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Performance assessment of an R290 air conditioning system using hybrid ZnO–SiO₂ nanolubricant

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Abstract

This study investigates the performance of a split air conditioning system using hybrid ZnO–SiO₂ nano lubricant with R290 refrigerant. Experiments were conducted under steady-state conditions at an ambient temperature of $27 \pm 1^\circ\text{C}$ with a constant cooling load. Nano lubricant concentrations of 0.18%, 0.36%, 0.91%, 1.79%, and 2.67% by mass were prepared using a two-step dispersion method involving mechanical stirring and ultrasonic agitation. System performance was evaluated based on energy consumption and Coefficient of Performance (COP). The results show that the addition of ZnO–SiO₂ nano lubricant improves system performance at optimal concentrations. The highest performance was observed at concentrations of 0.36% and 0.91%, resulting in an energy consumption reduction of approximately 9.7% compared to pure lubricant. The maximum COP value of 2.77 was obtained at a concentration of 0.91%. However, further increases in nanoparticle concentration led to performance degradation due to increased viscosity and particle agglomeration, which negatively affected compressor work and heat transfer. These findings indicate that the application of ZnO–SiO₂ nano lubricant can enhance the energy efficiency of air conditioning systems when applied at optimal concentrations.

Keywords:

Nano lubricant, ZnO–SiO₂ nanoparticles, air conditioner, energy consumption, coefficient of performance, R290 refrigerant.

1 Introduction

Air Conditioning (AC) systems play a crucial role in maintaining thermal comfort in residential, commercial, and industrial buildings, particularly in tropical and subtropical regions where ambient temperatures are relatively high throughout the year. The rapid growth of air conditioner utilization has significantly increased global electricity consumption and contributed to environmental concerns related to greenhouse gas emissions. Recent studies indicate that the global share of households equipped with residential air conditioning systems may increase from approximately 27% to 41%, resulting in a substantial rise in electricity demand for cooling. This increase could potentially double residential cooling electricity consumption from around 1220 TWh to nearly 1940 TWh annually, contributing to carbon emissions ranging from 590 to 1365 MtCO_{2e} if energy efficiency improvements are not implemented [1].

Improving the energy efficiency of air conditioning systems has therefore become an important research focus in thermal

engineering and refrigeration technology. Various approaches have been explored to enhance the performance of vapor compression refrigeration systems, including the development of environmentally friendly refrigerants, improvements in compressor design, optimization of heat exchanger performance, and enhancement of lubricant properties used in compressors. Among these approaches, the application of nano fluids and nano lubricants has received increasing attention due to their potential to improve heat transfer characteristics and reduce mechanical friction within refrigeration systems [2].

Nano lubricants are formed by dispersing nano particles into conventional base lubricants, which can significantly enhance thermo physical and tribological properties. The presence of nanoparticles can improve thermal conductivity, reduce friction between moving mechanical components, and enhance heat transfer within the compressor and refrigeration cycle. Previous studies have demonstrated that the incorporation of nanoparticles into lubricants can lead to improved thermal conductivity, enhanced convective heat transfer, and reduced friction losses in refrigeration systems, ultimately resulting in improved system performance and energy efficiency [3], [4].

Several experimental studies have investigated the application of nano lubricants in vapor compression refrigeration systems. Senthilkumar, *et al.* (2020) reported that the addition of ZnO and SiO₂ nano particles with a concentration of 0.6 g/L in a refrigeration system using R600a refrigerant resulted in an increase of approximately 42% in the Coefficient of Performance (COP) [5], [6]. Zawawi, *et al.* (2022) investigated hybrid Al₂O₃–SiO₂/PAG nano lubricants with a volume concentration of 0.06% and various composition ratios, reporting improvements in COP and reductions in compressor work of up to 16.31% and 18.65%, respectively [7] [8]. Similarly, Irwansyah, *et al.* (2023) found that the addition of 1.5 g SiO₂ nanoparticles increased COP by 25.88%, while the addition of 1.0 g ZnO nano particles improved COP by approximately 13.6%, demonstrating the potential of these nano particles to enhance refrigeration system performance [9] [10].

In addition to lubricant modification, the selection of refrigerant plays an important role in determining the environmental impact and thermodynamic performance of refrigeration systems. Hydrocarbon refrigerants such as R290 (propane) have attracted significant attention as environmentally friendly alternatives to conventional refrigerants due to their low Global Warming Potential (GWP) and favorable thermodynamic properties. Previous research has shown that refrigeration systems using R290 refrigerant can achieve better performance compared with systems using R22 refrigerant [11]. For instance, the power consumption of an R22-based system was reported to be approximately 0.30 kW, whereas an R290-based system required only around 0.26 kW under similar operating conditions, indicating improved energy efficiency [12].

Despite the growing interest in nano lubricant applications in refrigeration systems, research investigating the combined use of hybrid ZnO–SiO₂ nano lubricants and R290 refrigerant in air conditioning systems remains relatively limited. In this study, the ZnO–SiO₂ nano lubricant is not a commercially available product but is prepared in the laboratory by dispersing ZnO and SiO₂ nanoparticles into a conventional compressor base lubricant using a two-step method (mechanical stirring and ultrasonic agitation). The nanoparticles used are commercially available in powder form, while the nano lubricant itself is formulated specifically for experimental purposes. This approach allows precise control of nanoparticle concentration and dispersion stability, which cannot be achieved using standard commercial lubricants. Most previous studies have focused on single nanoparticles or different nanoparticle combinations using refrigerants such as R134a and R600a. Furthermore, existing studies often evaluate only limited nanoparticle concentrations, making it difficult to determine the optimal concentration that provides maximum performance

improvement without causing adverse effects such as excessive viscosity increase or nanoparticle agglomeration [13].

However, from a scientific perspective, it remains unclear how hybrid ZnO–SiO₂ nano lubricants influence the energy consumption and COP of air conditioning systems operating with R290 refrigerant under controlled operating conditions. Previous studies have demonstrated that the addition of nanoparticles into lubricants can enhance thermal conductivity, reduce friction, and improve overall system performance; however, these effects are highly dependent on nanoparticle type, size, and concentration [14][15]. In particular, the relationship between nanoparticle concentration, lubrication characteristics, and overall system efficiency has not been systematically evaluated across a wide range of concentrations, especially for hybrid nanomaterials such as ZnO–SiO₂ [8], [10]. Moreover, while R290 (propane) is recognized as an environmentally friendly refrigerant with excellent thermodynamic properties, studies combining R290 with hybrid nano lubricants remain limited [16], [17]. This indicates a clear research gap regarding the determination of optimal nano lubricant concentration and its corresponding performance behavior in real air conditioning systems.

Therefore, further investigation is required to better understand the influence of ZnO–SiO₂ nano lubricant concentration on the performance of air conditioning systems operating with environmentally friendly refrigerants. Identifying the optimal concentration of hybrid nanoparticles is essential to ensure improved energy efficiency while maintaining stable lubricant properties and effective heat transfer performance [18].

Based on this gap, the research question of this study can be formulated as: how does the concentration of ZnO–SiO₂ nano lubricant affect the energy consumption and COP of an R290-based air conditioning system, and what is the optimal concentration that yields maximum performance improvement?

Based on these considerations, this study aims to analyze the performance of an air conditioning system using ZnO–SiO₂ nano lubricant at different concentrations. The experiment was conducted using a split air conditioning system operating with R290 refrigerant. Five different nano lubricant concentrations (0.18%, 0.36%, 0.91%, 1.79%, and 2.67% by mass) are investigated and compared with pure lubricant. System performance is evaluated based on energy consumption and COP. The expected outcome of this study is to identify the optimal nano lubricant concentration that provides significant energy savings and COP improvement, while avoiding negative effects such as excessive viscosity and nanoparticle agglomeration. Furthermore, this study contributes to the development of energy-efficient and environmentally friendly air conditioning systems through the application of hybrid nano lubricants.

2 Method

2.1 Experimental setup

The experimental study was carried out using a split-type air conditioning system operating with R290 refrigerant. The system follows the conventional vapor compression refrigeration cycle consisting of four main components: compressor, condenser, expansion valve, and evaporator shown in Fig. 1. The purpose of the experiment was to evaluate the influence of ZnO–SiO₂ nano lubricant concentration on the energy consumption and COP of the air conditioning system. The compressor lubricant was modified by adding hybrid ZnO–SiO₂ nanoparticles at different mass concentrations. The tested concentrations were 0.18%, 0.36%, 0.91%, 1.79%, and 2.67% relative to the total mass of the lubricant–nanoparticle mixture. These concentrations were selected to evaluate the influence of nanoparticle dispersion on lubricant viscosity and overall refrigeration system performance.

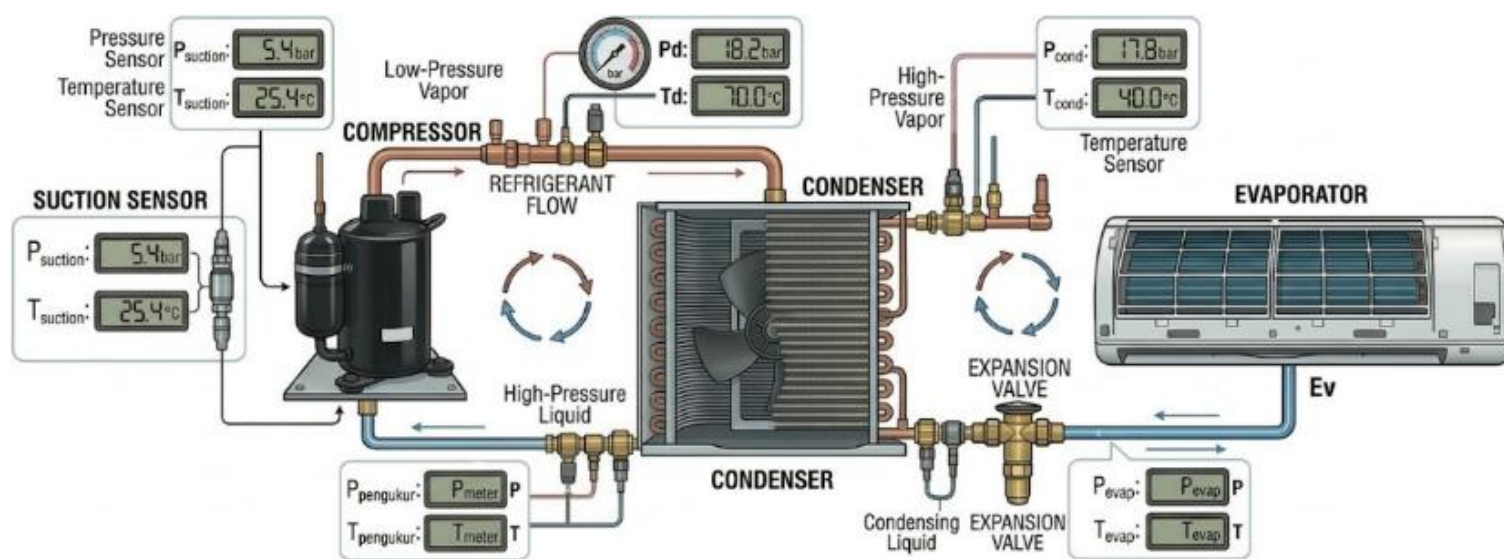


Fig. 1. Schematic diagram of the vapor compression refrigeration system used in the experiment.

During the experiment, the air conditioning unit was operated under steady-state conditions. Electrical power consumption and temperature variations within the refrigeration cycle were measured to determine the system performance under each nano lubricant concentration.

2.2 Preparation of ZnO–SiO₂ nano lubricant

The preparation of the ZnO–SiO₂ nano lubricant was performed through a two-step dispersion process to ensure homogeneous mixing of nanoparticles within the base lubricant shown in Fig. 2.

The ZnO and SiO₂ nanoparticles used in this study were obtained from commercially available laboratory-grade suppliers with a purity of approximately 99%. The average particle size of both ZnO and SiO₂ nanoparticles was in the range of 20–50 nm according to the manufacturer specifications. The base lubricant

used was a conventional compressor lubricant commonly applied in split air conditioning systems, ensuring compatibility with the refrigeration cycle and compressor components.

Initially, the required mass of ZnO and SiO₂ nanoparticles was measured using a digital precision balance according to the predetermined concentration levels.

The nanoparticles were gradually added to the base lubricant and mixed using a mechanical stirrer for approximately 30 minutes to achieve preliminary dispersion. After mechanical mixing, the mixture was subjected to ultrasonic agitation for 45 minutes to break nanoparticle agglomerations and enhance the stability of the nano lubricant suspension. The combination of mechanical stirring and ultrasonic mixing improves nanoparticle dispersion and reduces the possibility of particle clustering, which can negatively affect lubricant viscosity and system performance. The use of

ultrasonic agitation plays a critical role in maintaining the nanoparticles within the nanoscale range by minimizing agglomeration and promoting uniform dispersion throughout the lubricant. The nanoscale characteristics of the particles were

ensured based on the manufacturer specifications, which are widely accepted in experimental studies. This preparation approach enables consistent nanoparticle distribution and reliable evaluation of the effect of nanoparticle concentration on system performance.

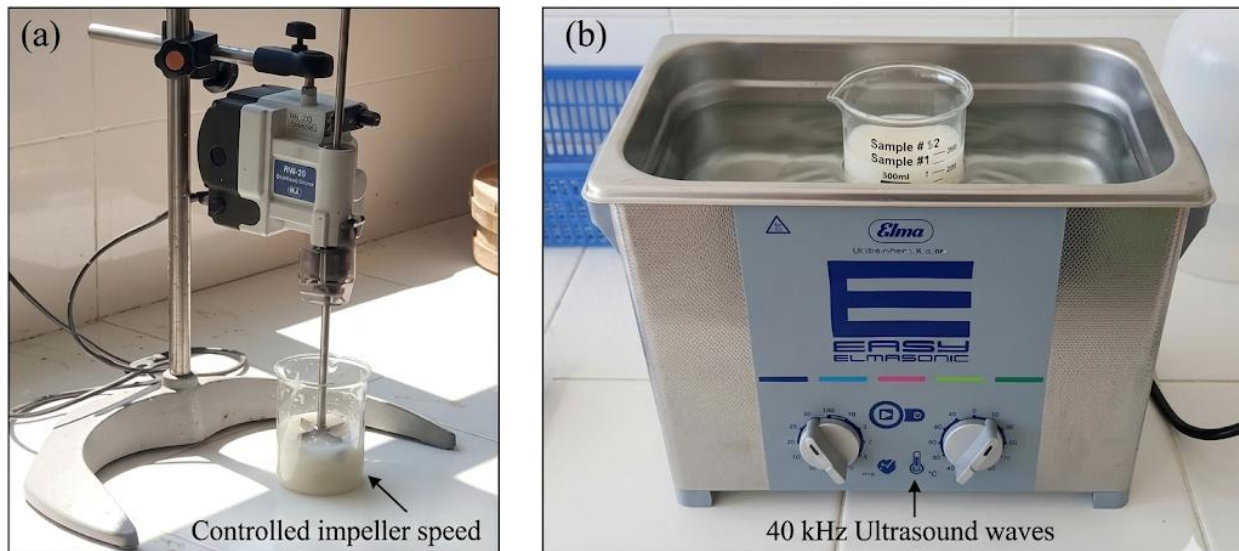


Fig. 2. Nano lubricant preparation process: (a) mechanical stirring, (b) ultrasonic mixing.

2.3 Viscosity measurement

The viscosity of the prepared nano lubricant samples was measured using an Iwata Cup viscometer (NK-2 type). Approximately 50 ml of nano lubricant was poured into the viscosity cup, and the time required for the lubricant to flow through the orifice was recorded using a stopwatch. The recorded

flow time was used as an indicator of the lubricant viscosity. Viscosity measurement is important for evaluating the influence of nanoparticle concentration on the flow characteristics of the lubricant. Changes in lubricant viscosity may affect compressor friction losses, lubricant circulation, and heat transfer performance within the refrigeration system shown in Fig. 3.

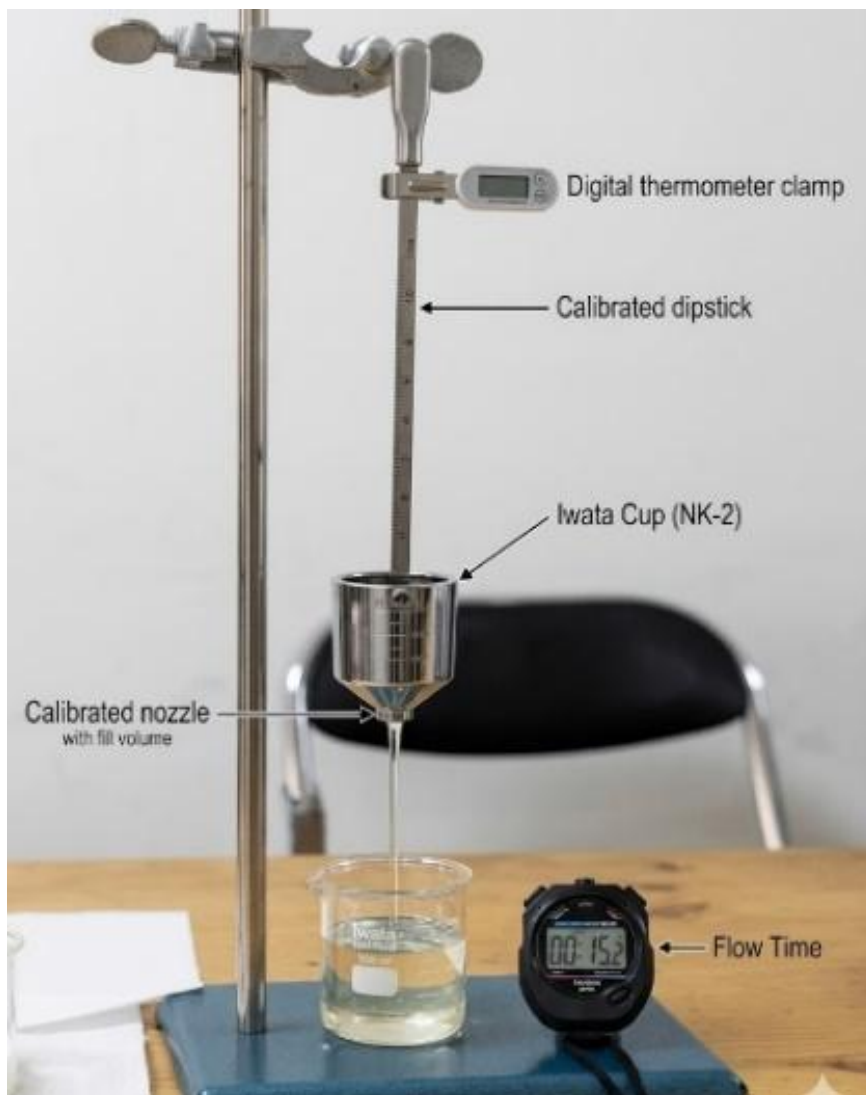


Fig. 3. Viscosity measurement using an Iwata Cup viscometer.

2.4 Air conditioning system components and instrumentation

The experimental test rig shown in Fig. 4 consists of a split air conditioning system equipped with several measuring instruments to monitor operating conditions during the experiment. Temperature measurements were conducted using calibrated K-type thermocouples ($\pm 0.5^\circ\text{C}$ accuracy) installed at key locations, including the evaporator inlet and outlet, condenser inlet and outlet, as well as the compressor suction and discharge lines. Pressure measurements were obtained using pressure gauges with an accuracy of $\pm 1\%$ to monitor the suction and discharge pressures of the system.

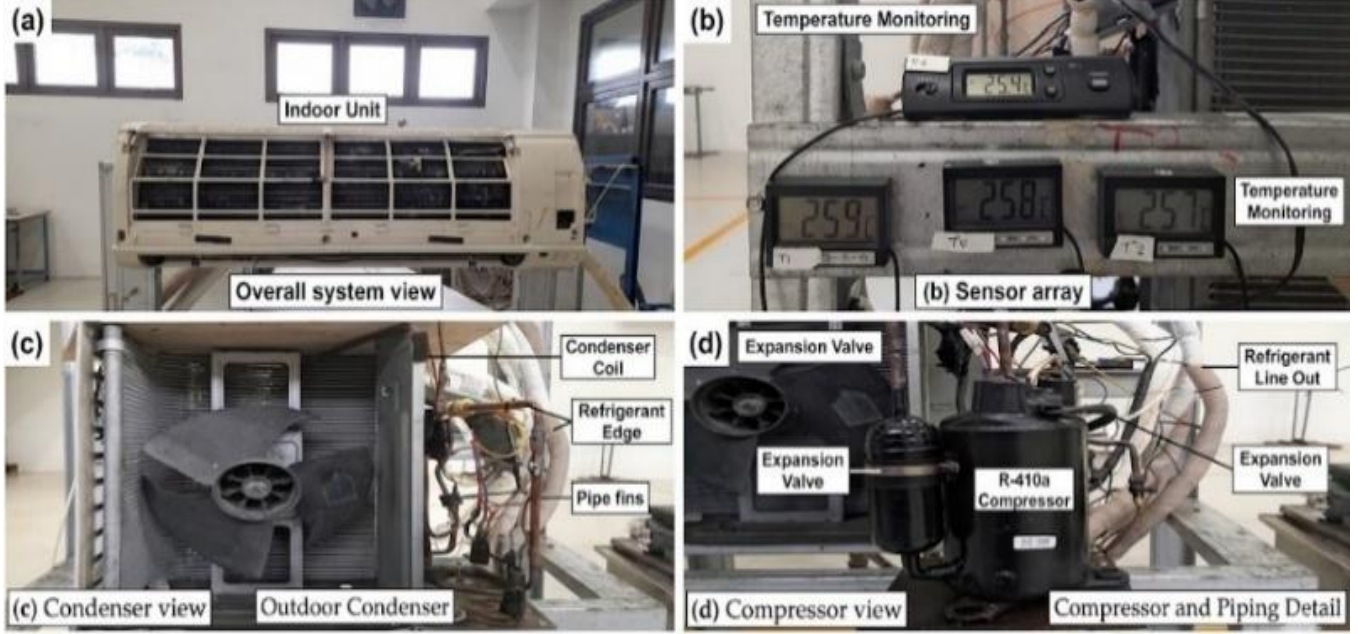


Fig. 4. Experimental test rig of the split air conditioning system.

2.5 Density calculation

The density of the nano lubricant mixture can be estimated theoretically using the volumetric relationship between the components forming the mixture. The theoretical density of the nano lubricant can be expressed as the weighted contribution of each component based on its density and volume fraction (Eq. (1)).

$$\rho = \frac{(\rho_1)V_1 + (\rho_2)V_2 + (\rho_3)V_3}{V_1 + V_2 + V_3} \quad (1)$$

In Eq. (1), the density of the nano lubricant is obtained by combining the densities and volumes of the ZnO nanoparticles, SiO₂ nanoparticles, and base lubricant. Each component contributes proportionally according to its respective volume fraction within the mixture. The experimental density of the nano lubricant can also be determined using the ratio between mass and volume, this relationship, the density is obtained by dividing the mass (m) of the nano lubricant by its measured volume (V) (Eq. (2)).

$$\rho = \frac{m}{V} \quad (2)$$

2.6 Performance analysis of refrigeration system

The performance of the vapor compression refrigeration system was evaluated using the COP, which represents the ratio between the refrigeration effect produced in the evaporator and the compressor work input required to circulate the refrigerant (Eq. (3)).

$$COP = \frac{Q_e}{W_{comp}} \quad (3)$$

In this experiment, the refrigeration effect (Q_e) was determined based on the air-side method at the evaporator. The cooling

Electrical power consumption of the compressor was measured using a digital power meter connected directly to the compressor power supply, which records voltage, current, and power factor. All measurements were taken after the system reached steady-state conditions to ensure data consistency and reliability.

The measured parameters were used to evaluate the performance of the refrigeration system under different nano lubricant concentrations. In addition, the collected data were used to calculate the cooling capacity and COP of the system based on experimentally measured temperature, airflow, and electrical power input.

capacity was calculated using the temperature difference between the inlet and outlet air across the evaporator and the air mass flow rate. The air mass flow rate was estimated from the measured air velocity and the cross-sectional area of the evaporator duct. The refrigeration effect was calculated using the Eq. (4), where \dot{m}_{air} is the air mass flow rate, C_p is the specific heat capacity of air, and T_{in} and T_{out} are the inlet and outlet air temperatures at the evaporator, respectively.

$$Q_e = \dot{m}_{air} \cdot C_p (T_{in} - T_{out}) \quad (4)$$

The compressor work (W_{comp}) was obtained from direct electrical measurements using a digital power meter connected to the air conditioning system. The electrical power consumption was calculated based on the measured voltage, current, and power factor, as expressed by Eq. (5), where V is the supply voltage, I is the electric current, and $\cos \phi$ is the power factor. The measurements were taken under steady-state operating conditions to ensure accuracy and consistency of the performance evaluation.

$$W_{comp} = V \cdot I \cdot \cos \phi \quad (5)$$

The coefficient of performance represents the efficiency of the refrigeration system. The refrigeration effect corresponds to the amount of heat absorbed by the refrigerant in the evaporator during the cooling process, while the compressor work represents the electrical energy required to drive the compressor and maintain refrigerant circulation within the cycle. A higher COP value indicates that the refrigeration system can produce a greater cooling effect relative to the energy consumed by the compressor.

The COP values in this study were calculated based on the measured operating parameters of the air conditioning system under different ZnO–SiO₂ nano lubricant concentrations.

2.7 Experimental uncertainty analysis

Experimental measurements are subject to uncertainties arising from limitations in measurement instruments and environmental conditions. Therefore, uncertainty analysis was conducted to evaluate the reliability of the experimental results obtained in this study.

The uncertainty of a calculated parameter can be estimated using the Root-Sum-Square (RSS) method based on the propagation of errors from the measured variables (Eq. (6)).

$$U_R = \sqrt{\sum_{i=1}^n \left(\frac{\partial R}{\partial x_i} U_{xi} \right)^2} \quad (6)$$

In Eq. (6), the overall uncertainty of a calculated result depends on the uncertainties of each measured variable contributing to the calculation. The partial derivatives represent the sensitivity of the calculated parameter to each measured variable. In this experiment, the uncertainty sources mainly originated from temperature measurement, electrical power measurement, and timing measurements used during viscosity testing. These uncertainties were considered in evaluating the reliability of the calculated COP and energy consumption values.

3 Results and discussion

3.1 Effect of ZnO–SiO₂ nano lubricant on lubricant viscosity

The addition of nanoparticles to the compressor lubricant significantly affects the thermophysical properties of the lubricant, particularly viscosity shown in Fig. 5. Viscosity plays a critical role in determining lubrication performance, friction losses in the compressor, and heat transfer characteristics within refrigeration systems. In general, the presence of nanoparticles in lubricants tends to increase the viscosity due to interactions between suspended particles and the base fluid. Previous studies have shown that increasing nanoparticle concentration leads to higher lubricant viscosity. Nugroho, *et al.* (2024) reported that the addition of TiO₂ nanoparticles into compressor lubricant resulted in a gradual increase in viscosity as the nanoparticle concentration increased [19]. Similarly, Mizan observed that the viscosity of compressor lubricant remained approximately constant at 30 cSt for pure lubricant and low nanoparticle concentrations, but increased significantly when the concentration exceeded certain levels, reaching approximately 40 cSt at higher concentrations [20].

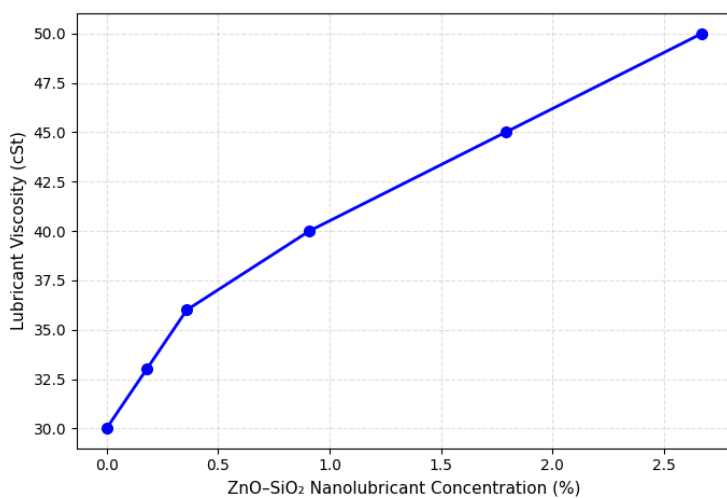


Fig. 5. Effect of ZnO–SiO₂ nano lubricant on lubricant viscosity.

In the present study, a similar trend was observed for the ZnO–SiO₂ nano lubricant. The addition of hybrid nanoparticles into the base lubricant increased the viscosity of the mixture as the nanoparticle concentration increased. This increase in viscosity can improve lubrication performance by forming a more stable lubricating film between moving compressor components, thereby reducing friction and wear.

However, excessive nanoparticle concentration may also lead to negative effects. When the concentration becomes too high, nanoparticle agglomeration may occur, which increases internal resistance within the lubricant and reduces the effectiveness of lubricant circulation within the compressor system. Therefore, determining the optimal nanoparticle concentration is essential to balance improved lubrication performance and acceptable flow characteristics.

3.2 Effect of ZnO–SiO₂ nano lubricant on energy consumption

The influence of ZnO–SiO₂ nano lubricant on the energy consumption of the air conditioning system was evaluated by comparing the compressor power consumption using pure lubricant and nano lubricant mixtures shown in Fig. 6. In order to ensure consistency with the analysis, the energy consumption data are presented at a fixed steady-state operating condition, where energy consumption is plotted as a function of ZnO–SiO₂ concentration. The experimental results show that the addition of ZnO–SiO₂ nanoparticles can improve the energy efficiency of the air conditioning system at certain concentrations. Fig. 6 presents the comparison of energy consumption between pure lubricant and ZnO–SiO₂ nano lubricant under different concentration conditions.

Fig. 6 illustrates the relationship between nanoparticle concentration and energy consumption, providing a clearer interpretation of the nano lubricant effect.

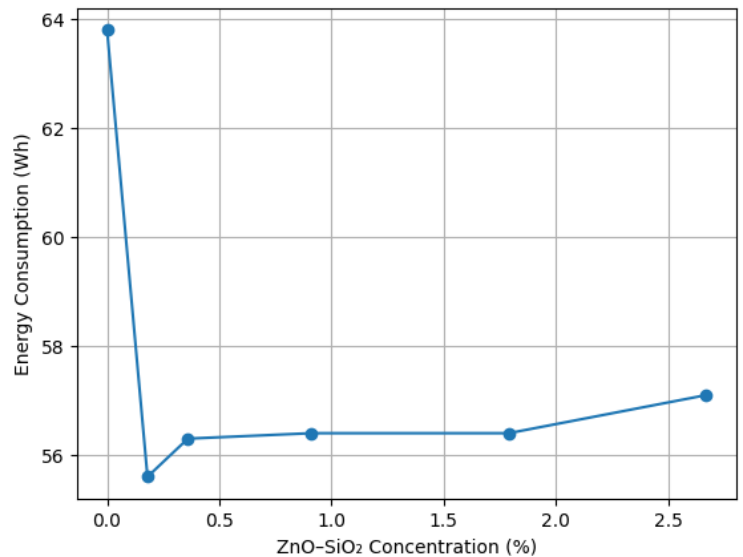


Fig. 6. Energy consumption comparison between pure lubricant and ZnO–SiO₂ nano lubricant.

The results indicate that the addition of ZnO–SiO₂ nano lubricant at concentrations of 0.36% and 0.91% resulted in the most significant reduction in energy consumption. At these concentrations, the air conditioning system achieved approximately 9.7% energy savings compared with the system operating with pure lubricant. The reduction in energy consumption can be explained by the improved tribological characteristics of the nano lubricant. The presence of nanoparticles can reduce friction between moving compressor components, thereby decreasing mechanical losses and improving compressor efficiency. In this study, compressor efficiency was not measured directly using a dedicated compressor efficiency measurement device. Instead, it was evaluated indirectly based on the measured electrical power consumption and the overall thermodynamic performance of the system. The compressor power input was measured using a calibrated digital power meter connected to the compressor electrical supply, which records voltage, current, and power factor to determine real power consumption.

In addition, temperature measurements at key locations in the refrigeration cycle (evaporator inlet and outlet, condenser inlet and outlet, and compressor suction and discharge) were obtained using calibrated thermocouples, while system pressures were measured

using pressure gauges. These measurements were used to determine the cooling capacity (Q_e) and the COP of the system under steady-state conditions.

Therefore, the improvement in compressor efficiency was inferred from the reduction in electrical power input (W_{comp}) and the simultaneous increase in COP. This approach is commonly used in experimental refrigeration studies, where compressor performance is evaluated based on system-level energy analysis rather than direct mechanical efficiency measurement. Similar findings have been reported in previous studies where nano lubricants were shown to reduce the energy consumption of refrigeration systems due to improved lubrication and heat transfer properties [19], [20]. However, when the nanoparticle concentration increased to 1.79% and 2.67%, the energy consumption of the system increased. This indicates the existence of an optimal nanoparticle concentration range, beyond which the performance of the system deteriorates. This phenomenon is primarily attributed to the increase in lubricant viscosity caused by excessive nanoparticle addition. Higher viscosity increases resistance to lubricant flow, which leads to increased compressor workload and consequently higher electrical energy consumption. Therefore, the balance between enhanced tribological effects and increased viscous resistance plays a critical role in determining the optimal nano lubricant concentration.

3.3 Effect of ZnO–SiO₂ nano lubricant on COP

The COP is an important indicator used to evaluate the efficiency of refrigeration systems. The experimental results show that the addition of ZnO–SiO₂ nano lubricant significantly influences the COP of the air conditioning system. To ensure consistency between the data presentation and analysis, the COP values are presented at a fixed steady-state operating condition, where COP is plotted as a function of ZnO–SiO₂ nanoparticle concentration. Fig. 7 illustrates the relationship between nanoparticle concentration and COP, allowing a clearer interpretation of the nano lubricant effect.

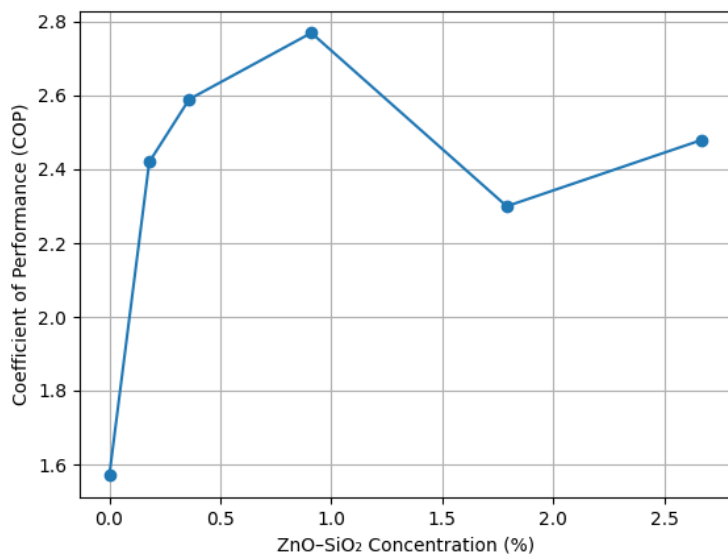


Fig. 7. COP comparison between pure lubricant and ZnO–SiO₂ Nano lubricant

The results in Fig. 7 shows that the COP value increased with the addition of nano lubricant at lower nanoparticle concentrations. The highest COP value obtained in this study was 2.7707 at a nano lubricant concentration of 0.91%. This value is significantly higher than that obtained using pure lubricant, which produced a COP value of approximately 1.5292. The increase in COP can be attributed to improved heat transfer characteristics and reduced friction losses within the compressor when nanoparticles are present in the lubricant. Nanoparticles enhance the thermal conductivity of the lubricant and improve the formation of protective tribological films on moving surfaces, which reduces

mechanical losses and improves compressor performance. In this study, the COP was calculated using Eq. (3), where $\text{COP} = Q_e/W_{\text{comp}}$. The cooling capacity (Q_e) was determined using the airside method by measuring the air temperature difference between the evaporator and the air velocity using Eq (4). The air mass flow rate was calculated from the measured air velocity and duct cross-sectional area, while the inlet and outlet air temperatures were measured using calibrated thermocouples. The compressor power input (W_{comp}) was directly measured using a digital power meter connected to the compressor electrical supply. All measurements were taken under steady-state conditions to ensure accuracy and repeatability. Therefore, the COP values presented reflect the actual system performance based on experimentally measured cooling capacity and compressor power consumption.

However, the COP decreased at higher nanoparticle concentrations of 1.79% and 2.67%. This decrease is associated with increased lubricant viscosity and the possibility of nanoparticle agglomeration. Excessive nanoparticle concentration can increase frictional resistance within the lubrication system and reduce the effectiveness of heat transfer processes within the refrigeration cycle. This result further confirms the existence of an optimal nanoparticle concentration, beyond which the performance of the system deteriorates due to the dominance of viscous and agglomeration effects.

The findings of this study are consistent with several previous studies investigating the application of nano lubricants in refrigeration systems. Sanukrishna, *et al.* (2018) reported that nano lubricants exhibit excellent friction reduction and anti-wear characteristics, with a maximum reduction in friction coefficient of approximately 37.76% and a wear scar reduction of about 40.83% [10], [21]. These improvements in tribological performance contribute to enhanced compressor efficiency and improved refrigeration system performance.

Similarly, Nugroho, *et al.* (2024) reported that the addition of TiO₂ nanoparticles into compressor lubricant improved COP values at certain concentrations, particularly between 1% and 3%, although excessive nanoparticle concentration resulted in reduced performance due to increased viscosity effects [8]. The results of the present study confirm that hybrid ZnO–SiO₂ nano lubricants can also improve the performance of air conditioning systems when applied at appropriate concentrations. The optimal concentration observed in this study was approximately 0.91%, which provided the highest COP value and significant energy savings. These results highlight the importance of optimizing nanoparticle concentration in nano lubricant applications. While nanoparticles can improve heat transfer and lubrication performance, excessive concentration may cause agglomeration and increased viscosity, which negatively affects compressor performance and system efficiency.

4 Conclusions

This study investigated the effect of ZnO–SiO₂ nanolubricant concentration on the performance of a split air conditioning system using R290 refrigerant. The experimental results demonstrate that the addition of hybrid ZnO–SiO₂ nanoparticles into the compressor lubricant significantly influences the energy consumption and COP of the system. The results indicate that the use of ZnO–SiO₂ nano lubricant improves system performance at certain concentrations. The optimal performance was obtained at nano lubricant concentrations of 0.36% and 0.91%, where the air conditioning system achieved an energy efficiency improvement of approximately 9.7% compared to the pure lubricant. The highest COP value of 2.7707 was achieved at a concentration of 0.91%, which is significantly higher than the COP obtained using pure lubricant (1.5292). These results indicate that the addition of nano lubricant can enhance compressor lubrication, reduce friction losses, and improve the mechanical performance of the compressor, leading to lower power consumption and higher system efficiency. The improvement in COP observed was primarily associated with

the reduction in compressor work rather than an increase in the heat absorption capacity of the evaporator. However, further increases in nanoparticle concentration to 1.79 wt% and 2.67 wt% resulted in a decrease in system performance. This reduction was attributed to the increase in lubricant viscosity and the potential agglomeration of nanoparticles, which could increase compressor workload and reduce system efficiency. Overall, the findings of this study demonstrate that ZnO–SiO₂ nano lubricant has strong potential to enhance the energy efficiency of air conditioning systems when applied at optimal concentrations.

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