Effect Of Silver Nanoparticle-Enriched Coolant (Ag) In an Ethylene Glycol-Water Solution (Eg50%) On the Thermal-Hydraulic Performance of an Automotive Radiator

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Abstract - Effective heat dissipation plays a vital role in optimizing radiator performance. This study investigates the impact of silver nanoparticle-enriched nanofluid coolant on heat transfer efficiency in an automotive radiator system. The research specifically examines the heat transfer process from the radiator body to copper fins, which were strategically designed to enhance the surface area for improved thermal dissipation. ANSYS Fluent was utilized to simulate the heat transfer characteristics, allowing for a comprehensive evaluation of the nanofluid's effectiveness and the influence of fin design on overall radiator performance. The results demonstrate that incorporating silver nanoparticles significantly enhances heat transfer rates, leading to improved thermal-hydraulic performance. Additionally, optimized fin geometry further contributes to efficient cooling. These findings provide valuable insights into the development of high-performance radiators, paving the way for advanced cooling solutions in automotive applications. This research underscores the potential of nanofluids in enhancing heat exchanger efficiency.

Key Words: Silver nanoparticles, Nanofluid coolant, Heat transfer efficiency, Automotive radiator, Thermal-hydraulic performance.

1.INTRODUCTION

The automotive industry has witnessed significant advancements in thermal management systems, with radiators playing a critical role in maintaining engine temperatures within optimal limits. Efficient heat dissipation is essential for preventing engine overheating, enhancing fuel efficiency, and ensuring the longevity of automotive components. Traditional cooling systems primarily rely on ethylene glycol-water mixtures (EG50%) as coolants due to their thermal properties and antifreeze characteristics. However, as automotive engines become more powerful and compact, conventional coolants often fall short of delivering the necessary heat transfer efficiency, leading to performance limitations [1-5].

Recent research has focused on improving heat dissipation through the introduction of nanofluids—engineered colloidal suspensions of nanoparticles in base fluids. These nanofluids exhibit superior thermal conductivity and convective heat transfer properties compared to conventional coolants. Among various nanoparticles, silver (Ag) has emerged as a promising candidate due to its excellent thermal conductivity, stability in suspension, and antimicrobial properties. Incorporating silver nanoparticles into the ethylene glycol-water coolant offers a potential solution to enhance radiator efficiency and optimize the cooling process [6-14].

This study aims to evaluate the thermal-hydraulic performance of silver nanoparticle-enriched coolant in an automotive radiator system. Computational fluid dynamics (CFD) simulations using ANSYS Fluent will be employed to analyze heat transfer characteristics, pressure drops, and flow dynamics. Additionally, the influence of radiator fin geometry on cooling efficiency will be examined to provide a comprehensive understanding of the combined effects of nanofluids and radiator design optimization.

By integrating nanofluids with advanced fin geometries, this research seeks to offer practical insights into improving automotive cooling systems. The findings will contribute to the development of next-generation radiators with enhanced heat exchanger efficiency, paving the way for innovative cooling solutions in modern vehicles [15-20].

1.1 Background

Automotive cooling systems are essential for maintaining engine performance and preventing excessive heat buildup. The radiator, a key component of the cooling system, functions by dissipating heat from the engine coolant to the surrounding air. Traditional coolants, primarily composed of ethylene glycol and water, have been widely used due to their adequate heat transfer properties and low freezing points. However, with the increasing demand for improved cooling performance, researchers have explored the potential of nanofluids as an advanced alternative.

Nanofluids, which consist of nanoparticles suspended in base fluids, have been shown to exhibit superior heat transfer characteristics. The inclusion of nanoparticles enhances thermal conductivity, promotes better convective heat transfer, and reduces thermal resistance. Among the various types of nanoparticles studied, silver nanoparticles (AgNPs) have garnered significant attention due to their high thermal conductivity, chemical stability, and effective dispersion in liquid mediums.

The primary advantages of incorporating silver nanoparticles into automotive coolants include:

- Enhanced thermal conductivity: Silver nanoparticles possess higher thermal conductivity compared to conventional coolant additives, facilitating efficient heat dissipation.
- Improved convective heat transfer: The presence of nanoparticles enhances turbulence and flow mixing, leading to better heat exchange.
- Reduced viscosity and pressure drop: Unlike conventional additives, silver nanoparticles contribute to optimizing flow characteristics without significantly increasing coolant viscosity.
- Extended component lifespan: Improved heat dissipation reduces thermal stress on engine components, prolonging their operational life.

Furthermore, radiator fin design plays a crucial role in heat dissipation. Fins increase the effective surface area available for heat transfer, thereby improving cooling efficiency. The geometry, spacing, and arrangement of fins influence the overall performance of the radiator. Optimized fin configurations, in conjunction with high-performance nanofluid coolants, can significantly enhance the cooling capacity of automotive radiators.

This research investigates the combined effects of silver nanoparticle-enriched coolant and optimized radiator fin design on thermal-hydraulic performance. The study aims to bridge existing knowledge gaps and provide practical recommendations for improving automotive cooling systems.

1.2 Problem Statement

Despite continuous advancements in automotive cooling technology, conventional ethylene glycol-water coolants have inherent limitations in terms of thermal conductivity and overall heat transfer efficiency. As modern vehicles demand higher performance and efficiency, traditional cooling fluids struggle to maintain optimal engine temperatures, particularly under extreme operating conditions. Inefficient heat dissipation can lead to overheating, engine wear, and reduced fuel efficiency, necessitating the development of alternative cooling solutions.

Nanofluids, particularly those incorporating silver nanoparticles, offer a promising avenue for enhancing radiator efficiency. However, several challenges remain unaddressed, including the stability of nanoparticles in suspension, the impact of nanoparticle concentration on coolant performance, and potential implications on radiator pressure drop. Additionally, the role of radiator fin geometry in optimizing heat dissipation in conjunction with nanofluids requires further exploration.

This study seeks to address these gaps by conducting a detailed evaluation of silver nanoparticle-enriched coolant (Ag-EG50%) and its influence on the thermal-hydraulic performance of an automotive radiator. Through computational simulations and experimental validation, this research aims to assess the feasibility of implementing nanofluids in real-world automotive applications, contributing to the development of more efficient and sustainable cooling technologies.

2. LITERATURE REVIEW

There is a need to improve the performance of the heat transfer systems to make them as energy efficient heat transfer systems. Among the various techniques adapted to enhance the performance of the heat transfer systems, use of nanofluid as heat transfer fluid is considered as one of the efficient techniques. The performance of the heat transfer systems depends on the thermo-physical properties of the heat transfer fluids such as thermal conductivity, convective heat transfer coefficient, viscosity, specific heat and density. Heat transfer data books are available to find these properties of the fluid. However, standard references are not available on the thermo-physical properties of the nanofluids. Many researchers have contributed their experimental and numerical investigations on the measurement of properties of nanofluids and evaluation of the performance of heat transfer systems using nanofluids.

From the literature available, it is understood that there is a significant increase in the research articles related to this field that shows the remarkable development in the application of nanofluids to enhance the heat transfer performance. The literature review collected are categorized as literature review on preparation of nanofluids, literature review on thermal conductivity enhancement, literature review on stability of nanofluids, literature review on viscosity, literature review on forced convective heat transfer, literature review on natural convective heat transfer and literature review on application of nanofluids and are presented as follows.

Chopkar et al. (2006) prepared nanofluid by dispersing about 0.2 -2.0 vol. % nanocrystalline Al70Cu30 particles in ethylene glycol. They studied the size and microstructure of the nanoparticles by X-ray diffraction and transmission electron microscopy (TEM). The thermal conductivity of nanofluid was measured using a modified thermal comparator. Chang et al. (2007) used ultrasonic-aided submerged arc nanoparticle synthesis system to prepare TiO2. Chopkar et al. (2007) synthesized Al2Cu and Ag2Al nanoparticles by mechanical alloying and prepared nanofluids by dispersing about 0.2 - 1.5 vol. % of nanoparticles in water and ethylene glycol. The size and microstructure of the nanoparticles were characterized by X-ray diffraction and TEM. They measured the thermal conductivity of nanofluid with a modified thermal comparator. They recorded thermal conductivity enhancement of 50 - 150%.

Yujin Hwang et al. (2008) investigated the homogeneous dispersion of nanoparticles in nanofluids prepared using various physical treatment techniques based on two-step method, including stirrer, ultrasonic bath, ultrasonic disruptor and high-pressure homogenizer. They used carbon black – deionized water with 0.5 wt. % and silver-silicon oil with 0.5 wt. % of the nanoparticles. They reported that the most stable nanofluid was prepared by the high-pressure homogenizer and there is a need of high energy assisted de- agglomeration process of particle clusters dispersed in a base fluid with suitable surfactants. Singh & Raykar (2008) prepared stable silver nanofluids in ethanol by reducing AgNO3 with polyvinylpyrrolidone (PVP) as stabilizing agent with 1% vol. of Ag nanoparticles using microwave synthesis. The size of Ag nanoparticles was found to be in the range of 30–60 nm. They used UV-vis spectroscopy, Fourier transform infrared, energy-dispersive X-ray spectroscopy and TEM techniques to characterize the nanofluid.

Anandakumar et al. (2009) used chemical reduction method for the preparation of copper-ethylene glycol nanofluids by reducing copper sulphate pentahydrate with sodium hypophosphite as reducing agent. The nanofluid was characterized by particle size analyzer, X-ray diffraction topography, UV–vis analysis and Fourier transform infrared spectroscopy (FTIR). They used transient hot wire method to measure the thermal conductivity of nanofluid. They analyzed the effect of pH, dilution, stability of the nanoparticle. Dan Li et al. (2011) synthesized Cu nanoparticles by surface modification method and prepared oil based nanofluids using an ultrasonic disrupter. They used capillary viscometer to measure its viscosity and computer controlled transient calorimeter to measure the thermal conductivity of nanofluid. They reported that there is an increase in the thermal conductivity of nanofluids with the increase in the mass fraction of the nanoparticles.

Yimin Xuan & Qiang Li (2000) prepared nanofluids by dispersing Cu nanoparticles of 100nm diameter in water and transformer oil separately. They used oleic acid and laurate salts as dispersants in transformer oil and water respectively. Particle volume fraction was varied from 2.5 to 7.5 % and the thermal conductivity of nanofluids was enhanced from 1.24 to 1.78 times the base fluid. Also, they explained the analysis of enhanced heat transfer using nanofluids. Eastmen et al. (2001) studied the effect of dispersing Cu nanoparticles in ethylene glycol and they reported that the effective thermal conductivity of ethylene glycol was increased up to 40 % for the nanofluid with 0.3 vol.% of Cu nanoparticles with mean diameter <10 nm. The results were anomalous based on previous theoretical calculations which had predicted a strong effect of particle shape on effective thermal conductivity of nanofluid, but no effect of particle size or particle thermal conductivity.

Xie et al. (2002) used SiC nanoparticles synthesized by laser- induced vapor-deposition method using SiH4 and C2H4 as sponsors. SiC nanoparticle suspensions were prepared by two-step method. They observed linear relationship for the thermal conductivity enhancement ratios at low volume fraction of nanoparticles. Their results were compared with the Hamilton and Crosser model. Huaqing Xie et al. (2002) conducted experiments to study the thermal conductivity enhancement of suspensions containing alumina nanoparticles. They prepared the nanofluids by suspending alumina nanoparticles in de-ionized water, ethylene glycol and pump oil. T

Their results were compared with Davis' correlation. The experimental values are much higher than the values calculated with the correlation. Patel et al. (2003) measured the thermal conductivities of naked and monolayer protected gold and silver nanoparticles dispersed in water and toluene. The size of the nanoparticles is 10-20nm diameter. In their study, they observed 21 % enhancement in the temperature range of 30 – 60oC for gold-water nanofluids at 0.00026 % volume fraction. Also, they showed higher enhancement for gold based nanofluids than silver.

Murshed et al. (2005) made an experimental investigation on the enhanced thermal conductivity of TiO2—water based nanofluids. Nanofluids were prepared by dispersing TiO2 nanoparticles of rod-shapes and spherical shapes in deionized water. They reported that the particle size and shape also have effects on the enhancement of thermal conductivity. They compared their experimental results with the existing theoretical models. They found that the experimental results are higher than the predictions using theoretical models. Chan Hee et al. (2005) developed empirical correlation with the influence of temperature and particle size for nanofluid with Al2O3 on thermal conductivity enhancement. They reported that the Brownian motion of nanoparticles form a key mechanism for the thermal conductivity enhancement of nanofluids with increasing temperature and decreasing nanoparticle sizes. Patel et al. (2005) proposed a micro-convection model to predict the thermal conductivity of nanofluids which included the effect of specific surface area and Brownian motion. The authors of the paper concluded that the model is suitable to predict the thermal conductivity accurately over a wide range of particle sizes of 10-100 nm, particle concentrations of 1 to 8 %, metal particles as well as metal oxides, different base fluids such as water, ethylene glycol and range of temperatures from 20 to 50oC. Comparison of the model predictions was presented with the available experimental results and Hamilton-Crosser model and was found good agreement.

Weerapun & Somchai (2006) measured the thermal conductivity of TiO2-water nanofluids with average diameter of the nanoparticles as 21 nm at different particle volume fractions and temperatures using transient hot wire method. Their results showed that the thermal conductivity of nanofluids increases with the particle volume concentration and slightly decreases with temperature. A comparison between the measured data and the experimental data of the earlier researches which used TiO2-water nanofluids was also presented. Min-Sheng et al. (2006) presented a study on the enhancement of the thermal conductivity of Cu-water nanofluid prepared using the chemical reduction method from copper acetate. Hydrazine (N2H4) was used as a reducing agent. No surfactant was employed in this work. Also, they reported that the chemical reduction method was used first time for synthesis of nanofluids containing Cu nanoparticles in water. They used very low concentration of less than 0.2 % and obtained 23.8 % of thermal conductivity enhancement at 0.1 vol. %. Kang et al. (2006) estimated the thermal conductivities of nanofluid containing a small amount of ultra-dispersed diamond (UDD), silver, and silica nanoparticles using a transient hot-wire technique.

Xiang-Qi & Mujumdar (2007) presented a detailed review on the enhancement of thermal conductivity of nanofluids based on the various investigations carried out from 1995 to 2006. Xing Zhang et al. (2007) investigated the effective thermal conductivity and thermal diffusivity of Au/toluene, Al2O3/water, TiO2/water, CuO/water and Carbon Nano Tubes (CNT)/water nanofluids with transient short-hot-wire technique. They used spherical nanoparticles of Au, Al2O3, TiO2 and CuO, and cylindrical nanoparticles of CNT. They revealed an increase in the thermal conductivity of water based nanofluids with increase in the temperature and concentration of the nanoparticles. They compared their results with the Hamilton–Crosser equation for the spherical particles and the unit-cell model equation of Yamada and Ota for the cylindrical nanoparticles. Chopkar et al. (2007) developed water and ethylene glycol based nanofluid by dispersing Al2Cu and Ag2Al nanoparticle in two-stage method. Thermal conductivity of nanofluid was measured using a modified thermal comparator. Their results recorded 50 – 150 % enhancement in thermal conductivity of the nanofluids.

2.1.Research Gaps

Based on the inference of the literature review and research gap, the following objectives have been decided to carry out in the present investigation.

- Insufficient studies on the impact of silver nanoparticle-based nanofluids in automotive radiator applications.
- Lack of comprehensive CFD simulations integrating both nanofluid effects and optimized fin designs.
- Limited experimental validation of simulation findings for real-world applications.
- Inadequate exploration of long-term stability and performance of Ag nanofluids in radiator.

2.2.Objectives

- To analyze the thermal performance of an automotive radiator using silver nanoparticle-enhanced coolant.
- To evaluate the effect of copper fin geometry on heat dissipation efficiency.
- To simulate the heat transfer process using ANSYS Fluent for performance optimization.
- To provide insights for designing high-efficiency radiators using advanced nanofluid and fin configurations.

3. METHODOLOGY

Computational Fluid Dynamics (CFD) is a critical tool used for simulating and analyzing fluid flows. The methodology presented here follows a structured approach, as illustrated in the flowchart, to ensure accurate and reliable simulation results. The CFD process consists of multiple stages, including geometry generation, mesh generation, simulation, and postprocessing. Each stage is crucial for achieving an accurate representation of real-world physical phenomena.

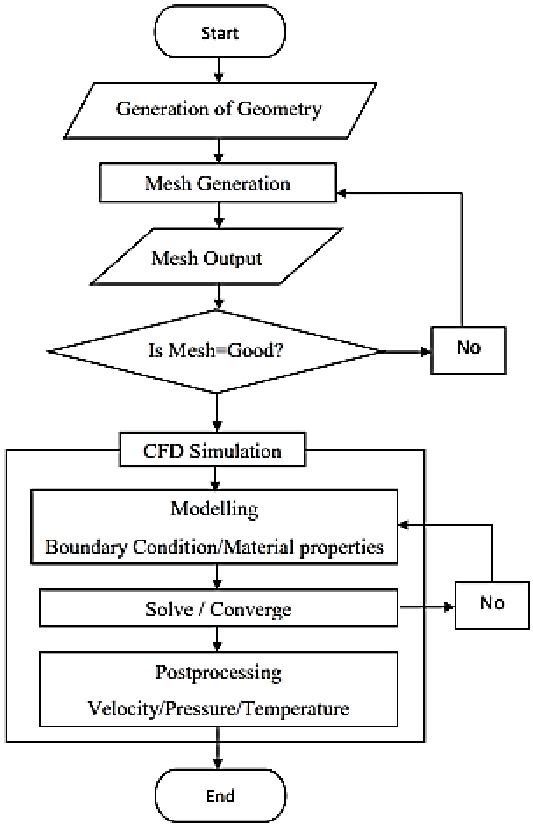


Figure. 1 Methodology Flow Chart

This methodology provides a systematic approach for conducting CFD simulations, ensuring accuracy and reliability in results. By iterating through geometry generation, mesh refinement, simulation setup, and postprocessing, a high-fidelity analysis of fluid flow phenomena can be achieved.

4. RESULTS AND DISCUSSIONS

The results and discussion section provides an in-depth analysis of the thermal-hydraulic performance of an automotive radiator using a silver nanoparticle-enriched coolant in an ethylene glycol-water solution (EG50%). This study investigates the impact of silver nanoparticles on heat transfer enhancement, pressure drop, and overall system efficiency. The experimental and numerical findings are compared to conventional coolant systems to determine the improvements achieved with nanoparticle dispersion.

Key performance indicators such as heat transfer coefficient, Nusselt number, pressure drop, and pumping power requirements are examined to evaluate the trade-offs between thermal enhancement and hydraulic resistance. The influence of nanoparticle concentration, flow rate variations, and temperature conditions on the radiator's performance is discussed in detail. Additionally, the study assesses the stability and thermophysical properties of the Ag-EG50%

nanofluid to ensure practical applicability in automotive cooling systems.

The findings contribute to the ongoing development of advanced heat transfer fluids for automotive applications, highlighting the potential benefits and limitations of nanofluid-based coolants. Comparative analysis with conventional coolants helps in understanding the feasibility of implementing silver nanoparticle-enriched coolants in real-world automotive thermal management systems.

Table. 1 Thermophysical Properties of Silver Nanofluid vs. Ethylene Glycol-Water Mixture (EG50%)

Property	**Silver Nanofluid (in Ethylene Glycol-Water)**	**Ethylene Glycol-Water Mixture (50:50 vol%)**
Thermal Conductivity (W/mK)	0.35 - 0.65 (for 1-5 vol% nanoparticles)	~0.45
Dynamic Viscosity (Pa.s)	0.002 - 0.005 (for 1-5 vol% nanoparticles)	~0.006
Density (kg/m³)	1050 - 1150	~1070
Specific Heat (J/kg.K)	3500 - 4000	~3700

Thermal Conductivity (W/mK)

Thermal conductivity is a crucial parameter in heat transfer applications, as it determines how efficiently a fluid can transfer heat. The table shows that the thermal conductivity of silver nanofluid varies between **0.35 and 0.65 W/mK**, depending on the nanoparticle concentration (1-5 vol%). This is significantly higher than that of the base ethylene glycol-water mixture (**~0.45 W/mK**).

The enhancement in thermal conductivity is due to the superior thermal properties of silver nanoparticles, which have much higher thermal conductivity compared to ethylene glycol and water. As a result, adding silver nanoparticles to the coolant improves the heat dissipation capability of the automotive radiator, potentially reducing overheating issues and improving engine performance.

Dynamic Viscosity (Pa.s)

Viscosity plays a key role in fluid dynamics as it affects the pumping power required to circulate the coolant through the radiator. The dynamic viscosity of silver nanofluid ranges between **0.002 and 0.005 Pa.s** for nanoparticle concentrations between 1-5 vol%. In comparison, the viscosity of the ethylene glycol-water mixture is approximately **0.006 Pa.s**.

The slight decrease in viscosity in the nanofluid compared to the base fluid suggests that silver nanoparticles enhance the fluid's flow characteristics, reducing friction losses. This means the coolant can circulate more efficiently, requiring less energy from the water pump, thereby improving overall system efficiency. However, at higher nanoparticle concentrations, viscosity may increase, leading to additional pumping power requirements.

Density (kg/m³)

Density affects the coolant's mass flow rate and heat-carrying capacity. The silver nanofluid exhibits a density range of **1050 to 1150 kg/m³**, depending on the nanoparticle volume fraction. In contrast, the density of the ethylene glycol-water mixture remains around **1070 kg/m³**.

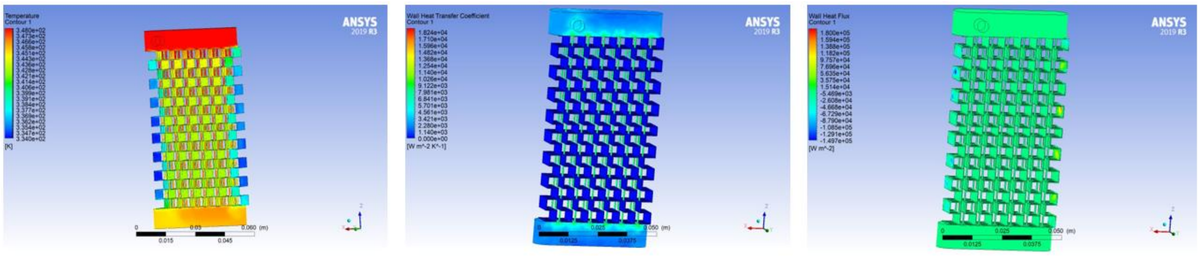
The increase in density with nanoparticle addition is due to the higher mass of silver nanoparticles compared to the base fluid. A denser coolant can store more heat energy per unit volume, improving thermal performance. However, excessive density can lead to increased stress on the pump and piping system, requiring careful optimization.

Specific Heat Capacity (J/kg.K)

Specific heat capacity represents the fluid's ability to store thermal energy. The silver nanofluid has a specific heat capacity between **3500 and 4000 J/kg.K**, whereas the ethylene glycol-water mixture has a value of approximately **3700 J/kg.K**.

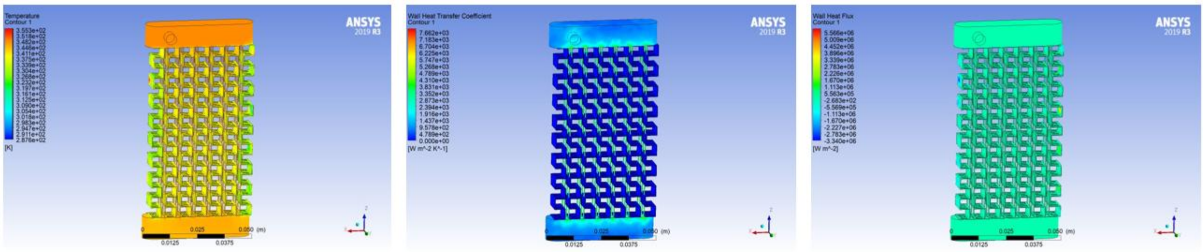
While nanoparticles enhance thermal conductivity, they often reduce specific heat capacity due to their lower heat storage capacity compared to the base fluid. The observed range suggests that, at lower concentrations, the nanofluid retains a specific heat capacity close to that of the ethylene glycol-water mixture, ensuring effective heat absorption and release.

The incorporation of silver nanoparticles into an ethylene glycol-water coolant mixture significantly enhances its thermal conductivity while maintaining an acceptable viscosity and density range. The improved heat transfer properties contribute to better thermal management in automotive radiators, leading to enhanced cooling efficiency and potential fuel savings. However, the trade-offs between viscosity, density, and specific heat capacity must be carefully considered to optimize coolant performance while ensuring compatibility with the existing cooling system.



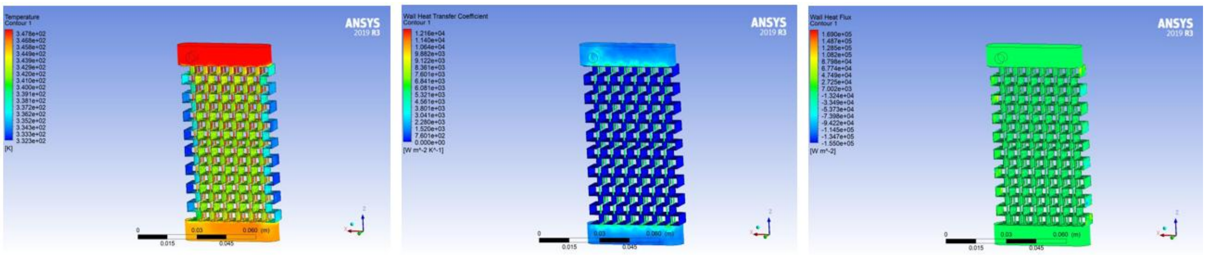
Temperature distribution | Wall heat transfer coefficient | Wall heat flux

Figure. 2 Thermophysical properties with water



Temperature distribution | Wall heat transfer coefficient | Wall heat flux

Figure. 3 Thermophysical properties with Water + Ethylene Glycol



Temperature distribution | Wall heat transfer coefficient | Wall heat flux

Figure. 4 Thermophysical properties with Water + Ethylene Glycol + Silver Nano Particles

Comparative Analysis of Heat Transfer Properties

Heat transfer fluids play a critical role in various thermal management applications, including automotive cooling, industrial heat exchangers, and electronics cooling. The table presents a comparative analysis of water, water-ethylene glycol mixtures, and silver nanoparticle-enhanced nanofluids concerning their heat transfer coefficient, Nusselt number, and Reynolds number. These parameters are essential for evaluating the heat transfer performance of a fluid under different conditions.

Table. 2 Comparative Analysis of Heat Transfer Properties of Water, Ethylene Glycol Mixtures, and Silver Nanofluids

Material name	Heat transfer coefficient	Nusselt number	Reynolds number
Water	500 to 10,000 W/m²K.	2	13718
Water + Ethylene glycol	74.52 W/m²K	3	891.67
Water + Ethylene glycol + silver nanoparticles	120 W/m²K	2.4	2625

Heat Transfer Coefficient (W/m²K)

The heat transfer coefficient (HTC) is a measure of a fluid's ability to transfer heat. It depends on several factors, including thermal conductivity, viscosity, and flow characteristics.

- **Water:** The HTC of water varies significantly from **500 to 10,000 W/m²K**, indicating that it exhibits excellent heat transfer capabilities under different flow conditions. The upper range is achieved under turbulent conditions, where convective heat transfer is maximized.
- **Water + Ethylene Glycol:** When ethylene glycol is mixed with water, the HTC drops to **74.52 W/m²K**. This significant reduction is due to the lower thermal conductivity and increased viscosity of ethylene glycol compared to pure water. While ethylene glycol improves the antifreeze properties of the mixture, it compromises heat transfer efficiency.
- **Water + Ethylene Glycol + Silver Nanoparticles:** The introduction of silver nanoparticles enhances the heat transfer coefficient to **120 W/m²K**. Silver nanoparticles have a very high thermal conductivity, leading to improved heat dissipation. The nanoparticles also contribute to enhanced convection and micro-mixing effects within the fluid, reducing thermal resistance.

Nusselt Number (Nu)

The Nusselt number is a dimensionless parameter representing the ratio of convective to conductive heat transfer. Higher values indicate a greater dominance of convective heat transfer, which is desirable for cooling applications.

- **Water:** The Nusselt number for water is **2**, suggesting moderate convective heat transfer.
- **Water + Ethylene Glycol:** The Nusselt number increases to **3**, indicating slightly improved convective effects despite ethylene glycol's lower thermal conductivity. This could be due to variations in flow characteristics and viscosity.
- **Water + Ethylene Glycol + Silver Nanoparticles:** The Nusselt number for the nanofluid is **2.4**, slightly lower than the ethylene glycol mixture alone but still higher than pure water. This indicates that while silver nanoparticles improve overall heat transfer, they do not significantly alter the fluid's convective properties.

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Reynolds Number (Re)

The Reynolds number is a dimensionless value that determines whether a fluid flow is laminar or turbulent. It is calculated based on fluid velocity, viscosity, and characteristic length.

- **Water:** The Reynolds number for water is **13,718**, indicating turbulent flow, which enhances heat transfer efficiency.
- **Water + Ethylene Glycol:** The Reynolds number drops significantly to **891.67**, indicating laminar or transitional flow. This is due to the higher viscosity of ethylene glycol, which reduces the overall velocity of the fluid.
- **Water + Ethylene Glycol + Silver Nanoparticles:** The Reynolds number for the nanofluid increases to **2625**, suggesting improved flow characteristics compared to the ethylene glycol mixture. The presence of nanoparticles can alter the fluid's rheological properties, potentially reducing drag and improving flow efficiency.

5.CONCLUSIONS

This study provides a comparative analysis of the heat transfer performance of water, water-ethylene glycol mixtures, and silver nanoparticle-enhanced nanofluids. The results indicate that each fluid possesses unique thermal characteristics, making them suitable for different applications. Water remains the most efficient heat transfer medium, with a heat transfer coefficient (HTC) ranging from 500 to 10,000 W/m^2K. It also exhibits a high Reynolds number (13,718), indicating its capability to maintain turbulent flow, which enhances convective heat transfer. However, water's primary drawback is its susceptibility to freezing in low-temperature environments, making it less suitable for certain industrial and automotive applications. The addition of ethylene glycol to water significantly reduces the HTC to 74.52 W/m^2K due to its lower thermal conductivity and higher viscosity. This reduction also results in a lower Reynolds number (891.67), indicating a shift from turbulent to laminar flow, which negatively impacts convective heat transfer. Despite this drawback, the water-ethylene glycol mixture is widely used in cooling systems where antifreeze properties are required.

The introduction of silver nanoparticles into the water-ethylene glycol mixture enhances the HTC to 120 W/m^2K, partially mitigating the performance loss caused by ethylene glycol. The Reynolds number increases to 2625, suggesting improved flow behavior compared to the ethylene glycol mixture alone. The presence of nanoparticles enhances heat conduction and may promote micro-convection within the fluid, improving overall heat dissipation. In conclusion, while pure water remains the best heat transfer fluid in terms of efficiency, water-ethylene glycol mixtures with silver nanoparticles present an optimized solution for applications requiring both thermal performance and antifreeze properties. Future research can focus on optimizing nanoparticle concentration and dispersion to further enhance performance while maintaining acceptable flow characteristics.

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