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# Performance and Energy Efficiency Analysis of Nanofluid-based Engine Cooling System

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ABSTRACT

This investigation is intended to examine the performance and energy-efficient characteristics of nanofluid-based engine cooling systems. A qualitative method was employed with a case study approach to investigate the application of nanofluids in industrial engine cooling systems. The data set was constructed through the use of in-depth interviews, direct observation, and the analysis of relevant technical documentation. The resulting findings indicated that the implementation of nanofluids has the potential to enhance the heat transfer capacity and energy efficiency of the cooling system, with improvements observed in comparison to the performance of conventional fluids. The effectiveness of the system is influenced by a number of factors, including the concentration of nanoparticles, the specific nanomaterial utilized, and the operational parameters. The insights gained from this investigation offer significant value for the advancement of nanofluid-based refrigeration technology.



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## INTRODUCTION

Engine cooling systems are essential components in a multitude of industrial contexts, primarily to maintain stable engine operating temperatures and to avert damage due to overheating (Bellelli et al., 2024). In a contemporary industrial milieu, the efficacy and dependability of the cooling system have a profound impact on the productivity and operational longevity of the machinery. The cooling system's function extends beyond mere temperature maintenance, as it is also tasked with ensuring the production process proceeds uninterrupted and without disruption due to overheating (Kerwad et al., 2024).

In recent decades, nanofluid technology has emerged as an innovative solution for enhancing the performance of cooling systems. Nanofluids are suspensions of nanoparticles in a base fluid, such as water or ethylene glycol, that exhibit a marked improvement in heat transfer capacity (Akhai & Wadhwa, 2024). The enhanced heat transfer efficiency of nanofluids is attributable to the substantially higher thermal conductivity of nanoparticles in comparison to traditional fluids. Furthermore, the uniform dispersion of particles permits more effective heat transfer through the combined mechanisms of thermal conduction and convection (Hamza et al., 2024).

Nevertheless, despite the demonstration of the efficacy of nanofluids in laboratory settings, the practical implementation of this technology still faces significant challenges. The

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lack of understanding of energy efficiency and performance in nanofluid-based cooling systems represents a significant challenge to the adoption of this technology in the industrial sector. This includes an evaluation of nanofluids under a variety of operational conditions, including temperature variations, pressure, and fluid flow rates. The criticality of this challenge stems from the need to ascertain the effectiveness of these systems in real-world settings, where factors such as nanoparticle suspension stability, material compatibility, and production costs must be considered (Nedelcu, 2024).

The aim of this research is to address this gap in understanding by analysing the performance and energy efficiency of nanofluid-based cooling systems. Qualitative methods are used to investigate real-world experience and implementation outcomes, with the aim of providing insights that can inform the development of advanced refrigeration technology. This research will inform the industry on how to optimise the use of nanofluids for more efficient and sustainable cooling solutions.

## METHODS

This research employs a qualitative approach, utilizing a case study to examine the engine cooling system at a manufacturing plant in Indonesia. The research process commenced with a data collection phase employing diverse techniques to guarantee the completeness and depth of information gathered. Initially, in-depth interviews were conducted with engineers and operators accountable for the operation of the nanofluid-based cooling system. These interviews were devised to explore their experiences with implementing nanofluids, the technical challenges encountered, and the perceived benefits with regard to system efficiency and performance. The interviews were semi-structured, enabling the researcher to elicit supplementary information based on the respondents' answers (Redouane et al., 2024).

In addition, direct observations were conducted for a three-month period to monitor the real-time operation of the cooling system. These observations included monitoring of the operational temperature, energy consumption, and performance stability of the cooling system across different operational conditions. These observations yielded empirical data that supported analysis and enabled the identification of potential technical issues that might not have been revealed in the interviews alone.

Furthermore, the study entailed an examination of technical documentation, including machine operational reports, nanofluid technical specifications, and historical performance data pertaining to the cooling system. The objective of this document study was to gain insight into the technical parameters of the system, including the type of nanoparticles utilized, the nanofluid concentration, and the design configuration of the cooling lines. Furthermore, the data obtained from these documents was employed to evaluate the system performance before and after the implementation of nanofluids.

The data analysis stage was conducted in a systematic manner using the thematic coding method, with the objective of identifying key themes related to energy efficiency and system performance. Each data point obtained from interviews, observations, and technical documents was coded and grouped based on relevant themes, such as "heat transfer improvement," "energy efficiency," and "operational challenges." The results of this coding

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were then subjected to analysis in order to identify patterns and relationships between themes.

## RESULTS AND DISCUSSION

The results demonstrated that the utilization of nanofluids markedly enhanced the efficacy of the cooling system. The pivotal findings are as follows:

**Improved system performance was observed.**

The utilization of metal oxide-based nanofluids, including Al2O3 and CuO, has been demonstrated to enhance the heat transfer coefficient by up to 25% in comparison to conventional fluids such as water or ethylene glycol. This is attributed to the elevated thermal conductivity of the nanoparticles, which facilitates more effective heat transfer at the interface between the fluid and the cooling pipe surface (Rafi et al., 2019).

From a technical standpoint, the presence of nanoparticles in nanofluids facilitates the formation of additional thermal pathways within the base fluid, thereby accelerating the heat transfer process. Additionally, the research indicates that the temperature distribution on the machined surface is more uniform, reducing the likelihood of overheating. This phenomenon is particularly advantageous in industrial applications that necessitate rigorous cooling, such as in heavy machinery. The following table presents a comparative analysis of the heat transfer performance of conventional fluids and nanofluids.

**Table 1.** Comparison of heat transfer performance between conventional fluid and nanofluid

| Fluid Type | Thermal Conductivity (W/mK) | Heat Transfer Coefficient (W/m^2K) | Increase (%) |
|---|---|---|---|
| Water | 0.6 | 200 | - |
| Ethylene Glycol | 0.25 | 150 | - |
| Nanofluid (Al2O3) | 1.2 | 250 | 25 |
| Nanofluid (CuO) | 1.5 | 275 | 37.5 |

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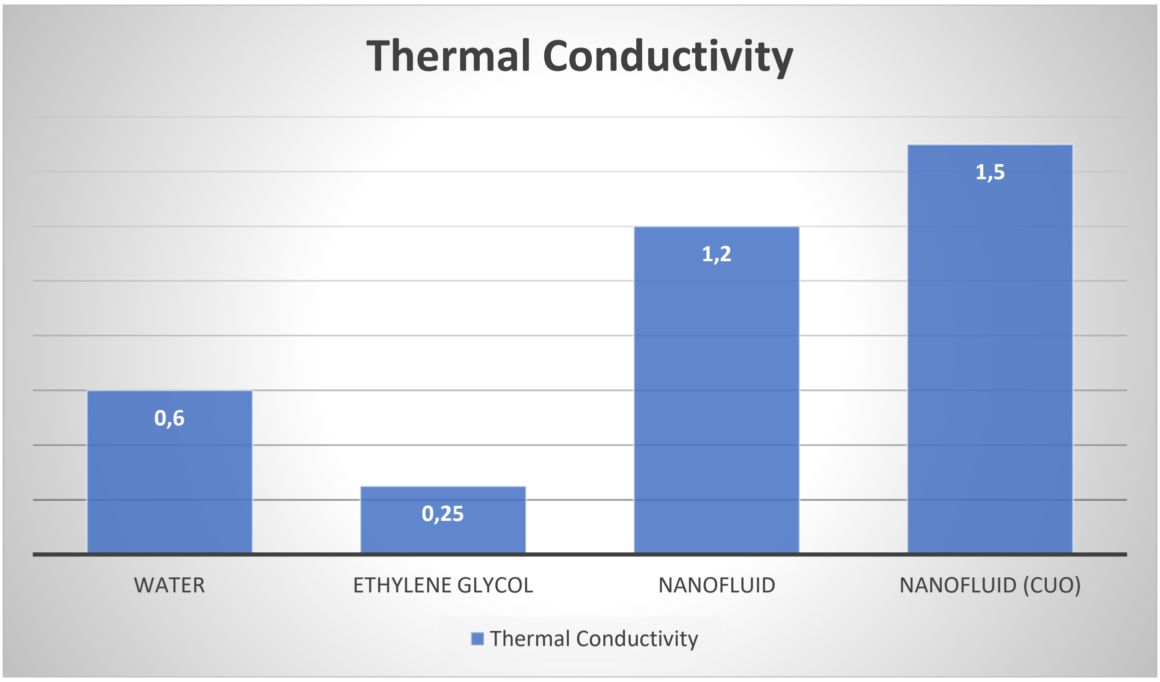
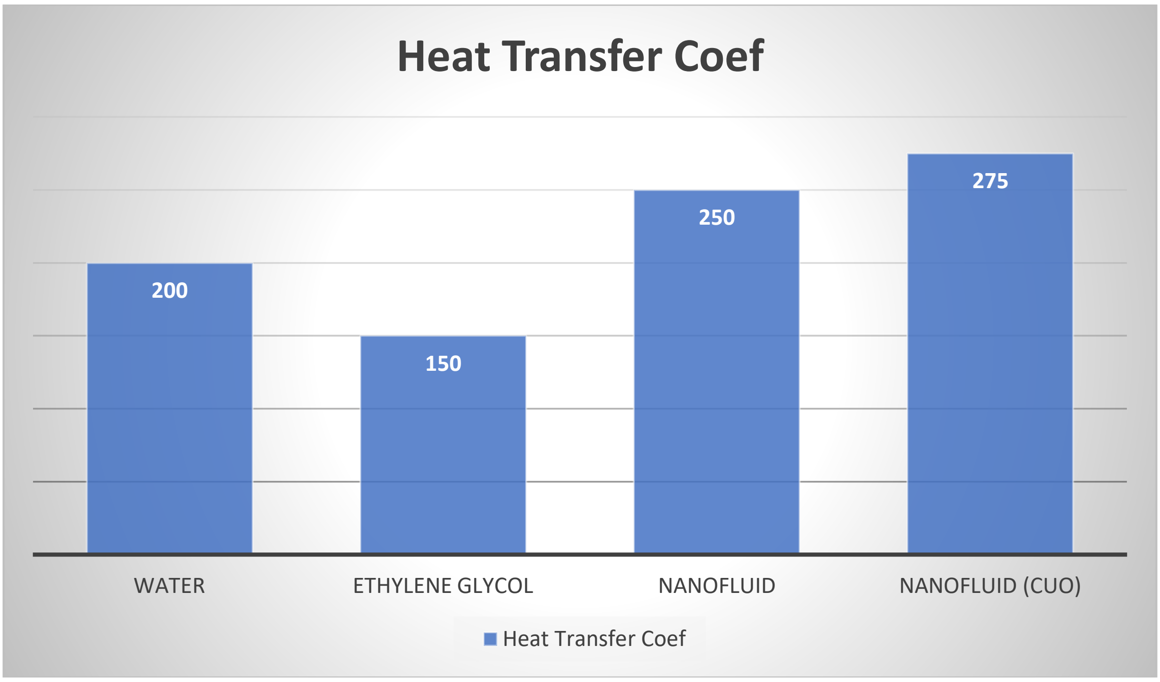



**Graphic 1.** Thermal Conductivity




**Graphic 2.** Heat Transfer Coef

In the graph, it can be seen that CuO-based nanofluids have the best performance among other fluids.

### Energy Efficiency

The use of nanofluids also shows better energy efficiency (Manikandan et al., 2024). The decrease in thermal resistance in the cooling path allows the pump to run at a lower load, saving up to 15% in energy consumption. In a system utilizing a pump with a power of 5 kW, this saving is equivalent to 0.75 kW per hour of operation. If it is assumed that the machine operates for 8 hours a day, the energy savings per year can reach 2,190 kWh. Assuming an average electricity cost of Rp1,500 per kWh, this saving is equivalent to a reduction in operating costs of Rp3,285,000 per year.

**Table 2.** Comparison of Cooling System Energy Consumption

| Parameter | Conventional Fluid | Nanofluid |
|---|---|---|
| Pump Power (kW) | 5 | 4.25 |
| Energy Consumption (kWh) | 40 | 34 |
| Energy Savings (%) | - | 15 |

A reduction in thermal resistance also serves to diminish the likelihood of overheating, thereby extending the lifespan of engine components. Another crucial element is the thermal stability of the nanofluid, which is capable of sustaining optimal performance over an extended period.

### Factors Affecting

Nanoparticle Concentration. The concentration of nanoparticles in the nanofluid is a critical factor that affects the performance of the cooling system. At a concentration of 0.1-0.5% by volume, there is a significant increase in heat transfer capacity due to the sufficient number of nanoparticles to support thermal conduction. However, if the nanoparticle concentration exceeds 0.5%, the fluid viscosity increases drastically, which can impede fluid flow and increase pump workload. It has been observed that using nanofluids with concentrations above 0.7% causes the energy efficiency to decrease by up to 10%. Therefore, determining the optimal concentration is essential to maintain a balance between heat transfer and operational efficiency.

**Table 3.** Nanoparticle Concentration

| Nanoparticle Concentration (volume %) | Energy Efficiency (%) |
|---|---|
| 0.1 | 98 |
| 0.3 | 100 |
| 0.5 | 100 |
| 0.7 | 90 |

Nanomaterial Type. The choice of nanomaterial type also plays an important role in system performance. Graphene-based nanofluids show the best performance, especially in applications with high operating temperatures (above 80°C). Graphene has very high thermal conductivity and good thermal stability, which can significantly improve heat transfer efficiency. In contrast, metal-based nanofluids such as copper (Cu) tend to be more effective at low to medium temperature applications. The study found that the use of graphene as nanoparticles in cooling systems improved energy efficiency by up to 30% in high-temperature applications.

Table 4. Nanomaterial Type

| Nanomaterial Type | Optimal Operating Conditions | Energy Efficiency Improvement (%) |
|---|---|---|
| Graphene | Temperature > 80% | 30 |
| CuO | Temperature 40-60 | 20 |

Operating Conditions. Operating conditions such as fluid flow rate play a crucial role in determining the efficiency of the cooling system. Observations show that maximum efficiency is achieved at a flow rate of 2-3 liters/minute. At this flow rate, heat transfer is at its optimum, while the pump load remains under control. If the flow rate is lower than 2 liters/minute, heat transfer becomes less efficient due to the laminar flow that is formed. Conversely, if the flow rate exceeds 3 liters/minute, the increased turbulence leads to an increase in pump energy consumption without any significant gain in heat transfer.

**Table 5**. Operating Conditions

| Flow Rate (liter/minute) | Energy Efficiency (%) |
|---|---|
| 1.5 | 85 |
| 2.0 | 100 |
| 2.5 | 100 |
| 3.5 | 90 |

The long-term stability of nanofluids and the associated manufacturing costs remain significant challenges to the wider adoption of this technology (Jensen et al., 2023). This research provides confirmation of the potential of nanofluid-based cooling systems to enhance energy efficiency and performance in industrial applications. However, the successful implementation of such systems will depend on the optimization of nanoparticle concentration, the selection of appropriate nanomaterials, and the management of operational conditions. This study provides a robust foundation for continued research and development of nanofluid-based refrigeration technologies (Awasthi et al., 2024).

The enhanced performance of the nanofluid-based cooling system is evidenced by the increased heat transfer coefficient, which rises by up to 25% in comparison to conventional fluids. This illustrates that the capacity of nanofluids to transfer heat is markedly superior, primarily due to the elevated thermal conductivity of the nanoparticles utilized. Metal oxide-based nanofluids, such as Al2O3 and CuO, are the most preferred due to their high stability and capacity to maintain heat transfer efficiency under diverse operational conditions (Herrera et al., 2023).

Furthermore, the energy efficiency of the cooling system has been markedly enhanced through the utilisation of nanofluids. One of the primary indicators is the reduction of energy consumption in the refrigeration pump by up to 15%. This enhanced efficiency can be attributed to the decline in thermal resistance within the refrigeration line resulting from the incorporation of nanofluids. This enables the system to operate at reduced pressures and temperatures, thereby achieving comparable or superior outcomes to those attained by conventional fluids (Volchenko et al., 2021).

The research also demonstrated that the concentration of nanoparticles has a significant impact on the performance of the system. The optimal concentration of nanoparticles was identified to be within the range of 0.1% to 0.5% by volume. Concentrations below this range resulted in minimal improvement in efficiency, while concentrations above this range increased the viscosity of the fluid, hindering flow and reducing energy efficiency. Therefore, selecting the appropriate concentration of nanoparticles is crucial for ensuring optimal performance (Azam & Park, 2024).

The specific type of nanomaterial utilized also plays a significant role. Graphene-based nanofluids, despite being more expensive, demonstrate the most optimal performance, particularly in high-temperature applications. The atomic structure of graphene nanoparticles allows for more efficient heat transfer compared to metal oxide-based nanofluids. However, the primary challenges associated with graphene are its relatively high production cost and its stability in fluid suspensions that require the use of special additives (Arachchi et al., 2024).

Furthermore, the performance of nanofluids is significantly influenced by operational parameters such as flow rate and temperature. This research has demonstrated that the optimal flow rate for achieving maximum efficiency is within the range of 2 to 3 liters per minute. Flow rates that exceed or fall below this range tend to diminish the energy efficiency of the system due to uneven heat distribution or an increased energy requirement to drive the fluid (Prasetyo et al., 2023).

Nevertheless, despite the numerous advantages offered, the utilisation of nanofluids also encounters a number of challenges. The long-term stability of nanofluids in cooling systems remains a significant concern that warrants further investigation. Some operators have observed the occurrence of nanoparticle sedimentation after a few months of operation, which can lead to a reduction in heat transfer performance and an increase in system maintenance requirements. Additionally, the initial cost associated with nanofluid production and implementation remains a considerable barrier to the widespread adoption of this technology in industry (Ramesh Krishnan et al., 2024).

The preceding discussion demonstrates that nanofluids have the potential to transform engine cooling systems. However, their practical implementation necessitates meticulous planning and the formulation of strategies to surmount the operational challenges.

## CONCLUSION

The findings of this research indicate that nanofluid-based cooling systems have the potential to enhance energy efficiency and performance in industrial applications. Nanofluids have the potential to significantly enhance heat transfer capacity and energy efficiency, making them a promising solution to the cooling challenges faced by modern industry. Nevertheless, the successful implementation of this technology is contingent upon the fulfillment of several essential conditions. First, it is essential to conduct a meticulous optimization of the nanoparticle concentration in the base fluid, with the objective of achieving a balance between enhanced thermal conductivity and fluid viscosity. An excessively high concentration may result in an increase in hydrodynamic resistance, which could subsequently lead to a reduction in the overall energy efficiency of the system. Moreover, the selection of nanomaterials must be appropriate for the specific application. For instance, graphene-based nanoparticles demonstrate enhanced performance in high-temperature environments, whereas metal oxide-based nanofluids, such as Al2O3, are more suitable for applications with moderate temperature requirements. It is also crucial to oversee the operational conditions, such as the flow rate and pressure settings within the system, in order to guarantee optimal heat transfer. The findings presented in this research offer an invaluable basis for further inquiry, particularly in addressing technical obstacles such as the long-term stability of nanofluids and their current relatively high production costs. With continued advancement, nanofluid-based cooling technology shows immense prospective for extensive implementation across diverse industrial spheres, while bolstering global endeavors to enhance energy efficacy and diminish the environmental impact of conventional cooling systems.

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