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Experimental Analysis of Heat Transfer Enhancement in Automotive Radiators Using H_2O-Ag Nanofluids

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Abstract

This study investigates water-silver nanofluid as a high-performance coolant for automobile radiators to improve heat transfer performance. The radiators are one of the most vital parts of an engine cooling system because the engine performance must be maintained by rejecting heat to the environment. To improve the heat transfer performance, silver nanoparticles (5–8 nm) dispersed in water at a concentration of 4000 ppm were used instead of the conventional coolant fluids. Experiments were carried out at different flow rates (0.04–0.38 L/s) and inlet temperatures to establish the thermal behavior and performance of this nanofluid. The result is an enhancement of 13% in heat transfer coefficient compared to the base fluid, and improvements were found to correlate positively with increases in flow rates and inlet temperatures. This enhancement is attributed to the improved thermal conductivity of the nanofluid and its action in breaking the thermal boundary layer, hence, enabling the increase in convective heat transfer. These results show the tremendous potential for the water-silver nanofluids to be an eco-friendly, energy-saving alternative in automotive cooling systems. The present paper is one addition to a growing number of works dealing with nanofluid applications in thermal management and provides information on their feasibility and benefits. Future work should concentrate on the optimization of nanoparticle concentrations to ensure long-term stability and address economic factors in order to promote the adoption of nanofluids in commercial and industrial systems.

Keywords: Nanofluid, Heat transfer coefficient, Radiator, Flow rate.

1 | Introduction

These days, energy resources and environmental problems are now top agenda items in most countries. Any rise in the prices of fossil fuels increases the demand worldwide for more efficient engines, which impels

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improvement in energy systems to aid industry and the environment. Improvement in sustainable energy systems is very critical in meeting the energy needs of the world and controlling climate change. Previous studies have shown that Computational Fluid Dynamics (CFD) and thermophysical properties significantly influence heat transfer and flow behavior. These findings emphasize the importance of exploring nanofluids under varying thermal conditions to enhance radiator efficiency [1–3]. Technologies like Carbon Capture and Storage (CCS) are going to be very important for the reduction of industrial emissions of CO2 and, along with it, play a major role in the reduction of environmental damage caused by these emissions. In recent years, researchers have investigated various methods to improve the heat transfer efficiency of automotive radiators, since advancements in thermal management systems are crucial for reducing energy losses and lessening environmental impacts. Among these methods, the use of nanofluids has gained considerable attention due to their improved thermal properties, such as high conductivity and the ability to break the thermal boundary layers. Continuous research efforts are directed toward developing eco-friendly industrial practices, driven by the need to mitigate environmental impacts.

Among these endeavors, the exploration of biodiesel derived from kolanut oil and the development of natural corrosion inhibitors have garnered significant attention. These studies aim to provide sustainable alternatives to conventional industrial materials and processes, thereby contributing to a reduction in the ecological footprint of industrial activities. In this respect, it has been an imperative area of investigation to enhance heat transfer performance in heat engines. New heat transfer technologies have been developed using nanofluids and other novel cooling agents, aiming at improving thermal efficiency. These fluids, with their superior thermal conductivity and convective heat transfer characteristics, become advantageous substitutes for traditional cooling fluids in a wide range of applications, from automotive radiators to industrial cooling systems. The effect of disrupting thermal boundary layers and optimized flow dynamics enables nanofluids to achieve remarkable improvement in heat transfer performance, furthering the objectives of energy efficiency and sustainability. Changes in flow regimes, among other parameters, have a significant effect on the heat transfer characteristics of systems in engineering.

It has been observed that such changes in flow patterns affect the efficiency and stability of the heat exchange processes; hence, they are essential in optimizing performance in different applications [4–9]. Radiators are among the significant components in the vehicle's engines and play a crucial role in the performance of the engine by transferring heat to the environment through cooling fins [10]. The application of nanofluids in radiators has been explored in many studies to improve their thermal behavior. Naraki et al. [11] conducted an experiment on water-CuO nanofluid applied in a car radiator, and the results indicated that when the volume concentration rose from 0.15 vol% to 0.4 vol%, the overall heat transfer coefficient was enhanced by approximately 6% to 8%. On the other hand, Hussein et al. [12] also revealed that water-TiO_2 and water-SiO_2 nanofluids, running at the inlet temperature of 80°C, could effectively enhance the heat transfer rate by 20% and 32%, respectively, along with the associated efficiency improvement of 24% and 29.5%. Similarly, the effects of alumina nanoparticle concentration, inlet temperature, and flow rate on convective heat transfer in aluminum radiators were studied by Payghambarzade et al. [13].

Their results revealed that the addition of Al_2O_3 nanoparticles increased the Nusselt number up to 40%. Bazdidi-Tehrani et al. [14] investigated hybrid nanofluids containing Al_2O_3 and nano-encapsulated phase change material (n-octadecane); their results showed that such combinations bring a reduction in the fluid and wall temperatures while increasing the efficiency, especially at higher Reynolds numbers. Kia et al. [4] experimentally investigated the heat transfer and pressure drop for Al_2O_3 and SiO_2 oil-based nanofluids under constant wall heat flux and reported a maximum heat transfer enhancement of 41.4% for Al_2O_3 and 23.7% for SiO_2, when compared to base fluids.

Mirzaei et al. [15] investigated the characteristics of Jeffrey nanofluid in the presence of a magnetic field and showed that higher nanoparticle concentrations significantly enhance the thermal conductivity and heat transfer rate. Their results bring out the crucial role played by parameters like the Hartmann and Prandtl numbers in the optimization of nanofluids for different engineering applications. In related work, Dehghan

Afifi et al. [16] showed that in MHD fluid flows, the Nusselt number is strongly enhanced by higher Rayleigh numbers and heated obstacles, which significantly improves the thermal performance of the system. More works by Jalili et al. [17] have exhibited the critical roles of Reynolds and Hartmann numbers regarding the enhancement of efficiency in ferrofluid heat transfer and revealed how advanced techniques in flow dynamics optimization could be valuable. The Magnetohydrodynamic (MHD) heat transfer within a circular cavity has been comprehensively studied, which has led to the conclusion that the Nusselt number improves with the heating of the lower obstacles and reduces with the heating of the upper ones. The literature has also revealed that thermal radiation and the number of obstacles can be important factors in increasing heat transfer efficiency and thus the engineering utilization of MHD flows [18]. Additionally, numerous papers have explored the role of nanofluids in improving efficiency in thermal management systems. Armaghani et al. [19] numerically investigated forced convection heat transfer of nanofluids through porous channels and found the contribution of thermal non-equilibrium between phases.

Muhammad Ali et al. [20] reported the highest increase in heat transfer by 46% while using water-ZnO nanofluid in radiators made of aluminum tubes. Still, they observed that this enhancement had diminishing returns at higher concentrations. Fereidoon et al. [21] performed a numerical study of the behavior of water-aluminum oxide nanofluid in radiators using a Fortran-based computational solver to investigate the effects of Richardson number, volume fraction, and barrier height on the flow evolution and thermal performance.

Chavan and Pise [22] performed experimental measurements of the heat transfer coefficient for water-Al_2O_3 nanofluids while observing enhancements beyond the predictions offered by the Dittus-Boelter correlation. Similarly, Peyghambarzadeh [23] investigated the characteristics of water-CuO and water-Fe_2O_3 nanofluids under laminar flow conditions, achieving a 9% increase in the overall heat transfer coefficient. These outcomes clearly show that nanofluids are potential alternatives that can be used to improve the heat exchange process. Similarly, Dehghan Afifi et al. [24] also investigated the properties of water-based nanofluids with various nanoparticles and observed similar results in enhancing heat transfer performance under laminar flow conditions, further demonstrating the high potential of these nanofluids in improving heat exchange processes.

The present study is an experimental investigation of water-silver nanofluid as a coolant in an automotive radiator. This work investigates the effect of nanofluids on thermal efficiency with nanoparticle size varying between 5 and 8 nm, a flow rate between 0.04 and 0.38 L/s, and a fixed concentration of 4000 ppm. The results will add to the bourgeoning literature on environmentally friendly cooling options for automotive applications.

1.2 | Experimental process and data collection procedure

The diagram in Fig. 1 illustrates a schematic of the experimental apparatus. Nanofluid enters the heating tank and is heated using two 1400 W heating elements and one 2000 W heating element. Once the fluid reaches the desired temperature, the pump and fan are turned on, allowing the temperature variations to stabilize. The bulk inlet and outlet temperatures are measured using a data logger. Additionally, the average temperature of the radiator walls is determined using six randomly placed K-type thermocouples attached to the radiator walls.

To prevent heat loss, both the tank and connecting hoses are fully insulated. The heat exchanger used is an automobile radiator with 40 vertical aluminum tubes. For cooling the fluid passing through the radiator, a fan is installed behind the radiator so that the airflow and fluid flow cross each other indirectly. It is noteworthy that the system design allows for filling the heat exchanger from both the top and bottom. Finally, a drain valve is used to discharge the nanofluid from the tank.

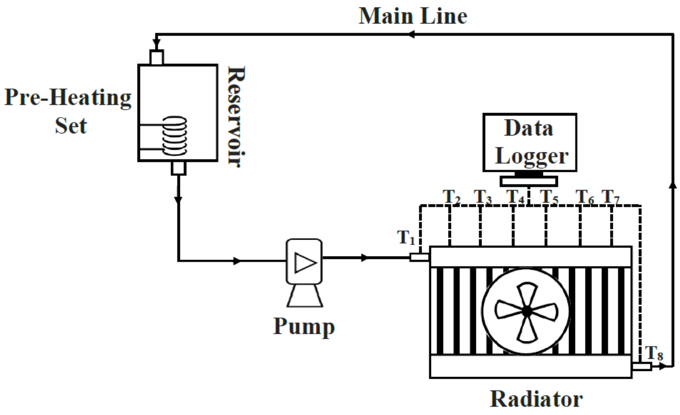


Fig. 1. Schematic of setup.

2 | Governing Equation

Assuming the nanoparticles are well-dispersed within the base fluid, the physical properties of the nanofluid can be determined using equations applicable to two-phase fluids. In this project, the relationships proposed by researchers were used to calculate the density, specific heat capacity, and thermal conductivity of the nanofluid at different nanoparticle volume fractions. It is noteworthy that all properties were calculated at the bulk fluid temperature. The density of the nanofluid is calculated using the following equation [25].

$$\rho_{nf} = \phi\rho_{nf} + (1-\phi)\rho_{nf}. \tag{1}$$

The specific heat capacity of the nanofluid is determined using the following equation.

$$c_{pnf} = \frac{\phi\rho_n c_{pn} + (1-\phi)\rho_f c_{pf}}{\rho_{nf}}. \tag{2}$$

The thermal conductivity of the nanofluid is described by *Eq. (3)*.

$$K_{nf} = \frac{K_n + (\varphi - 1)K_f - \phi(\varphi - 1)(K_f - K_n)}{K_n + (\varphi - 1)K_f + \phi(K_f - K_n)} \times K_f. \tag{3}$$

The Reynolds number is calculated using *Eq.(4)*.

$$Re_{nf} = \frac{\rho_{nf} \times V \times D_{hyd}}{\mu_{nf}}. \tag{4}$$

The main equation used in this paper relates to the heat transfer coefficient, defined by *Eq. (5)* and *Eq. (6)*.

$$h_{nf} = \frac{\dot{m}c_{pnf}(T_{in} - T_{out})}{A(T_b - T_w)}. \tag{5}$$

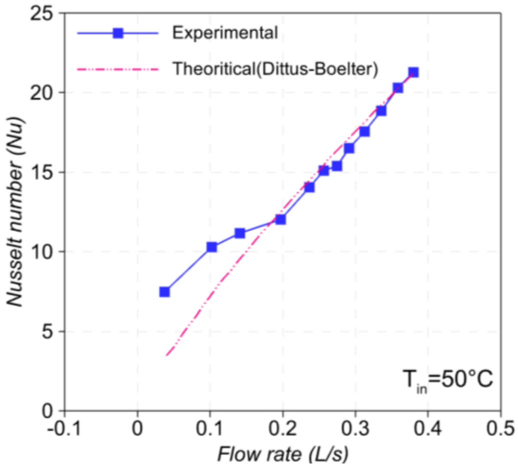
$$Nu = \frac{h_{nf}D_{hyd}}{K_{nf}}. \tag{6}$$

3 | Results and Discussion

3.1 | Validation

In this study, experiments were performed on pure water to enhance the precision and reliability of the data before testing on nanofluids. To examine the experimental results with theoretical data, the Dittos-Boulter equation (*Eq. (7)*) has been used. In *Figs. 2a-2c*, the Nusselt number is plotted as a function of flow rate under conditions of inlet temperature of 50◦C, 60 ◦C, and 70◦C, respectively.

$$Nu = \frac{h \times D}{k} = 0.0236 \times Re^{0.8} \times Pr^{0.3}. \quad (7)$$



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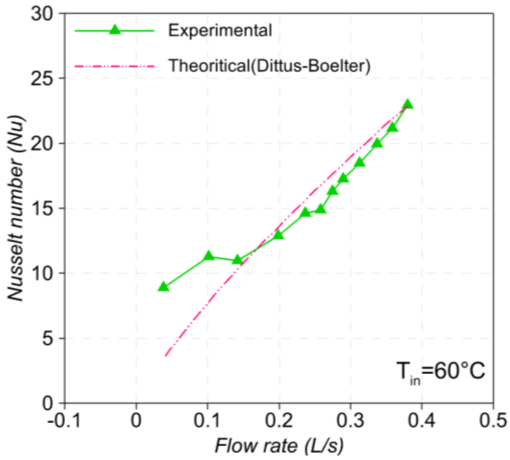

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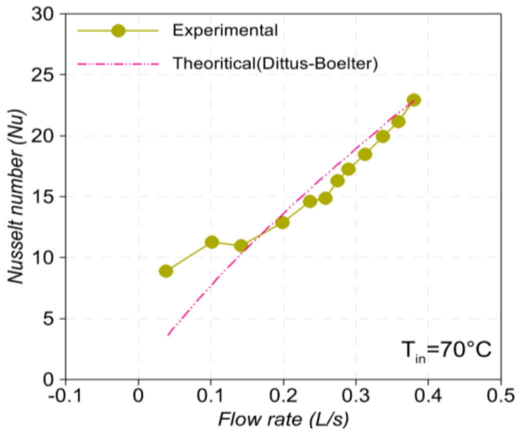


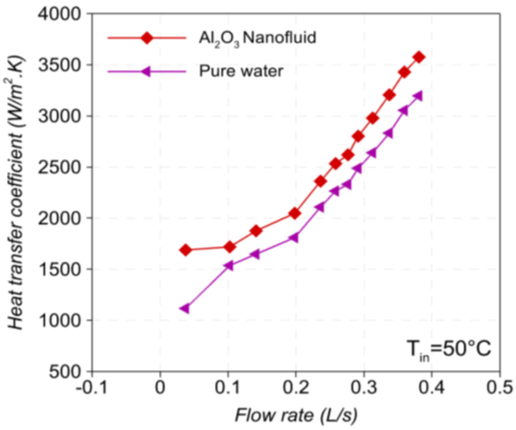
c.

Fig. 2. Theoretical and experimental comparisons for pure water at: a. Tin=50℃, b. Tin=60℃, and c. Tin=70℃.

Based on the *Figs. 2a-2c*, the values gained from the experimentation conform to the theoretical outcomes, and the difference at temperatures of 50, 60, and 70 degrees is 3%, 6%, and 6%, respectively, which are less than 10%. Thus, the findings of this study are authentic and verified.

3.2 | Heat Transfer

The nanofluids were prepared with Al_2O_3 nanoparticles (ranging from 5 to 8 nm) in pure water at a concentration of 4000 ppm. The effect of two key parameters, including different flow rates (0.04 to 0.38 L/s) and various inlet temperatures (40 ◦C, 50 ◦C, and 60 ◦C) on the heat transfer coefficient of the flow, is investigated.



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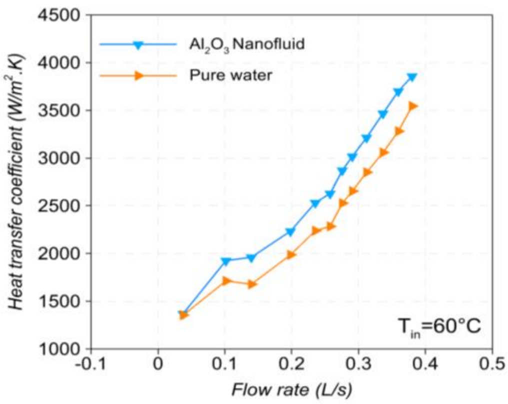

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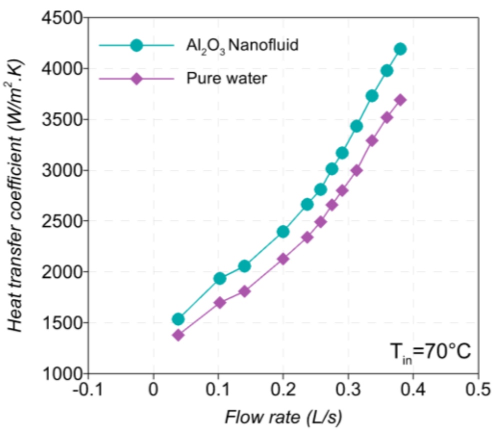

c.

Fig. 3. Variations of heat transfer coefficient with flow rate at: a. Tin= 50℃, b. Tin=60℃, and c. Tin=70℃.

As illustrated in *Fig. 3*, using nanofluid in comparison to pure water increased the heat transfer coefficient by an average of approximately 13%, 13%, and 12.9% for inlet temperatures of 50, 60, and 70°C, respectively. When nanoparticles are added to a pure fluid, there is a remarkable improvement in the thermal conductivity of the mixture. The reason behind such an increment in heat transfer is mostly related to the ratio of thermal conductivity by the reduced thickness of the thermal boundary layer (k/δt). The highly thermally conductive and chaotic inflow of nanoparticles disturbs and diminishes the thickness of this layer at the surfaces of tubes. Such an effect prolongs the interaction of nanoparticles with the heat transfer mechanism.

This would delay the development of the thermal boundary layer, allowing more nanoparticles to take part in heat exchange and consequently increasing the average heat transfer coefficient and the Nusselt number. The presence of nanoparticles affects fluid dynamics by introducing random movements and collisions that elevate energy transfer rates even more. Since the interactions become frequent with an increase in the concentration of nanoparticles in the fluid, the heat transfer is accelerated. Higher concentrations hence, favour better convective heat transfer characteristics. An increase in the Reynolds number increases the nanoparticles dispersion, emulates the turbulence, and therefore leads to a better overall heat transfer coefficient.

5 | Conclusion

This study established that using water-Al_2O_3 nanofluid in a car radiator gives a 13% increase in the heat transfer coefficient compared to conventional water, since the nanofluid has higher thermal conductivity and enhances convection. The heat transfer coefficient showed an increase with the increase in the flow rate and temperature, meaning that nanofluids are really good for the enhancement of thermal management. These findings will still prove the potential of nanofluids as an efficient alternative in automotive cooling systems by enhancing energy transport and disrupting thermal boundary layers. Further research should be focused on the optimization of nanoparticle concentration to address any cost and stability considerations necessary for broader application in cooling technologies.

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