q_e is the total heat load in the evaporator, h_{1evap} is the heat content at the evaporator outlet, and h_{4evap} is the heat content at the evaporator inlet.

The volume fraction of the nanofluid (Φ) is the ratio of the volume of the dispersed nanoparticles to the total volume of the mixture, as shown in Eq. 5 [37, 38]:

$$(\emptyset) = \frac{V_i}{V_{total}} \quad (5)$$

where: V_i is the volume of the dispersed nanoparticles, and V_{total} is the total volume of the mixture.

3.6 Repeatability Evaluation

Statistical techniques were employed to observe and determine the reliability of the refrigeration system while operating with pure compressor oil and when the oil is mixed with various volume concentrations of Al_2O_3 bionanolubricants at 0.1%, 0.5%, and 1.0%, which provide objective evidence to support results derived from experimental data using equations 6 and 7. More so, Table 5 represents the mean, standard deviation, and standard error [39, 40].

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots x_n}{N} \quad (6)$$

Where: $\bar{x}$ is the mean value of the performance parameter, x_1 is the first measured value observed, and N is the total number of observations.

$$SD = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \quad (7)$$

Where: SD is the standard deviation, and Σ is the summation of experimental observations.

Table 5. Comparison of experimental samples for the COP

Experimental condition	Volume fraction (%)	Number of independent replicates - n	Mean COP	The standard deviation - SD	The standard error - SE
Control (base fluid)	-	3	4.40	1.02	0.59
Mango peel (MP)	0.1	3	8.35	0.46	0.27
	0.5	3	10.7	0.23	0.13
	1.0	3	9.85	0.59	0.34
Mango leaf (ML)	0.1	3	7.64	0.31	0.18
	0.5	3	9.77	0.47	0.27
	1.0	3	8.54	0.65	0.38

4. RESULTS AND DISCUSSION

Fig. 10 shows the variation in COP of a VCRS while working with the base fluid (control) and the three different bionanolubricants at volume concentrations of 0.1%, 0.5%, and 1.0% under the same conditions. It was observed that the bionanolubricant has an optimal effect on the COP. The maximum performance measure was found at 0.5% volume concentration from the mango peel, suggesting the best impact on the COP of the system; the variation in the SE of the mean COP among the experimental test conditions remains moderate.

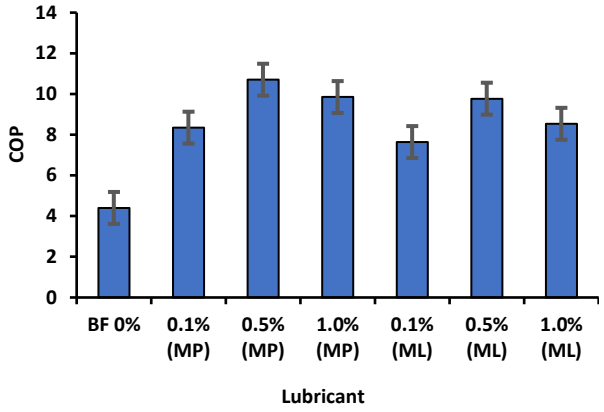

Fig. 10. Effect of bionanolubricant on the COP

The COP was measured with time. Fig. 11 shows the variation of the COP of the refrigeration system operating with the base fluid and 0.1, 0.5, and 1.0% volume concentrations of bionanolubricants. The results reveal that the system attained the maximum COP while using 0.5% of Al_2O_3 bionanoparticles obtained from MP with performance enhancements of 62% compared to the base fluid, and for other bionanolubricants, 0.1% of Al_2O_3/MP, 1.0% of Al_2O_3/MP, 0.1% of Al_2O_3/ML, 0.5% of Al_2O_3/ML, and 1.0% of Al_2O_3/ML, the COP improved by 25.3%, 9.3%, 27.8%, 8.3%, and 22.5%, respectively. The experimental investigation shows the potential of biowaste nanomaterials as sustainable and performance-enhancing materials in refrigeration applications. The significant COP of MP and ML compared to the base fluid is attributed to Al_2O_3 nanoparticles, the environmentally friendly refrigerant, the controlled ambient temperature, and the choice of the experimental test rig [41, 42].

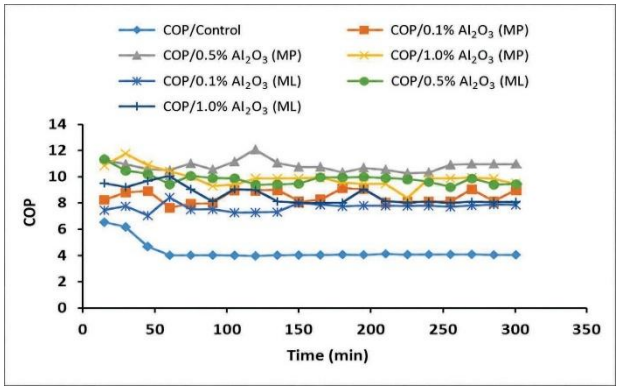

Fig. 11. COP of Al_2O_3 (MP, ML) and base fluid

Fig. 12 indicates the impact of bionanolubricants on the evaporator temperature of the VCRS using multiple concentrations of nanofluids: 0.1%, 0.5%, and 1.0% volume concentrations. The results show that the system achieved its lowest evaporator temperature (ET) of -23 °C in 120 min when the system operated with 0.5% of Al_2O_3/MP. The rapid attainment of the lowest temperature reveals enhanced thermal conductivity and latent heat absorbed in the evaporator. 0.5% of Al_2O_3/MP demonstrated significant improvements of 78.3%, 56.5%, 17.4%, 34.8%, 43.5%, and 21.7% compared to the control, 0.1% of Al_2O_3/ML, 0.5% of Al_2O_3/ML, 1.0% of Al_2O_3/ML, 0.1% of Al_2O_3/MP, and 1.0% of Al_2O_3/MP, respectively. From the results obtained, a 0.5% volume concentration of Al_2O_3 nanofluid maximally enhances the performance of the system. Furthermore, it was observed that the base fluid provides the least performance compared to the bionanolubricants due to the inability to interact with the nanoparticles.

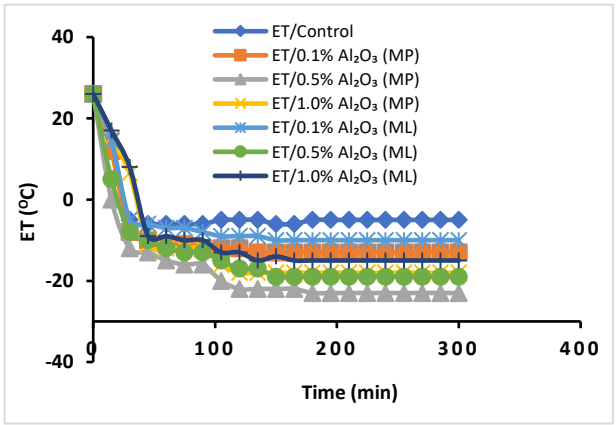

Fig. 12. Evaporator temperature for Al_2O_3 (MP, ML) and base fluid

The energy consumption rate is another essential metric to determine the performance and reliability of a refrigeration system. Fig. 13 shows the trend of the energy consumed by a VCRS

operating with the base fluid and 0.1%, 0.5%, and 1.0% volume concentrations of bionanolubricant. The results indicate that the system experienced significant energy reductions when using bionanolubricant, particularly 0.5% of Al_2O_3/MP, compared with the base fluid and other volume concentrations of 0.1% of Al_2O_3/ML, 0.5% of Al_2O_3/ML, 1.0% of Al_2O_3/ML, 0.1% of Al_2O_3/MP, and 1.0% of Al_2O_3/MP. It was observed that the system improved in energy savings by 17.6%, 16.9%, 11.5%, 15.9%, 12.7%, and 10.4%, respectively.

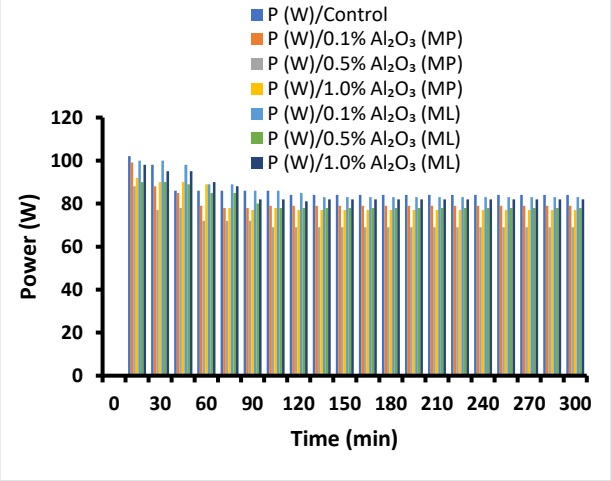

Fig. 13. Compressor power input for Al_2O_3 (MP, ML) and base fluid

The limitations of this work are as follows:

- The long-term stability of the nanolubricant, lubricant degradation, and compatibility with refrigeration components were not investigated.
- Although the nanolubricant was prepared using a standardized synthesis and dispersion procedure, potential nanoparticle agglomeration during prolonged operation was not continuously monitored.

5. CONCLUSION

The use of R600a in this study is a function of low GWP and zero ODP, among other characteristics. However, the application of bionanolubricant serves as an outstanding practice in terms of energy savings and COP enhancement. The impact of these processes will further enable the continuous use of sustainable nanomaterials in refrigeration engineering, thereby improving its performance. The biosynthesis approach to preparing nanolubricants using MP and ML extract is novel, as the commonly used methods were destructive to the immediate environment. For economic purposes and to reduce the risk of an unforeseen accident, a biological method was used and applied to the VCRS to enhance the rate of heat transfer within the system, thereby increasing the system's performance, reducing the work done by the compressor, and ultimately improving the COP. For future research, the use of nanorefrigerants, different compressor oil grades, and various refrigerant mass charges can be investigated under the same environmentally controlled conditions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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