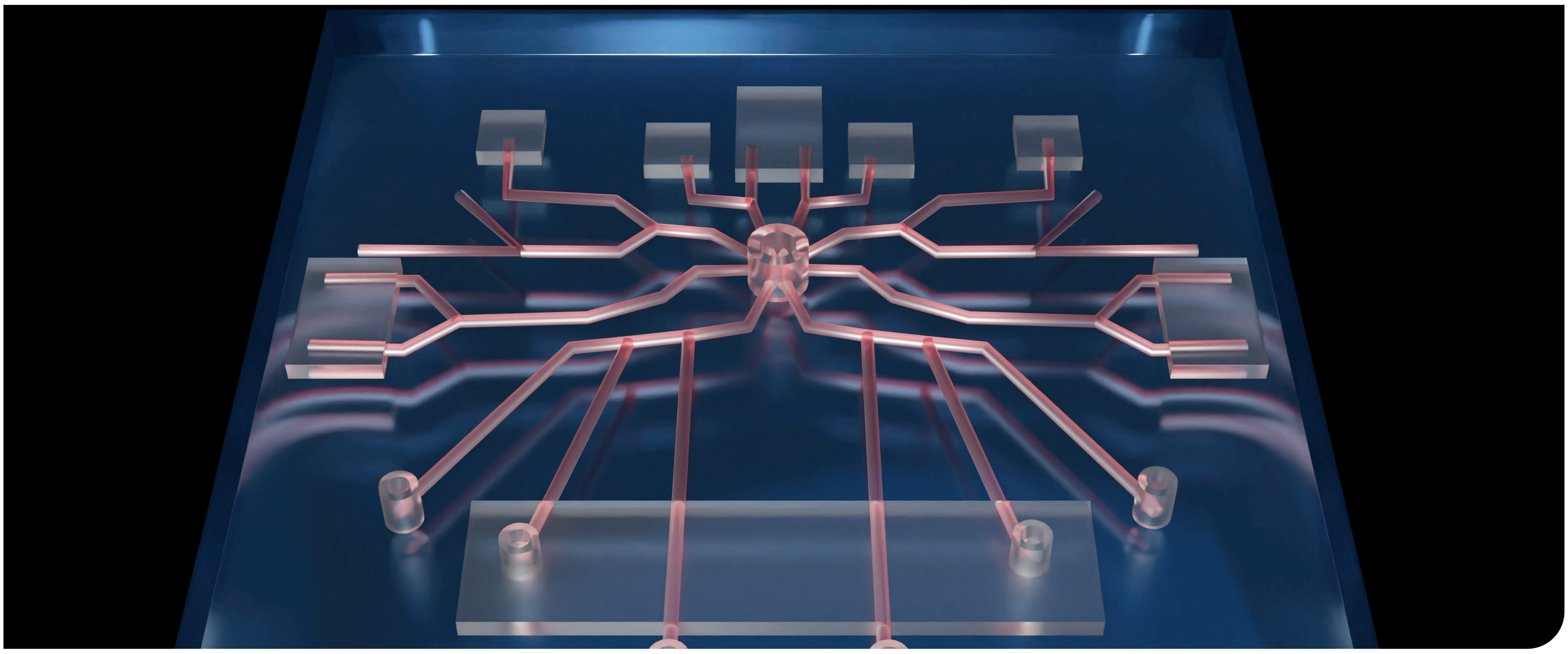
ANALYSIS OF THE APPLICATION OF NANOFLUID COOLANTS IN VEHICLE'S COOLING SYSTEM



1. Introduction

Car performance is important for the development of an eco-friendly environment. Minimizing gas use through motor efficiency advances the motor industry closer to a healthier environment. Both lithium-ion batteries in EV vehicles and gas-powered engines suffer from lost work which leads to a reduction in lifespan and acts at the expense of fuel economy, respectively. One way of providing higher levels of performance is through the power efficiency of the motor. It is very valuable to minimize heat loss to create a higher quality vehicle with a longer lifespan and greater fuel economy. Nanoparticles can be infused with a glycol-water mixture and serve as a vehicle coolant, increasing thermal conductivity and resulting in higher viscosity at higher temperatures. This paper will discuss how nanofluid-based coolants will improve the performance of standard coolants in terms of thermal conductivity and viscosity, which impact the heat transfer of the coolant. In addition, the paper will discuss limitations in using nanofluids in coolants.

2. Heat Transfer Enhancement in Nanofluid-Based Coolants

The goal of using nanofluids in coolants is to increase thermal conductivity which in turn allows more heat to be transferred from the engine to the fluid, allowing enhanced engine performance. Several studies have been conducted in investigating the nanofluid impact on thermal conductivity. Sundar et al. [1] investigated the thermal conductivity of Fe_3O_4–water nanofluids, exploring different Fe_3O_4 nanoparticle concentrations. The paper observed a steady increase in thermal conductivity of Fe_3O_4 nanofluids as the volume fraction of nanoparticles rose from 0.2% to 2%, as seen in Fig. 1.

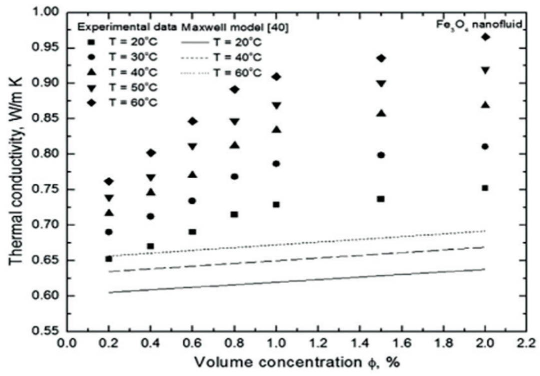


Fig. 1. Effect on volume concentration on thermal conductivity in comparison to Maxwell model. Sundar et al. [1].

This rise in thermal conductivity is attributed to the heightened Brownian motion of nanoparticles at higher concentrations. The amplified movement of nanoparticles resulted in increased collisions with surrounding fluid molecules, thereby enhancing thermal conductivity. However, the thermal conductivity failed to align with the Maxwell model depicted in Fig. 1. Raja et al. defines the Maxwell model with the following equation (Equation 1).

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)}$$

(Equation 1)

Nomenclature

k_{eff} = effective thermal conductivity
k_f = base fluid thermal conductivity
k_p = particle carbon nanotube based thermal conductivity
ϕ = volume fraction (%)
Ψ = particle sphericity
n = empirical shape factor

The Maxwell equation estimates thermal conductivity of a mixture assuming a low volume fraction of spherical particles [2]. While the nanoparticle fluid had low volume fraction, Fe_3O_4 particles have cubic geometry. Therefore, this variation from the Maxwell model may be caused by the non-spherical shape of the Fe_3O_4 particles. Other equations such as the Hamilton and Crosser equation (Equation 2) consider the empirical shape factor (n) of the nanoparticle fluid.

$$\frac{k_{eff}}{k_f} = \frac{k_p + (n-1)k_f - (n-1)\phi(k_f - k_p)}{k_p + (n-1)k_f + \phi(k_f - k_p)}$$

(Equation 2)

The empirical shape factor is calculated from 3/Ψ, where Ψ is the particle sphericity. Spherical particles are given the value of Ψ = 3 [2]. Results in Fig. 1 may align closer to the Hamilton and Crosser equation in comparison to the Maxwell equation.

MgO-based ethylene glycol nanofluids were studied by Xie et al. [2], which measured thermal conductivity at concentrations of MgO nanoparticles ranging from 0.5% to 5% and across temperatures of 10 to 60℃. They also compared ethylene glycol nanofluids based on MgO nanoparticles with previously researched nanoparticles. Shown in Fig. 2, researchers found that higher nanoparticle concentrations led to increased thermal conductivity. The 5% volume fraction showed the most significant increase, with a 40.6% increase at 30℃. The study suggests that this rise might be due to particle aggregation, potentially increasing contact among particles and boosting thermal interaction and conductivity. As it is shown in Fig. 2, MgO particles underperformed in comparison to the other nanoparticles studies in the literature. For instance, at their highest volume fraction of 3%, CuO nanoparticles exhibited a 25% increase in thermal conductivity in comparison to MgO nanoparticles which only performed at around 14% increase.

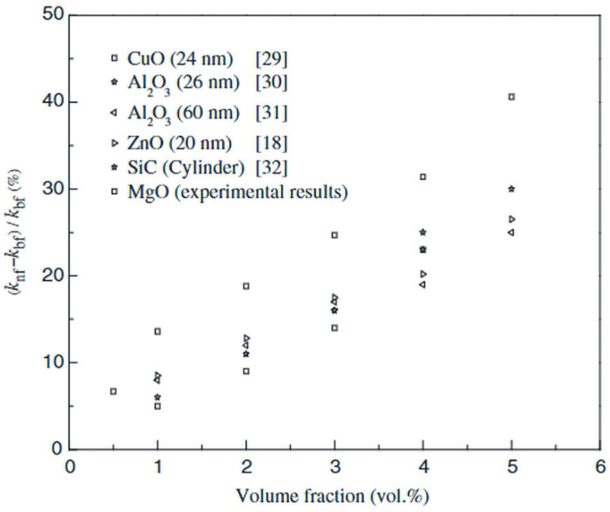


Fig. 2. Effect of volume fraction on thermal conductivity. Xie et al. [2].

Another study by Leong et al. [3] investigated heat transfer and its relation to volume concentration. From a range of concentrations between 0% to 2%, heat transfer increased 3.8% with the incorporation of 2% copper nanoparticles at 6000 and 5000 Reynolds numbers (turbulent flow). Fig. 3 results show a linear relationship between air Reynolds number and heat transfer.

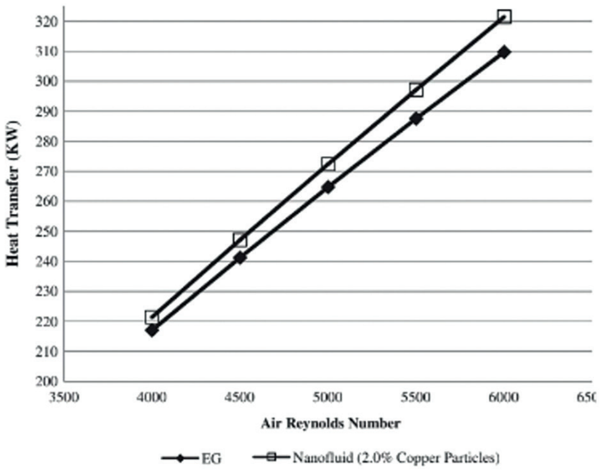


Fig. 3. Effect of air Reynolds number and particle concentration on heat transfer. Leong et al. [3].

The same study found that the overall thermal performance of a radiator using nanofluid coolant revealed a measurable increase in heat transfer when compared to the case of using ethylene glycol as coolant. As demonstrated in Fig. 4, higher concentrations of copper nanofluid lead to an increase on overall heat transfer in contrast to ethylene glycol base fluid. 2.0% copper particles were measured to have a heat transfer of 222 kW at 7000 Reynolds number, while the thermal conductivity of ethylene glycol base fluid at the same Reynolds number was 219 kW.

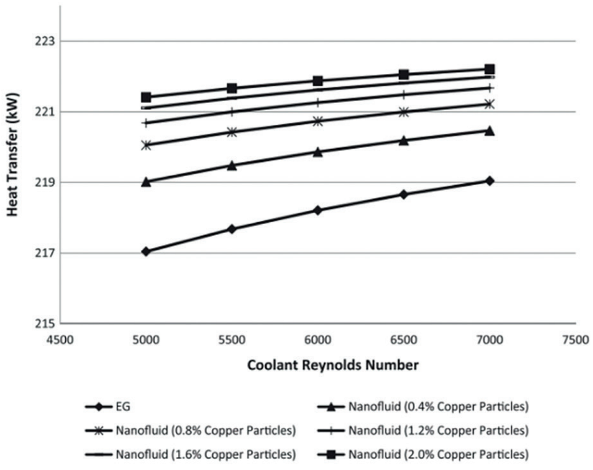


Fig. 4. Effect of nanofluid Reynolds Number on heat transfer with varying concentrations of copper particles in nanofluid. Leong et al. [3].

The exact reason for this trend in thermal conductivity was explained by S. Wiriyasart et al. [4], concluding that the larger concentrations of nanoparticles within a fluid allow for more molecular collisions that transfer momentum and energy, thus allowing for heat exchange to occur more frequently. The addition of nanoparticles into the fluid increases heat conductivity and heat transfer of a coolant, and the resulting nanofluid can therefore be a promising candidate for the automotive industry. The relation of concentration to heat transfer and Reynolds number demonstrates a positive gain from implementing nanofluids as coolants. The increase in concentration and Reynolds numbers will allow more energy to be transferred into the coolant, reducing the stress on lithium-ion batteries and gas-powered engines. Therefore, the longevity of lithium-ion batteries will increase, and the amount of gas used in engines will be reduced.

3. Nanofluid-Based Coolants Influence on Viscosity

A property of coolants that allows for their efficient use is the viscosity. Lower viscosity is preferred for coolants as it will allow the fluid to travel through the system with little resistance. With low viscosity, working in tandem with thermal conductivity, the nanoparticles within the fluid can absorb the heat energy from the engine and travel down the system. This will allow for other nanoparticles to absorb the energy that can be dispersed through the fluid more efficiently. A study performed by Kole et al. investigated the effect of nanoparticle concentration in Al_2O_3-water and CuO-water nanofluids [5]. The data shown in Fig. 5 reveals that at temperatures between 10 to 50℃, and volume fractions ranging from 0.01 to 0.015, as volume fraction increased, nanofluid viscosity also increased.

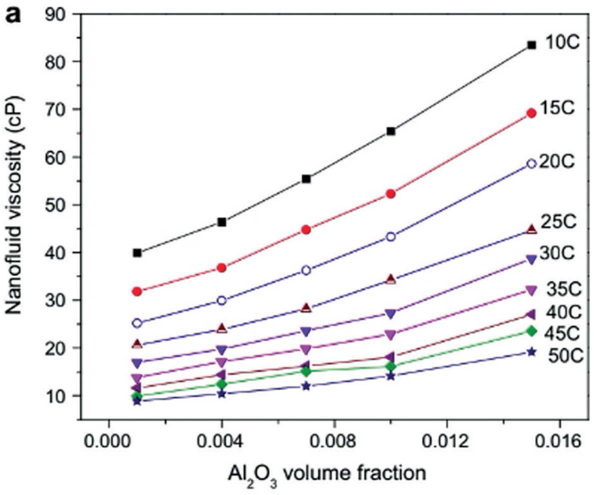


Fig. 5. Effect of Al_2O_3 volume fraction and temperature on nanofluid viscosity. Kole et al. [5].

Elias et al. observed similar results, using Al_2O_3 nanoparticles, consistently demonstrating higher viscosity compared to the base water/ethylene glycol coolant at all volume concentrations [6]. Additionally, as the nanoparticle concentration rises within the base fluid, the nanofluid's viscosity increases. However, this viscosity was noted to decline with rising temperature, as seen in Fig. 6.

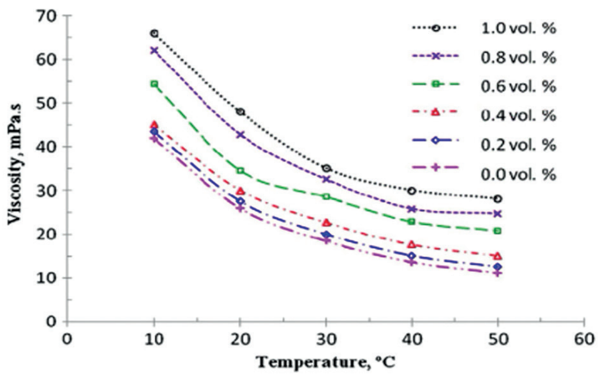
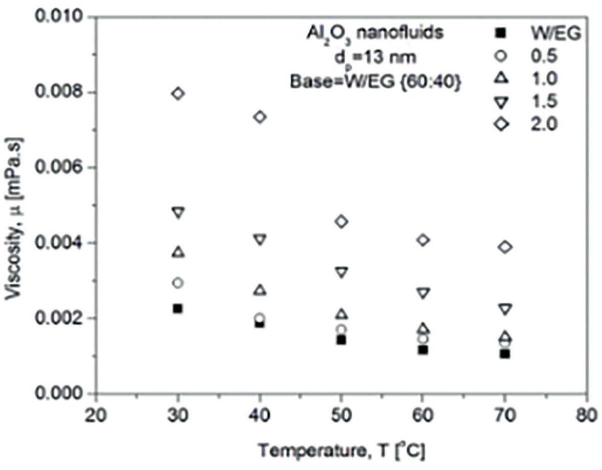


Fig. 6. Effect of temperature and volume concentration of nanofluid on viscosity. Elias et al. [6].

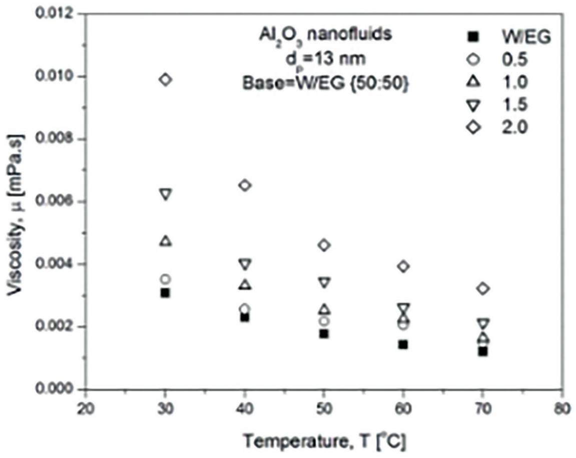
According to Hamid et al. [7] the paper concluded that the increase in nanoparticle concentration increased the fluid internal shear stress, which in turn increases viscosity. It can be concluded from the aforementioned studies that the addition of nanoparticles into the fluid increases viscosity. In addition, this alteration in the flow behavior is due to the interaction between nanoparticles whilst in the fluid. These findings do not demonstrate a positive enhancement of coolants. Coolants must have low viscosity in order to flow smoothly throughout a system. As such, this limitation must be balanced and optimized with tailored concentrations of the nanoparticle to increase thermal conductivity and reduce viscosity.

4. Temperature Influence on Thermal Conductivity and Viscosity

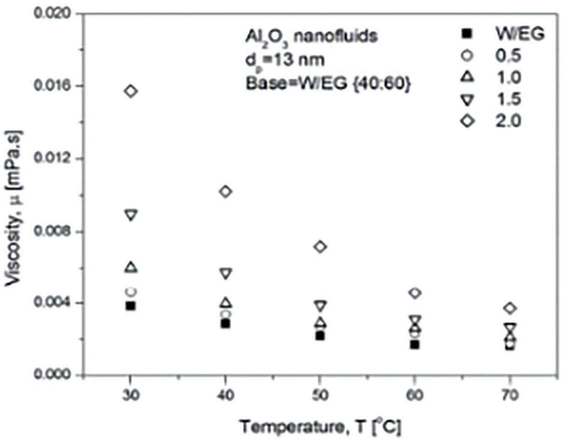
In the aforementioned study by Elias et al., the impact of temperature on nanofluids viscosity was investigated at temperature between 10 and 50℃. It was found that the temperature increase resulted in decreased viscosity by up to 73% with respect to the base fluid [6]. However, the EV lithium-ion batteries run optimally at 60℃, according to Ma et al. [8], whereas oil engines operate near 90 to 115℃, according to Mukhtar et al. [10]. Therefore, due to higher operating temperatures, researching how temperature affects thermal conductivity and viscosity is critical in applying nanofluids into coolants. Hamid et al. studied nanofluid viscosity of different water/ethylene glycol mixtures and concluded that as temperature increases, nanofluid viscosity decreases exponentially as seen in Fig. 7 [7].



(a) Base ratio (W/EG) of 60:40



(b) Base ratio (W/EG) of 50:50



(c) Base ratio (W/EG) of 40:60

Fig. 7. Effect of temperature on viscosity on Al_2O_3 nanofluid mixture with base fluids weight ratios of 60:40; 50:50; 40:60 water/ethylene glycol (W/EG). Hamid et al. [7]

This finding was supported by Li et al. [11] who studied the effect of temperature on the thermal conductivity of Fe2O3 nanoparticles in water/ethylene glycol mixtures at temperatures between 10 and 50℃. The authors found that thermal conductivity increases with an increase in temperature. It was also noted that this similar trend was observed in base engine coolant fluids. The increase in viscosity and thermal conductivity alongside temperature was also reported by Sundar et al. in their study on Fe_3O_4-water nanofluids [1] seen in Fig. 8.

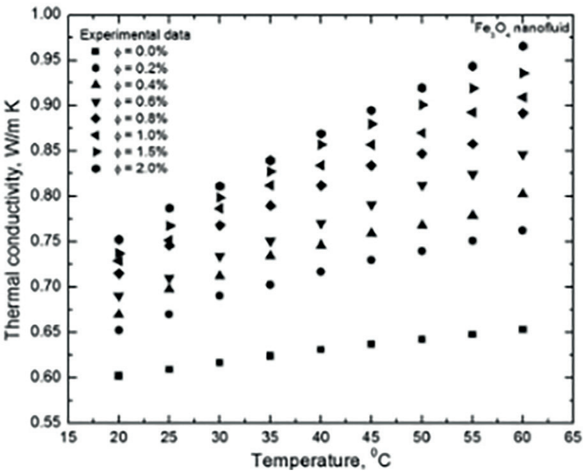


Fig. 8. Effect of temperature on thermal conductivity on Fe_3O_4 nanoparticles. Sundar et al [1].

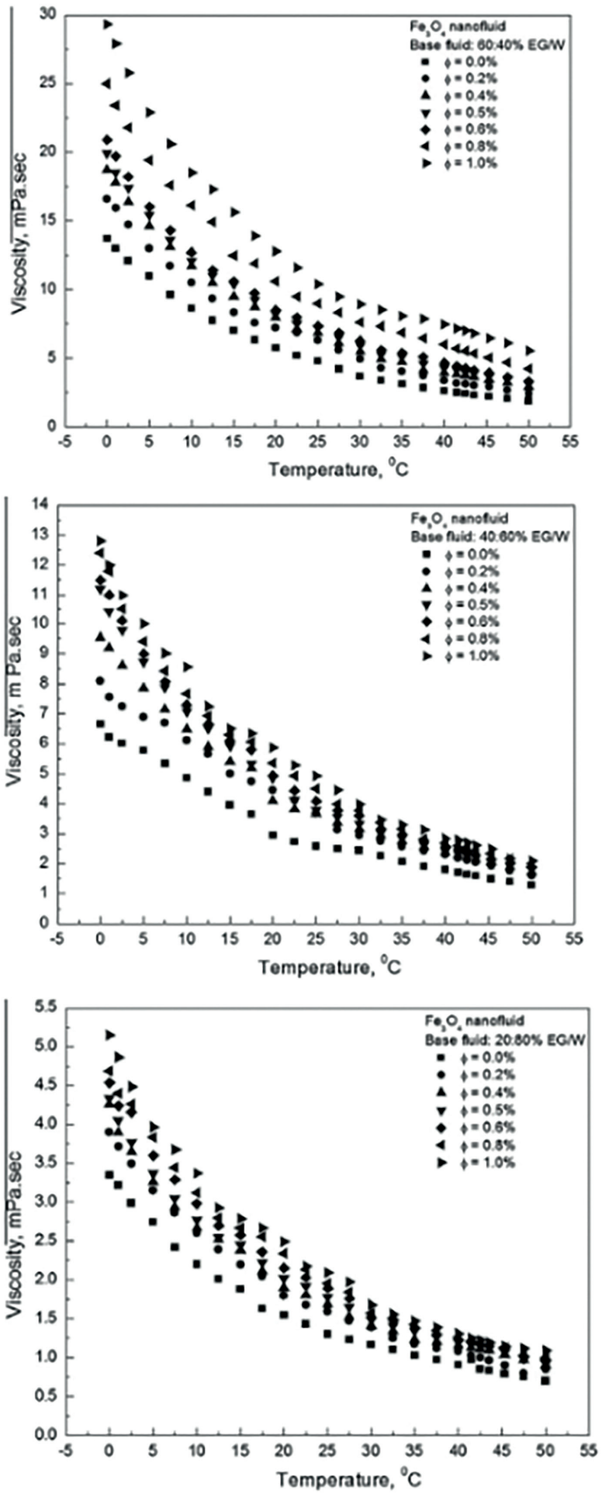


Fig. 9. Effect of temperature on viscosity in Fe_3O_4 nanofluid mixture with base fluids of 60:40; 40:60; 20:80 EG/W. Sundar et al. [12]

In another study, Sundar et al. [12] measured the viscosity of nanofluids of magnetic Fe_3O_4 nanoparticles dispersed at low volume concentrations in ethylene glycol/water (EG/W) mixtures of different EG/W ratios. Ethylene glycol water mixtures of 60:40, 40:60 and 20:80 (weight %) were used in the experiment at a temperature range between 0 to 50℃. As depicted in Fig. 9, viscosity increases with increase of the volume concentration of Fe_3O_4 nanoparticles and decreases with increase of temperature. The viscosity increase was specifically found to be more enhanced at an ethylene glycol water mixture of 60:40 compared to 40:60 and 20:80 mixtures under the same nanoparticle concentrations. At 50℃, the highest enhancement in viscosity in relation to temperature was found at 1.0% nanoparticle concentration, with the 60:40 mixture having 2.94 times increase in viscosity compared to the normal base EG/W fluids. An increase of 1.61 times in 40:60 mixture and 1.42 times in 20:80 mixture was also observed.

Study conducted by Afrand et al. [13] investigated the coolant and lubricant applications of SiO_2-multi-walled carbon nanotubes (MWCNTs), ¬¬in heat engines and it was found that as temperature increased between 20 to 60℃ with volume fractions of SiO_2 nanoparticles between 0% to 1%, viscosity decreased by 82%, as seen in Fig. 10.

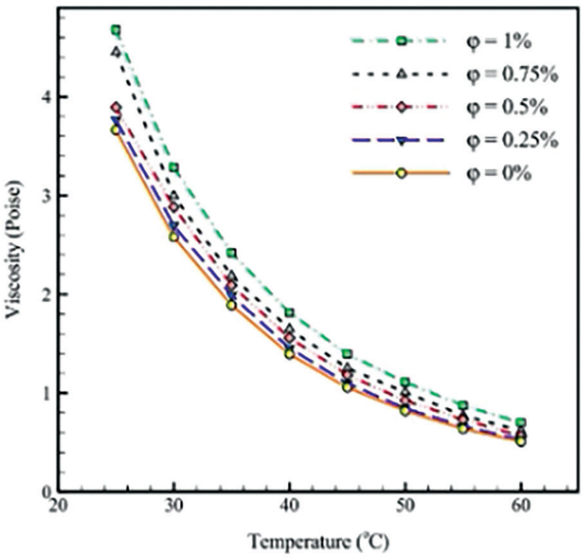


Fig. 10. Variations of dynamic viscosity with temperature at different solid (MWCNTs) volume fractions. Afrand et al. [13]

Finally, a study conducted by Tavernier et al. [14] on heat transfer performance of nano-enhanced propylene glycol water mixtures found that the heat transfer coefficient increased with increasing temperature of the nanofluid due to the drop in viscosity. The test was conducted at temperatures of 308.15 K and 318.15 K, and the increase in convection heat transfer coefficient varied between 12.4 to 25.6% in graphene nanoplatelet nanofluids of graphene mass fractions of 0.005, 0.075 and 0.010. Fig. 11 reveals an increase in flow rate for all temperatures of the experiment [14].

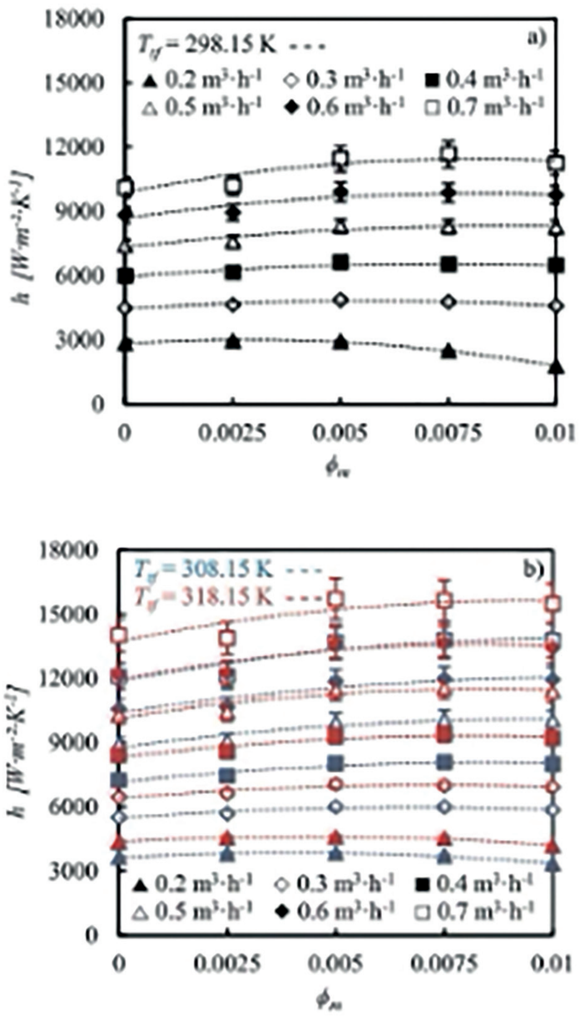


Fig. 11. Experimental convection heat transfer coefficients as a function of fGnP mass fraction at different flow rates for tested fluid/hot water average temperatures of: (a) 298.15 K/313.15 K and (b) 308.15 K/323.15 K and 318.15 K/333.15 K. Error bars indicate the expanded (k = 2) uncertainty. Tavernier et al. [14].

From evidence reported, nanofluids can perform at higher temperatures with increased performance due to the improved thermal conductivity and reduced viscosity. Following the trends established, nanofluids theoretically should be able to run at the temperatures required for the operation of lithium-ion batteries and oil engines.

5. Challenges and Considerations: Nanofluid Preparation and Behavior

There are several challenges when it comes to the implementation of nanoparticles into the automotive industry, such as the purity of the fluid. In addition, the behavior of nanofluids with respect to the physical characteristics of nanoparticles plays a role in the performance of the nano-coolant. According to Apmann et al., thermal conductivity decreases with the increase in the diameter of the nanoparticle, as demonstrated in Fig. 12 [15]. The decrease in thermal conductivity was determined to be caused by a decrease in Brownian motion.

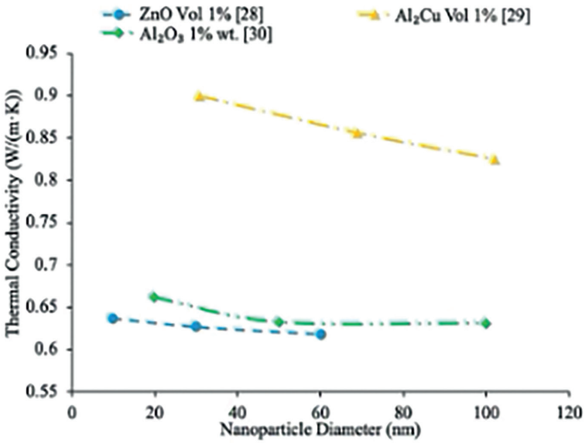


Fig. 12. Effect of nanoparticle diameter on thermal conductivity. Apmann et al. [15].

During the production of nanofluids, surfactants are used to create a stable fluid. Xuan et al. investigated the role of surfactants in preparing nanofluids [16]. In the paper it was concluded, based on the data from Fig. 13, that higher levels of surfactant sodium dodecyl benzoic sulfate (SDBS) in nanofluids reduced overall heat transfer performance of the fluid. Therefore, lower concentrations of surfactants present in nanofluids were determined to increase the overall performance of the nanofluid with respect to heat transfer, hence resulting in an increase of the engine's efficiency. The use of surfactants is necessary for the preparation of stable nanofluids, as they enable effective dispersion of the employed nanoparticles. However, for a vehicle to run more efficiently, it is best to minimize the concentration of surfactants present in nanofluid coolants.

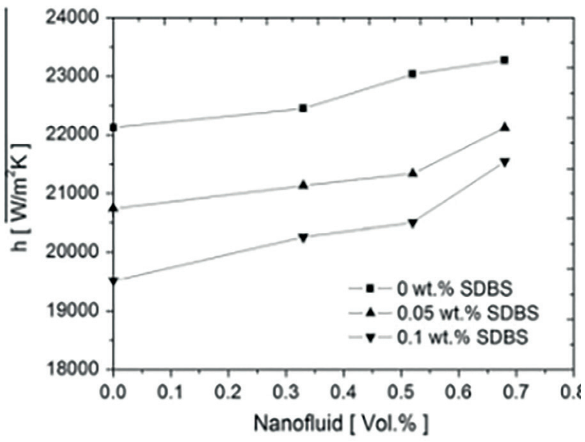


Fig. 13. Effect of surfactants (SDBS) on heat transfer. Xuan et al. [16].

The effect of nanofluid on pumping power is also a factor that should be considered. According to Leong et al., adding copper nanoparticles resulted in an escalation of coolant pressure drop of the studied Cu nanofluids, as seen in Fig. 14 [3]. Specifically, 2% copper particles led to a pressure drop of 110.97 kPa, contrasting with 98.93 kPa for the base ethylene glycol. This increased pressure necessitates higher coolant pumping power. Calculations made in the paper concluded a 12.13% rise in pumping power at the 2% inclusion of copper nanofluids in comparison to the base fluid. This decrease in pressure and increase in power can cause the coolant to boil at low temperatures which can overheat the engine.

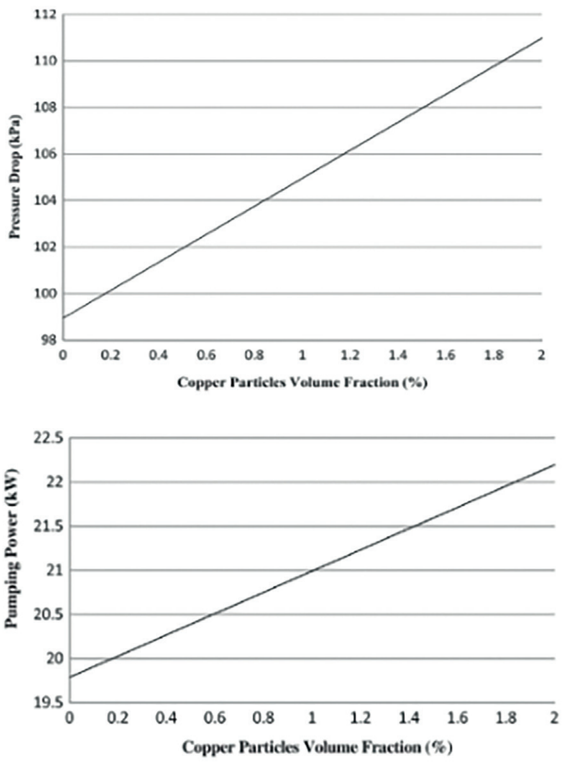


Fig. 14. Effect of Cu particle volume fraction on pressure drop and pumping power. Leong et al. [3].

Other important parameters to be considered are the dispersion of nanoparticles in the nanofluid and the age of the nano-coolant. A paper by Bhogarem et al. studied the applications and challenges of nanofluids acting as coolants in engines and studied the change of the dispersion behavior over time. According to Fig. 15, it was found that when left idle, Al_2O_3 nanofluid accumulates at the bottom of the container [17]. Therefore, when a motor vehicle is not operating, the nanofluid coolant will accumulate near the lowest points in the coolant system, compromising the performance of the coolant when the engine is activated.

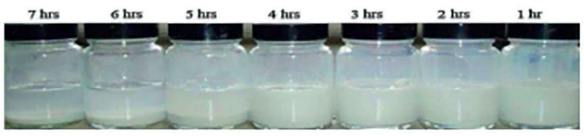


Fig. 15. Al_2O_3 nanofluids stability overtime. Bhogarem et al. [17].

Eastman et al. studied the dispersion behavior of copper nanoparticles that are influenced by age. The study used copper nanoparticles of various volume fractions for 3 samples. The samples contained a copper solution that was prepared 2 months prior to the experiment, a copper solution of the same age as the previous one, which also contains thioglycolic acid, and a fresh copper solution prepared 2 days prior to the experiment. The experiment used thioglycolic acid in order to investigate its behavior as a stabilizing agent and its impact on thermal conductivity [18]. As seen in Fig. 16, a greater thermal conductivity is observed in the 2-day-old copper sample with respect to the 2-month-old sample. The sample containing thioglycolic acid also exhibited a dramatic increase in thermal conductivity.

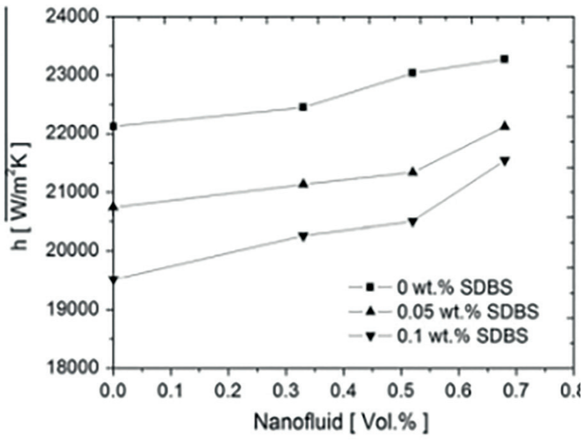


Fig. 16. Thermal conductivity of ethylene glycol trend with volume fraction with different ages of nano-fluid. Eastman et al. [18].

Typical water ethylene glycol coolants used in motor vehicles are changed in order to prevent overheating of the engine, however, knowing this trend in copper nanoparticles, further studies must be carried out in order to determine the overall thermal conductivity performance change over time compared to water ethylene glycol coolants. Preparation of the nanofluid and particle behavior play a key role in ensuring safety and improvement in engine performance. If these challenges can be overcome, then the use of nanofluid in the motor vehicle industry is plausible.

6. Conclusions and Future Research

Thermal conductivity and viscosity have a key role in heat transfer in a motor vehicle, and it is the responsibility of the engineers to make the most efficient use of these properties. Nanoparticles in coolants are the key to making a more efficient coolant. Several studies have shown the impact nanoparticles have on fluids: with increased concentration, there is an increase in thermal conductivity and heat transfer. In addition to this increase of conductivity, there is an increase in viscosity and an optimized concentration should be identified in each case study.

Despite the aforementioned benefits of nanoparticles, there are limitations of having nanofluids acting as a coolant. The cost of the manufacturing of nanofluid coolants was not taken into consideration in the paper and must be considered for the widespread market of the motor industry. In addition, motor design may need to be altered to get the maximum performance from nanofluid coolants. While nanofluids seem to be a promising start into a more efficient future, much more research needs to be done before large-scale implementation.

Future research should focus on mitigating potential environmental and safety concerns associated with nanofluids use. Developing eco-friendly nanoparticles, assessing long-term environmental effects, and ensuring the recyclability or proper disposal of nanofluid-based coolants will be crucial. Efforts to improve the scalability and cost-effectiveness of nanofluid production will be essential for widespread adoption in the automotive industry. Streamlining manufacturing processes and conducting comprehensive cost-benefit analyses will determine the feasibility of integrating nanofluids into mass-produced vehicles. In addition, integrating responsive nanoparticles or additives that can adapt to changing temperatures or conditions within the cooling system could optimize heat transfer performance dynamically. These 'smart' nanofluids might alter their viscosity or thermal conductivity based on temperature fluctuations, ensuring efficient heat dissipation across varying operational conditions. Investigating the compatibility of nanofluids with varied materials commonly used in automotive cooling systems is essential. Understanding potential corrosion or erosion effects and developing strategies to mitigate these issues will be crucial for system longevity.

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About the Authors

Dr. Raj Shah serves in the role of Director at Koehler Instrument Company in New York, boasting an impressive 28-year tenure with the organization. Recognized as a Fellow by eminent organizations such as IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute, and The Royal Society of Chemistry, he stands as a distinguished recipient of the ASTM Eagle award. Dr. Shah, a luminary in the field, recently coedited the highly acclaimed “Fuels and Lubricants Handbook,” a bestseller that unravels industry insights. Explore the intricacies at ASTM’s Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY).

His academic journey includes a doctorate in Chemical Engineering from The Pennsylvania State University, complemented by the title of Fellow from The Chartered Management Institute, London. Dr. Shah holds the esteemed status of a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute, and a Chartered Engineer with the Engineering Council, UK. Recently honored as “Eminent Engineer” by Tau Beta Pi, the largest engineering society in the USA, Dr. Shah serves on the Advisory Board of Directors at Farmingdale University (Mechanical Technology), Auburn University (Tribology), SUNY Farmingdale (Engineering Management), and the State University of NY, Stony Brook (Chemical Engineering/Material Science and Engineering).

In tandem with his role as an Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Dr. Shah’s impact spans over three decades in the energy industry, with a prolific portfolio of over 600 publications. Dive deeper into Dr. Raj Shah’s journey at https://bit.ly/3QvfaLX.

For further correspondence, reach out to Dr. Shah at rshah@koehlerinstrument.com.

Dr. Stefanos (Steve) Nitodas is a chemical engineer by training and the holder of a Ph.D. degree in Materials Science and Chemical Engineering from the University of Rochester, New York. He has been a member of the Faculty of the Department of Materials Science and Chemical Engineering at Stony Brook University, NY, since 2018. He teaches core chemical engineering courses, including process control, reaction engineering and separation processes. Prior to Stony Brook University, he worked for several years in the industry as R&D Director and also as Industrial Business Development Manager, starting in the microelectronics sector and then continuing in the nanotechnology industry for 12 years. His expertise lies in reaction engineering, advanced process control and novel nanomaterials development through catalytic processes, as well as in the synthesis and applications of nanostructured carbon and polymer nanocomposites. Dr. Nitodas is the recipient of the Morris Cohen Distinguished Award of the Corrosion Division of the Electrochemical Society. He is also a member of the American Institute of Chemical Engineers (AIChE) and the faculty advisor of the AIChE chapter at Stony Brook University. He has served as guest editor in MDPI and the Journal of Nanoscience with Advanced Technology.

Steve.nitodas@stonybrook.edu

Stefanos Nitodas

Simultaneously, within the dynamic internship program at Koehler Instrument Company in Holtsville, **Daniel Baek** emerges as standout participant. He is pursuing his studies in Chemical Engineering at Stony Brook University, Long Island, NY.

Daniel.baek@stonybrook.edu

Daniel Baek

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com