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REVIEW

# A Review of the Applications of Nanofluids and Related Hybrid Variants in Flat Tube Car Radiators

**Saeed Dinarvand***, **Amirmohammad Abbasi and Sogol Gharsi**

Department of Mechanical Engineering, Central Tehran Branch, Islamic Azad University, Tehran, 1469669191, Iran

*Corresponding Author: Saeed Dinarvand. Email: saeed_dinarvand@yahoo.com; sae.dinarvand@iauctb.ac.ir

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**ABSTRACT**

The present review explores the promising role of nanofluids and related hybrid variants in enhancing the efficiency of flat tube car radiators. As vehicles become more advanced and demand better thermal performance, traditional coolants are starting to fall short. Nanofluids, which involve tiny nanoparticles dispersed into standard cooling liquids, offer a new solution by significantly improving heat transfer capabilities. The article categorizes the different types of nanofluids (ranging from those based on metals and metal oxides to carbon materials and hybrid combinations) and examines their effects on the improvement of radiator performance. General consensus exists in the literature that nanofluids can support better heat dissipation and enable accordingly the development of smaller and lighter radiators, which require less coolant and allow more compact vehicle designs. However, this review demonstrates that the use of nanofluids does not come without challenges. These include the long-term stability of these fluids and material compatibility issues. A critical discussion is therefore elaborated about the gaps to be filled and the steps to be undertaken to promote and standardize the use of these fluids in the industry.

**KEYWORDS**

Flat tube car radiator; nano-coolant; stability; metal-based nanoparticle; heat transfer enhancement; ethylene glycol

## 1 Introduction

Effective thermal management is a critical objective for researchers in the field of engineering systems. The pursuit of improved heat transfer and enhanced thermal efficiency is a critical challenge in mechanical engineering [1–4]. Heat exchangers, which are part of these systems, play a vital role in various industries, including electronics, space applications, automotive, waste recovery, and power plants. In the automotive field, radiators, which are a type of heat exchanger, ensure the efficient operation of the engine and prevent overheating by dissipating the heat produced during combustion [5–7]. The main parts of a radiator include the tubes, lower tank, and upper tank. The coolant, heated by the engine, enters the upper tank and flows through the tubes. As it moves, heat is transferred from the coolant to the metallic fins surrounding the tubes, which dissipate the heat into the air. Radiators come in various types, including tubular, cellular, and gilled tube designs [8–11]. Several factors influence the effectiveness of radiators, such as the material, air temperature, coolant type, fin design, air and coolant flow rates, and coolant inlet temperature [12,13]. Additionally, in automotive radiator, traditional methods such as incorporating microchannels and turbulators are used to boost efficiency [14,15]. In recent decades, significant research has focused on enhancing automotive cooling systems' performance. A notable strategy in this endeavor is the utilization of advanced coolants to enhance cooling efficiency. Presently, the market provides a range of radiator liquid coolants, each with unique heat absorption capabilities and heat transfer characteristics. Typical thermal fluids used in radiators include ethylene glycol, engine oil, propanol, water and various mixtures of ethylene glycol and water. However, the conventional coolants mentioned above exhibit suboptimal heat transfer properties, which can negatively impact the performance and efficiency of automotive components. Thermal fluids, especially mixtures of ethylene glycol and water, are vital in radiators due to their anti-freeze properties. These fluids adapt to both cold and hot climates, preventing freezing in low temperatures and aiding in heat dissipation in high temperatures. Due to the suboptimal thermal performance of traditional fluids, many researchers are investigating novel fluids to enhance heat transfer efficiency. These new fluids aim to have higher thermal conductivities, which would improve the overall efficiency of automotive cooling systems. Choi [16] pioneered the field of nanofluids, presenting this groundbreaking category of fluids. They asserted that nanofluids demonstrate superior thermal conductivity relative to conventional fluids. Nanofluids represent a fusion of solid and liquid states at the nanoscale, where tiny particles are suspended within a fluid medium. The extensive research on nanofluids, both experimental and theoretical, symbolizes the comprehensive effort required to achieve true understanding and innovation [17–20]. The fascination with nanofluids stems from their remarkable thermophysical characteristics and wide-ranging applications. The application of nanofluids covers many fields, including heat exchangers, medical applications, nuclear reactors, and more, which reflects their adaptability and innovative potential [21–25]. Scholars in mechanical engineering have employed numerous methods to improve heat transfer rates. One such approach involves combining two distinct types of solid nanoparticles within a single base fluid, resulting in a unique nanofluid referred to as a hybrid nanofluid. This concept was initially proposed by Suresh and his team [26,27], who used $Al_2O_3$ and $Cu$ as the solid particles within a water-based fluid. The assertion that hybrid nanofluids outperform both pure fluids and traditional nanofluids highlights the innovative nature of this research. Consequently, numerous researchers have focused their research on hybrid nanofluids, revealing a range of fascinating and promising results [28–31].

With the growing number of numerical and experimental investigations on various hybrid nanofluids and nanofluids in car flat tube radiators, it is crucial to review the advancements and methodologies in this domain. This review has been assembled to provide a comprehensive understanding of the advancements in the thermal conductivities of nanofluids and hybrid nanofluids, with the goal of making these innovative fluids more widely accessible and attainable for everyday applications. By synthesizing current research, we aim to illuminate the potential of nanofluids not just in enhancing the performance of automotive cooling systems but also in addressing critical challenges associated with heat management, particularly in hotter environments. The integration of nanofluids into automotive systems could lead to significant improvements in cooling efficiency, thereby reducing energy consumption and enhancing overall vehicle performance. Moreover, as nanofluids demonstrate remarkable thermal properties, their broader application could lead to a paradigm shift in how thermal management is approached across various industries. As such, facilitating a greater understanding and accessibility of nanofluids can drive innovation and support advancements that ultimately benefit consumers and industries alike.

## 2 Thermal Conductivity Enhancement and Mechanisms

The essential characteristics of heat transfer fluids reflect the intricate balance required for optimal thermal management. Each property (density, viscosity, specific heat, and thermal conductivity) plays a crucial role in the fluid's overall performance. Nanofluids, defined as stable colloidal suspensions of nanoparticles in a base fluid, exhibit remarkable physical properties, with thermal conductivity being a focal point of investigation [32]. The random movement of nanoparticles within a nanofluid, often referred to as Brownian motion, enhances heat transfer by increasing the interaction between the nanoparticles and the base fluid. This interaction improves the overall thermal conductivity of the nanofluid, allowing it to transfer heat more efficiently. The enhanced thermal conductivity results from the increased surface area and dynamic mixing of nanoparticles, which facilitate better energy transfer within the fluid. Research has shown that different nanoparticle compositions and preparation methods significantly influence the thermal conductivity of nanofluids. For example, Eastman et al. [32] demonstrated an anomalously high effective thermal conductivity in copper nanoparticles suspended in ethylene glycol, achieving enhancements of up to 20%. Similarly, Shahsavar et al. [33,34] indicated that temperature and concentration variations lead to significant improvements in thermal properties when using carbon nanotube-loaded ferrofluids. The viscosity of nanofluids is a key factor in heat transfer processes, as it influences the fluid's resistance to flow. A lower viscosity allows for better flow characteristics, thus enhancing heat transfer efficiency. Additionally, the specific heat of nanofluids represents the stringent divination of temperature mutations at a given heat transfer rate and fluid flow. The density of nanofluids also influences flow behavior, making it a vital parameter to consider. The heightened thermal conductivity of nanofluids leads to improved convective heat transfer coefficients, ultimately enhancing overall heat transfer performance. An overview of experimental findings on thermal conductivity enhancements (TCE) in nanofluids is presented in Table 1.

**Table 1:** Some experimental findings on thermal conductivity enhancements (TCE) in nanofluids

| Ref. | Nanofluid composition | Description | TCE (%) | Key findings |
|---|---|---|---|---|
| [32] | Cu/ethylene glycol | Direct synthesis and experimental test | 20% | Demonstrated significantly increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. |
| [33] | Ferrofluid/carbon nanotubes | Experimental study with temperature and concentration variation | 12% | Showed that increasing temperature and concentration enhances thermal conductivity and viscosity in ferrofluids loaded with carbon nanotubes. |
| [34] | Ferrofluid/carbon nanotubes | Ultrasonication and experimental test | 17% | Found that ultrasonication significantly improves thermal conductivity of carbon nanotube ferrofluids. |
| [35] | $Al_2O_3$-MWCNT/ thermal oil | Experimental and theoretical investigation | 33% | Highlighted the enhanced heat transfer efficiency in $Al_2O_3$-MWCNT hybrid nanofluids for thermal management applications. |
| [36] | $Al_2O_3$-Cu/ ethylene glycol | Experimental correlation | 25% | Developed a correlation indicating the improvement of thermal conductivity with $Al_2O_3$–Cu hybrid nanoparticles in ethylene glycol. |
| [37] | Diathermic oil-based hybrid/ diathermic oil | Evaluation of thermo-physical properties | 15% | Evaluated the properties of diathermic oil hybrid nanofluids, demonstrating considerable thermal conductivity enhancements. |
| [38] | Nitrogen-doped hybrid carbon/ solar collectors | Composite dispersion for solar collectors | 30% | Investigated the effectiveness of nitrogen-doped hybrid carbon nanofluids for low-temperature applications, showing improved thermal characteristics. |

## 3 Preparation of Nanofluid and Hybrid Nanofluid

In the realm of nanofluids, the method employed for their preparation plays a pivotal role in understanding their stability and thermophysical behavior [39]. Additionally, the steps involved in preparing nanofluids directly impact their suitability for heat transfer systems [40,41]. The nanofluid preparation process stands as a fundamental initial step in this field. Typically, two conventional approaches are utilized: the one-step and two-step preparation technique [42]. The one-step preparation method for nanofluids involves the simultaneous synthesis and dispersion of nanoparticles in a base liquid. Within this category, various techniques exist, including the Liquid Chemical approach and Physical Vapor Deposition (PVD). Notably, Akoh et al. [43] proposed the single-step direct evaporation method as a primary approach. By using the single-step method, we eliminate the separate handling of nanomaterials, storage and drying, and due to that, the accumulation and density of nanoparticles reaches its lowest level. For instance, Shahsavar et al. [44] used a single-step method to create $Fe_2O_3-CNT$ /distilled water nanofluids. In a study, Nikkam et al. [45] used a single-step method to produce copper nanofluids based on diethylene glycol. This approach aims to enhance nanofluid uniformity by minimizing nanoparticle agglomeration and achieving optimal stability for improved thermal properties [46]. The one-step method, while effective for synthesizing nanofluids, presents significant economic challenges due to its high costs. The two-step method for preparing nanofluids includes two separate phases. Initially, nanoparticles, nanotubes or nanocomposites are synthesized as dry powders through mechanical or chemical processes. These mentioned mechanical and chemical processes include vapor phase, grinding, milling and sol-gel techniques. In the next phase, these synthesized nanoparticles are dispersed in a base fluid. This method is generally more affordable and scalable compared to the one-step method. After dispersion, nanoparticles often accumulate due to cohesive force and van der Waals force, which has a negative effect on thermal and physical properties. To reduce this case, several techniques are used, such as: magnetic force agitation, ultrasonic agitation, ultrasonic baths, ultrasonic disruption, high-shear mixing, and high-pressure homogenization [47–49]. The paper by Dehkordi et al. [50] demonstrates that external factors, such as electric fields, can significantly enhance the dynamics of nanofluids, indicating that methods like ultrasonic agitation and high-shear mixing not only improve dispersion but also optimize the thermal performance of the nanofluid. Ultrasonic agitation, for example, utilizes high-frequency sound waves to disperse nanoparticles effectively, enhancing the uniformity of the nanofluid. Studies have shown that prolonged ultrasonication duration can significantly improve thermal properties and stability [51]. High-shear mixing applies mechanical force to create a uniform dispersion, which is crucial for optimizing heat transfer performance. The findings of Dehkordi et al. suggest that increasing the number of nanoparticles and applying external electric fields can further enhance the boiling phenomena in nanofluids, highlighting the importance of effective preparation methods in maximizing thermal efficiency [50]. These techniques help prevent agglomeration and maintain stability. It's important to note that no single material possesses all the desired characteristics and properties. A major limitation of this method is its frequent low stability and high propensity for agglomeration. To address this issue, various alternative techniques, such as one-step synthesis methods and green synthesis approaches, have been employed. Some research works with significant and educative content about the synthesis process can be found in [52–54]. A summary of the nanofluid preparation methods is presented in Table 2.

## 4 Nanoparticles Used in Nano-Coolants and Properties

Nanofluids are classified into four main types based on the nanoparticles they contain, each offering unique properties that enhance the base fluid's performance. Metal-based nanofluids are a category of nanofluids that include metallic nanoparticles like silver or copper. These nanoparticles are chosen for their exceptional thermal conductivity, which significantly enhances the heat transfer capabilities of the base fluid. The second type, metal oxide-based nanofluids, includes nanoparticles like alumina or zinc oxide, valued for their stability and effective heat transfer capabilities. The third category, carbon-based nanofluids, involves carbon nanoparticles such as carbon nanotubes or graphene, which provide excellent thermal conductivity and mechanical strength. The fourth type, hybrid nanofluids, combines more than one type of nanoparticle, such as mixing metal with metal oxide or carbon-based particles, to achieve enhanced or synergistic properties. Table 3 illustrates various nanoparticles used in numerous validated studies, classified according to these four types, showcasing the diversity and application potential of these advanced fluids.

**Table 2:** Overview of nanofluid preparation methods and their impact on stability and thermal properties [40,46,47,51,53,54]

| Preparation method | Description | Effects on nanofluid properties | Challenges |
|---|---|---|---|
| One-step method | Simultaneous synthesis and dispersion of nanoparticles in a base liquid. | Enhances uniformity and minimizes agglomeration. | High costs; economic challenges. |
| Two-step method | Involves separate synthesis of nanoparticles followed by dispersion in a base fluid. | More affordable; scalable. | Cohesive forces can lead to agglomeration post-dispersion. |
| Ultrasonic agitation | Uses high-frequency sound waves to disperse nanoparticles. | Improves uniformity and thermal performance. | Prolonged duration needed for optimal results. |
| High-shear mixing | Applies mechanical force to create a uniform dispersion. | Crucial for optimizing heat transfer performance. | Potential for equipment wear and energy consumption. |

**Table 3:** Various nanoparticles used in some investigations, classified according to four types

| Category | Nanofluid | Concentration (%) | Particle size (nm) | References |
|---|---|---|---|---|
| Metal based | | | | |
| | $Au$/water | 0.0001–0.004 | 10–30 | [55] |
| | $Au$/DI water | 0.0001–0.1 | 8.6–9.4 | [56] |
| | $Cu$/methanol | 0–10.0 | 25–75 | [57] |
| Metal-oxide based | | | | |
| | $Al_2O_3$/water | 5–10 | 20 | [58] |
| | $ZnO$/EG | 0.2–5.0 | 10–20 | [59] |
| | $TiO_2$/water | 0.25 | 14 | [60] |
| | $MgO$/water | 1.0 | 20–50 | [61] |

(Continued)

**Table 3 (continued)**

| Category | Nanofluid | Concentration (%) | Particle size (nm) | References |
|---|---|---|---|---|
| Carbon based | | | | |
| | *MWCNT*/kapok seed oil | 0.1 | D: 15.8–19.2 | [62] |
| | *CNT*/decane | 0.1–1.0 | D: 15; L: 30 (μm) | [63] |
| | $COOH-CNT$/DI water | 0.1–0.3 | D: 12–14; L: 1.5–2 (μm) | [64] |
| | *MWCNT*/water | 0.1–0.5 | Outer D: 50–80; Inner D: 5–15; L: 10–20 (μm) | [65] |
| | *MWCNT*/water | 0.0001–0.03 | Outer D: 50–80; Inner D: 5–15; L: 10–20 (μm) | [55] |
| Hybrid | | | | |
| | *Silver* (*Ag*)-multiwall carbon nanotube/DI water | 0.01–0.05 | *Ag*: 50; multiwall carbon nanotube: 20–30 | [66] |
| | $Au–TiO_2/DI\ water$ | 0.05–3.0 | *Au*: 45–85; $TiO_2$: 15–40 | [67] |
| | *Au–Ag*/DI water | 0.05–3.0 | *Au*: 45–85; *Ag*: 30–65 | [67] |
| | *Au–Al*/DI water | 0.05–3.0 | *Au*: 45–85; *Al*: 50–75 | [67] |

## 5 Stability of Nanofluids and Hybrid Nanofluid in Radiator Applications

Nanofluid stability is frequently linked to the electrical double-layer repulsive force (EDLRF) and the Van der Waals attractive forces; for the stability of a nanofluid, the repulsive force, which is known as the electrical double-layer repulsive force, must be greater than the van der Waals attractive forces. These attractive forces make the nanoparticles come closer together. As a result, nanoparticles begin to accumulate, which eventually leads to deposition. This deposition challenges the uniformity of the nanofluid [68].

Several evaluation methods have been used by scholars for investigations of the stability of nanofluids such as (1) Spectral analysis approach, (2) Electron microscopy, (3) Zeta potential analysis, (4) Sedimentation method, (5) Centrifugation method and (6) light scattering methods. Each of the mentioned methods has been evaluated for specific situations where their application can determine the maximum performance and improvement of a nanofluid for us. Although past research has shown that carbon-based nanofluids have the highest stability and the properties of hybrid nanofluids but generally increase with temperature and volume fraction., there are methods available to enhance the stability of HNFs and MNFS based on the necessary conditions and characteristics, which include: (1) Dispersant, (2) Magnetic stirring, (3) Sonication. The dispersant method involves adding dispersants or surfactants to the base fluid to reduce its surface tension. This reduction in surface tension enhances the stability of the nanofluid by preventing the nanoparticles from clumping together, a process known as agglomeration. However, the thermophysical characteristics of nanofluid, such as its chemical stability and thermal conductivity, may be compromised by the utilization of a dispersant. Thus, it's important to use dispersant in the quantity advised. The use of dispersants is a cost-effective strategy to improve the stability of hybrid nanofluids (HNFs) and magnetic nanofluids (MNFs). Magnetic stirrers, which generate a rotating magnetic field, are crucial in laboratory environments. They enhance the homogeneity of nanofluid solutions by continuously mixing the particles, thus maintaining a consistent suspension. By minimizing sedimentation, these devices contribute to the efficient mixing and dispersal of nanomaterials. Typically, magnetic stirrers feature two control knobs: the left knob regulates the stirring rate, allowing for precise control over the mixing speed, while the right knob manages the heating function, enabling temperature regulation as required for various experimental procedures. The combination of effective stirring and controlled heating facilitates the preparation of well-dispersed and thermally stable nanofluid samples, crucial for accurate characterization and experimental outcomes. The sonication method has been shown to offer superior dispersion of nanoparticles when compared to conventional magnetic stirring techniques. This improved dispersion is due to the application of ultrasonic waves within the nanofluid, which aids in creating a more homogenized suspension. The sonication process exposes the agglomerated nanoparticles to vibration, leading to the disintegration of the agglomerates through the creation of cavitation bubbles and the ensuing generation of localized high-pressure and high-temperature "hot spots." These hot spots effectively break down the agglomerated particles, resulting in a more uniform and stable dispersion. Furthermore, probe-type sonication has demonstrated superior performance to bath-type sonication in delivering a consistent and well-dispersed nanoparticle suspension [69]. The dielectric constant and pH of the base fluid are crucial factors influencing the stability of nanofluids. Adjusting the pH of the suspension can significantly improve the stability of hybrid nanofluids (HNFs) and magnetic nanofluids (MNFs). When nanoparticles are dispersed in a base fluid, they create surface electric charges affected by the pH level. By altering the pH away from the isoelectric point (IEP), the electrostatic repulsion between particles increases, thereby enhancing the stability of the nanofluid. This adjustment decreases issues such as sedimentation and agglomeration, making careful pH management crucial for optimal performance in different applications [70]. A summary of evaluation methods and factors influencing the stability of nanofluids is presented in Table 4.

**Table 4:** Evaluation methods and factors influencing the stability of nanofluids in radiator applications

| Method/parameter | Description | Quantitative outcomes |
|---|---|---|
| **Evaluation methods** (Techniques used to assess nanofluid stability): | | |
| *Spectral analysis* | Evaluates the size distribution of nanoparticles. | Specific quantitative outcomes not provided. |
| *Electron microscopy* | Provides visual confirmation of dispersion and agglomeration. | Specific quantitative outcomes not provided. |
| *Zeta potential analysis* | Measures the electrostatic stability of nanofluids. | Higher zeta potential indicates better stability. |
| *Sedimentation method* | Assesses the settling of nanoparticles over time. | Specific quantitative outcomes not provided. |
| *Centrifugation method* | Accelerates sedimentation for quicker analysis. | Specific quantitative outcomes not provided. |
| *Light scattering methods* | Analyzes particle size and distribution. | Specific quantitative outcomes not provided. |
| **Factors influencing stability** (Key elements affecting nanofluid stability): | | |
| *Dispersant* | Reduces surface tension, enhancing stability but may affect thermal properties. | Effective use can improve stability while managing thermal conductivity. |

(Continued)

**Table 4 (continued)**

| Method/parameter | Description | Quantitative outcomes |
|---|---|---|
| *Magnetic stirring* | Enhances homogeneity by mixing particles continuously. | Specific quantitative outcomes not provided. |
| *Sonication* | Uses ultrasonic waves to create a more uniform dispersion. | Improved dispersion compared to conventional methods; superior results with probe-type sonication [69]. |
| **Significant parameters:** | | |
| *Electrical double-layer repulsive force (EDLRF)* | The repulsive force that must exceed the van der Waals attractive forces to maintain stability in nanofluids. | Stability increases with effective EDLRF. |
| *pH and dielectric constant* | Adjusting the pH away from the isoelectric point improves stability through increased electrostatic repulsion. | Effective pH management enhances stability, reducing sedimentation and agglomeration [70]. |

## 6 Overall View on Remarkable Investigations

To enhance heat transfer in an automobile radiator that had aluminum fin-flat tubes, a hybrid nanofluid composed of $Fe_2O_3$ and $TiO_2$ nanoparticles was used in an experimental study by Abbas and her colleagues [71]. The preparation of the nanofluid entailed precisely measuring the nanoparticle mass with a digital scale and incorporating an optimal amount of Sodium dodecyl Benzene Sulfonate (SDBS) surfactant. The mixtures were agitated using a magnetic stirrer for 45 min at a speed of 1100 RPM and a temperature of 40°C. The blend was then processed in a homogenizer for 5 min at a speed of 5000 RPM. The mixture was placed in an ultrasonic bath with a power of 150 watts and a frequency of 40,000 Hz for 540 min to ensure the stability of the hybrid nanofluid. Even after 20 h, minimal sedimentation and excellent stability were observed for the prepared hybrid nanofluid. The experimental setup for nanofluid research included an electric heater with a built-in temperature controller, ensuring nanofluid inlet temperatures were maintained between 48°C and 56°C. A centrifugal pump delivered a constant flow rate of 25 LPM, while the flow rate during experiments ranged from 11 to 15 LPM, monitored by an omega FL-45100 flow meter. The rig featured two gate valves for fluid direction and recirculation, a cooling fan with speeds of 700–800 rpm, and a louvered fin-flat tube radiator. An Agilent data acquisition system recorded temperatures measured by omega 5 TC series thermocouples. All the mentioned items can be seen in Fig. 1. Three distinct concentrations of hybrid nanoparticles were evaluated: 0.005%, 0.007%, and 0.009% by volume. The results of this study showed that at a flow rate of 15 LPM, when the volume fraction changed from 0% to 0.009%, the greatest increase in the heat transfer rate increased by 26.7%. The Nusselt number saw a maximum enhancement of approximately 21% under the same flow conditions. The volume fraction and the flow rate are significantly effective in the heat transfer rate of the car cooling system. Considerable increase in Nusselt number and heat transfer rate occurred when volume concentration was changed from 0.005% to 0.009%. While the inlet temperature did contribute to an increased heat transfer rate, its impact was minor compared to that of the nanofluid's volume concentration and flow rate. The research demonstrated that hybrid nanofluids, with their exceptional heat transfer characteristics, hold significant promise for automotive radiator systems, enabling the design of smaller radiators and consequently reducing fuel consumption.

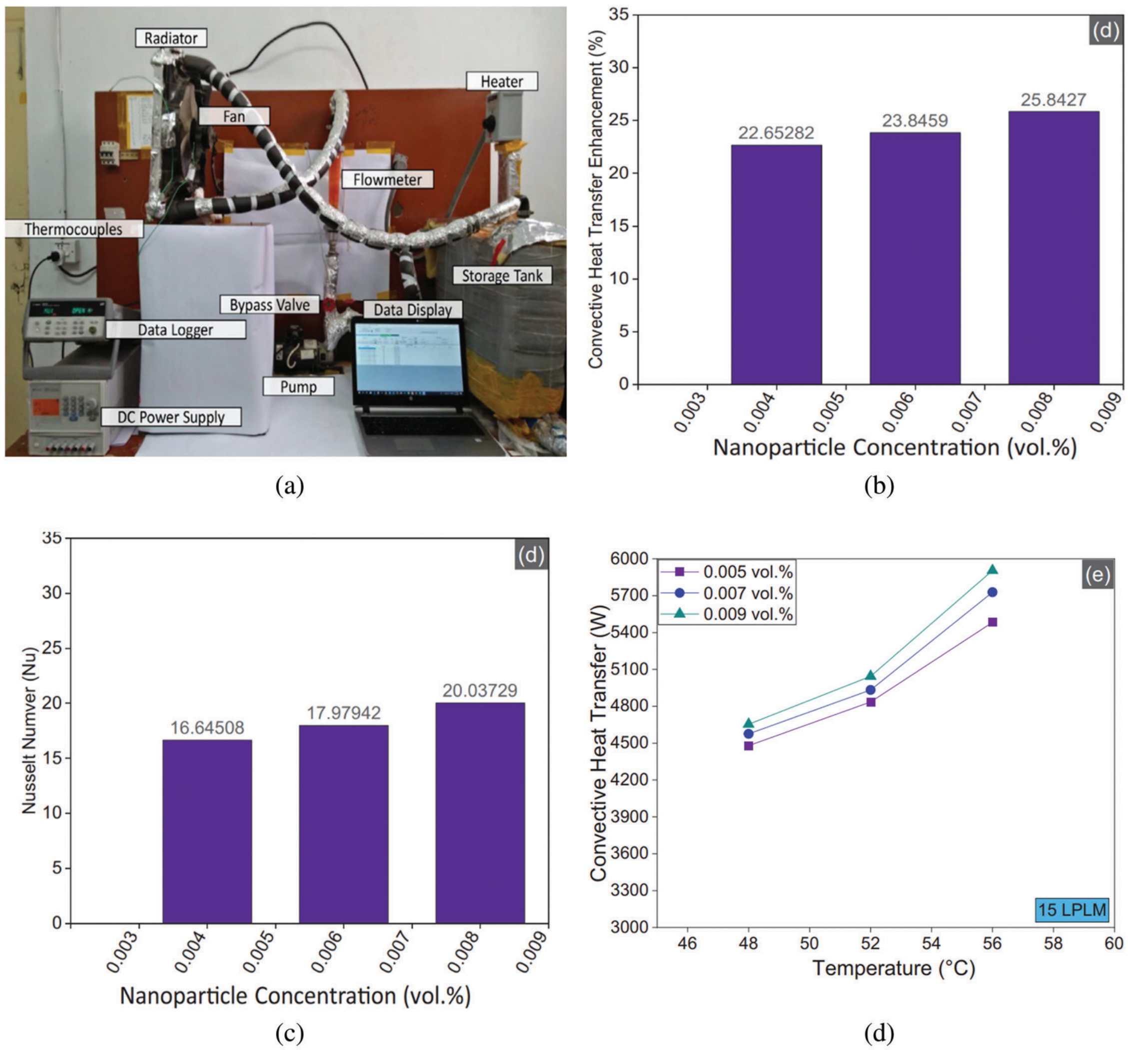



**Figure 1:** (a) Diagrammatic illustration of the experimental arrangement; (b) influence of nanoparticle concentration on convective heat transfer improvement; (c) impact of nanoparticle concentration on the Nusselt number; (d) effect of inlet temperature on convective heat transfer in radiator. Adapted with permission from Reference [71]. Copyright©2021, Elsevier

Naraki [72] performed an experimental investigation into the overall heat transfer coefficient of a CuO/water nanofluid in an automobile radiator operating under a laminar flow regime, utilizing an experimental system analogous to a car cooling system. The research effectively demonstrates the stabilization of 60 nm spherical copper oxide nanoparticles using SDS surfactant and pH tuning. The most stable nanofluid was achieved at pH = 10.1 with 0.2 wt.% SDS, showing minimal sedimentation after 60 h. The experimental setup of the empirical study conducted is displayed with all the equipment used in Fig. 2. The system circulated nanofluid at a rate of 0.6 $m^3$/h and maintained air entering at 35°C. The uncertainty analysis indicates a ±5.2% uncertainty in Reynolds number and ±15.1% in the overall heat transfer coefficient. Research confirmed the reproducibility of experiments by conducting repeated trials at a later stage. This study provides significant and promising results that will be discussed further. An inverse relationship between the hybrid nanofluid inlet temperature and the overall heat transfer coefficient was observed. In this study, the overall heat transfer coefficient was increased by adding $TiO_2$ and $Fe_2O_3$

nanoparticles to the base fluid. Specifically, at nanoparticle concentrations of 0.4 vol.% and 0.15 vol.%, the enhancements were 8% and 6%, respectively, compared to pure water. One of the reasons for the significant increase in the overall heat transfer coefficient is the increase in the nanofluid flow rate. The heat transfer coefficient saw an improvement with an increase in air flow rate, or equivalently, the Reynolds number for air. This research showed that challenges such as sedimentation and stability when the thermal efficiency of the car cooling system is increased by using hybrid nanofluids, need to be fully investigated. Optimal operating conditions, as determined by the Taguchi method, include the lowest temperature, highest nanofluid concentration, and maximum flow rates for both nanofluid and air. The study utilized Qualitek-4 software for this purpose, finding that air flow rate has the most influence, contributing 42% to the response. Optimal conditions were identified as 0.5 $m^3$/h for nanofluid flow, 1009 $m^3$/h for air flow, 0.4 vol.% for nanoparticle concentration, and 50°C for nanofluid temperature. The study's results reveal a robust alignment between the Taguchi method's [73] and the experimental data predictions, with an error margin as low as 2%. The Taguchi method predicted a value of 94.11 W/$m^2$K for the overall heat transfer coefficient, while the highest value recorded from experimental observations was 92.21 W/$m^2$K.

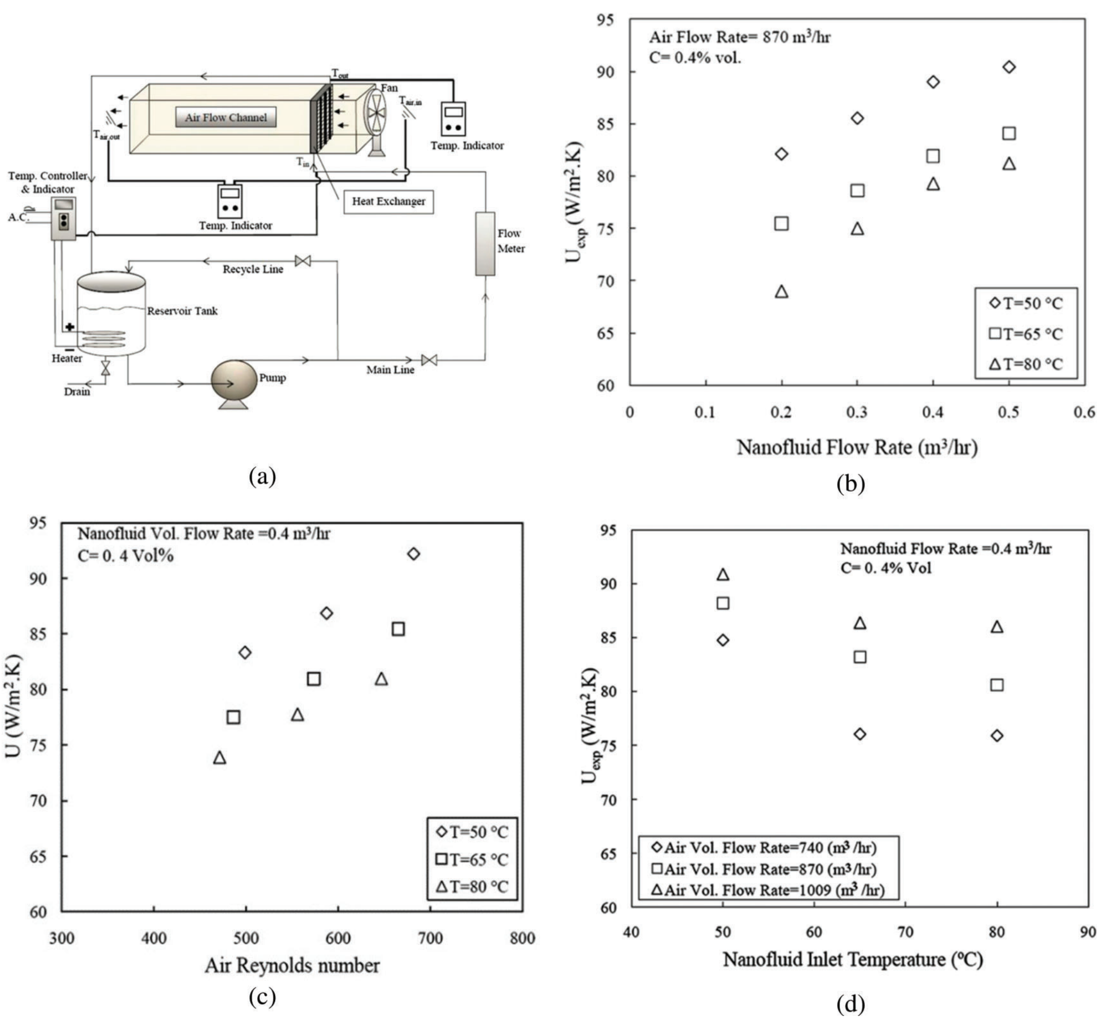
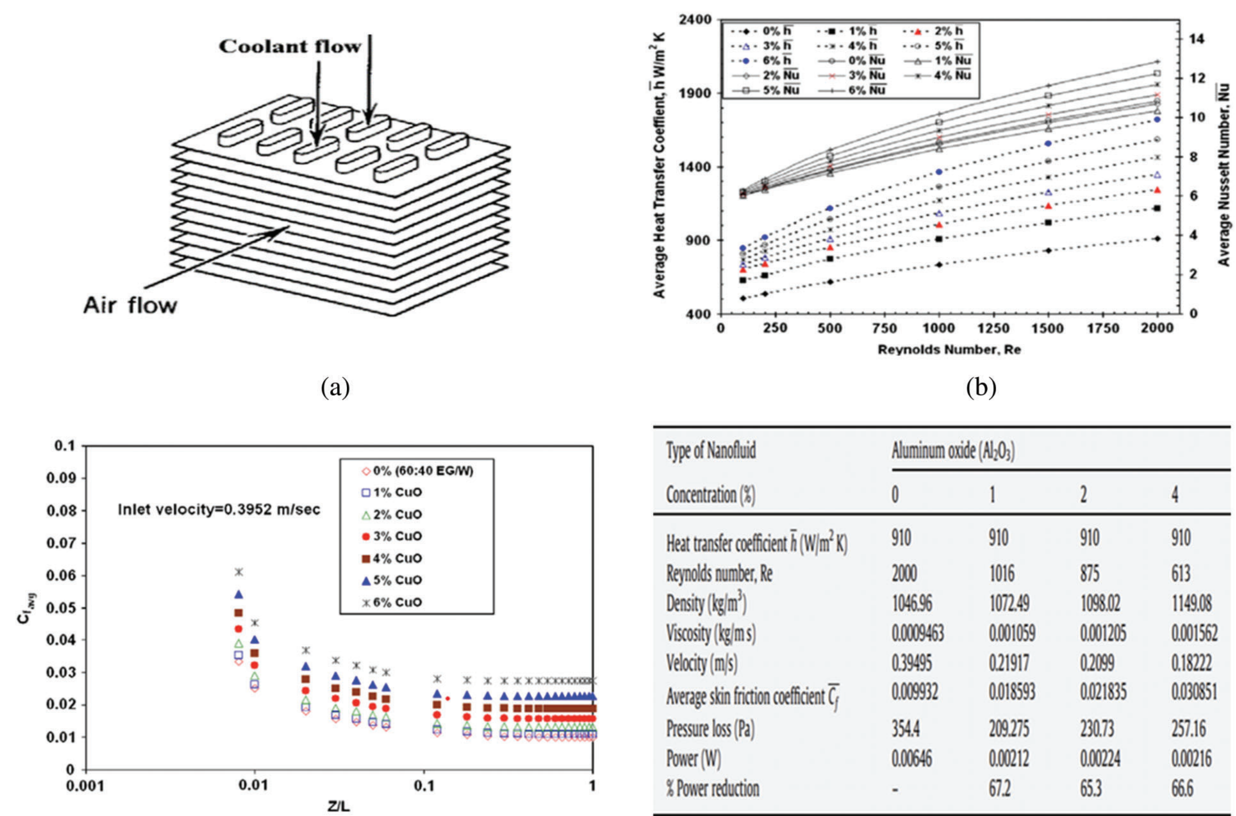



**Figure 2:** (a) Experimental setup diagram; (b) Influence of nanofluid volumetric flow rate on the overall heat transfer coefficient of CuO/water nanofluid in the car radiator, measured from 25°C–60°C; (c) The impact of air Reynolds number on the heat transfer coefficient in the car radiator with CuO/Water nanofluid; (d) Effect of inlet nanofluid temperature on the overall heat transfer coefficient with CuO/Water nanofluid. Adapted with permission from Reference [72]. Copyright©2013, Elsevier

Vajjha et al. [74] recently performed a numerical study on the advantages and limitations of using nanofluids in engine cooling systems. Their research aimed to thoroughly compare the cooling performance of nanofluids with that of traditional base fluid. The experiment involved two different nanofluids (CuO and $Al_2O_3$), prepared in a mixture with a 60:40 proportion of ethylene glycol (EG) and water (w). The purpose of using these nanofluids in an automobile radiator was to enhance cooling, as they were circulated through the flat tubes, as shown in Fig. 3a. To improve nanofluids compared to base fluids, researchers developed new correlations for their thermophysical properties, which were then used in numerical models to predict the behavior of nanofluids along the length of a tube. By accounting for the dynamic influence of Brownian motion on nanoparticles, along with the static aspects of Maxwell's theory, Vajjha et al. [74] adopted the model developed by Koo et al. [75]. Fig. 3b illustrates the relationship between Reynolds number and both average heat transfer coefficient (h) and Nusselt number (Nu) for various CuO nanofluid concentrations. When the Reynolds number reached 2000 and the volumetric concentration was set at 4%, the CuO nanofluid demonstrated a 61% increase in the average heat transfer coefficient compared to the base fluid. Fig. 3c illustrates how increasing nanoparticle concentration affects the skin friction coefficient ($c_{f\ avg}$). An increase in nanoparticle concentration leads to a rise in the skin friction coefficient, which in turn causes a higher pressure drop across the flat tube. With an inlet velocity held constant at 0.3952 m/s, the lower viscosity of the base fluid results in a Reynolds number of 2000, whereas the 6% CuO nanofluid corresponds to a Reynolds number of 725. At Reynolds numbers of 725 and 2000, with Z/L values of 0.33 and 0.91, respectively, in fully developed flow, the average skin friction coefficient ($c_{f\ avg}$) for the 6% CuO nanofluid is 2.75 times greater than that of the base fluid. Fig. 3d demonstrates how $Al_2O_3$ nanoparticle concentrations affect both heat transfer and pumping power in $Al_2O_3$ nanofluids. It shows that an equal level of heat transfer by nanofluids is achievable as base fluids but at lower velocities, which results in reduced pumping power. This is particularly beneficial in practical applications where energy efficiency is crucial. With an increase in particle concentration by volume, the required pumping power declines, even while maintaining constant heat transfer. This underscores the dual advantage of nanofluids in boosting heat transfer efficiency while also minimizing energy usage.

Experiments were performed on hybrid nanofluids by Li et al. [76], particularly those containing silicon carbide-multiwalled carbon nanotubes (SiC-MWCNTs), to evaluate their effectiveness as coolants in vehicle engine cooling systems (see Fig. 4). They assessed its thermal conductivity against ethylene glycol and found that the hybrid nanofluid can achieve a maximum increase of 32.01% in thermal conductivity just by concentration of 0.4 vol.%. The hybrid nanofluids, formulated with pure ethylene glycol (EG) and PVP-K30, were produced using a vertical closed sand mill. A combination of these components was mixed in a container at 500 rpm, then subjected to sand milling to yield stable nanofluids. Using ultrasonic oscillation, the high-concentration nanofluids were subsequently diluted to different levels, as shown in Fig. 4a. Thermal conductivity experiments were performed, where the base fluid was compared to hybrid nanofluids containing SiC-MWCNTs at concentrations of 0.04 vol.%, 0.1 vol.%, 0.2 vol.%, and 0.4 vol.%. The results, as demonstrated in Fig. 4c, indicated that with the increased nanoparticle concentration, there was an improvement in thermal conductivity, with the most significant enhancement occurring at 0.4 vol.%. The enhancement of the thermal conductivity of these hybrid nanofluids was observed with the rise in temperature, highlighting the critical importance of temperature regulation in optimizing their thermal performance. The authors had previously outlined the preparation method, which incorporates innovative techniques to improve the uniformity and distribution of nanoparticles, thereby enhancing their thermal properties. Furthermore, the study explored how the SiC-MWCNTs/EG hybrid nanofluid performed in terms of convective heat transfer within an aluminum alloy tube-fin radiator. The hybrid nanofluid effectively transferred the excess heat produced by the engine to be dissipated in the radiator. A thermostat was employed to ensure a steady flow rate of 1.5 m/s, maintaining the system's stability. Researchers observed that, regardless of the shear rate applied, the viscosity of these hybrid nanofluids displayed Newtonian behavior at all levels of particle concentration. As particle concentration increased, so did the viscosity, while higher temperatures resulted in lower viscosity. Traditional viscosity models failed to accurately predict these behaviors, necessitating the creation of a new formula specifically for SiC-MWCNTs hybrid nanofluids. This new predictive model is crucial for accurately designing and optimizing systems that utilize these advanced nanofluids for enhanced thermal management. Temperature's impact on SiC-MWCNTs/EG nanofluids' viscosity, measured from 25°C–60°C, revealed an inverse relationship between viscosity and temperature across all volume fractions, surpassing that of the pure fluid. As temperature rose, EG's viscosity naturally decreased, while heightened Brownian motion increased particle velocity, reducing inter-particle contact time and resulting in weakened adhesion between nanoparticles and molecules, ultimately lowering nanofluid viscosity [77]. The incorporation of SiC-MWCNTs nanoparticles into the coolant significantly boosted its convective heat transfer capability, with a 26% increase in the maximum heat transfer coefficient (α) observed at a concentration of 0.4 vol.% nanofluid and a temperature of 50°C compared to that of pure EG, as reported by Li et al. [76] in Fig. 4d. This observed trend suggests that the coolant is viable for operation at higher temperatures, showing that the said nano coolant is a promising option for improving heat dissipation efficiency in a car's cooling system [78].




(a) (b) (c) (d)

| Type of Nanofluid | Aluminum oxide ($Al_2O_3$) | | | |
|---|---|---|---|---|
| Concentration (%) | 0 | 1 | 2 | 4 |
| Heat transfer coefficient $\bar{h}$ (W/m² K) | 910 | 910 | 910 | 910 |
| Reynolds number, Re | 2000 | 1016 | 875 | 613 |
| Density (kg/m³) | 1046.96 | 1072.49 | 1098.02 | 1149.08 |
| Viscosity (kg/m s) | 0.0009463 | 0.001059 | 0.001205 | 0.001562 |
| Velocity (m/s) | 0.39495 | 0.21917 | 0.2099 | 0.18222 |
| Average skin friction coefficient $\overline{C_f}$ | 0.009932 | 0.018593 | 0.021835 | 0.030851 |
| Pressure loss (Pa) | 354.4 | 209.275 | 230.73 | 257.16 |
| Power (W) | 0.00646 | 0.00212 | 0.00224 | 0.00216 |
| % Power reduction | - | 67.2 | 65.3 | 66.6 |

**Figure 3:** (a) Illustration of a standard vehicle radiator configuration; (b) Variation of heat transfer coefficient (h) and Nusselt number (Nu) with Reynolds number for different particle volumetric concentrations of CuO nanofluid; (c) Variation of $(c_{f\,avg})$ along the tube length for different particle volumetric concentrations of CuO nanofluid; (d) Comparison of various parameters for different concentrations of the $Al_2O_3$ nanofluid with the base fluid for a constant heat transfer. Adapted with permission from Reference [74]. Copyright©2010, Elsevier

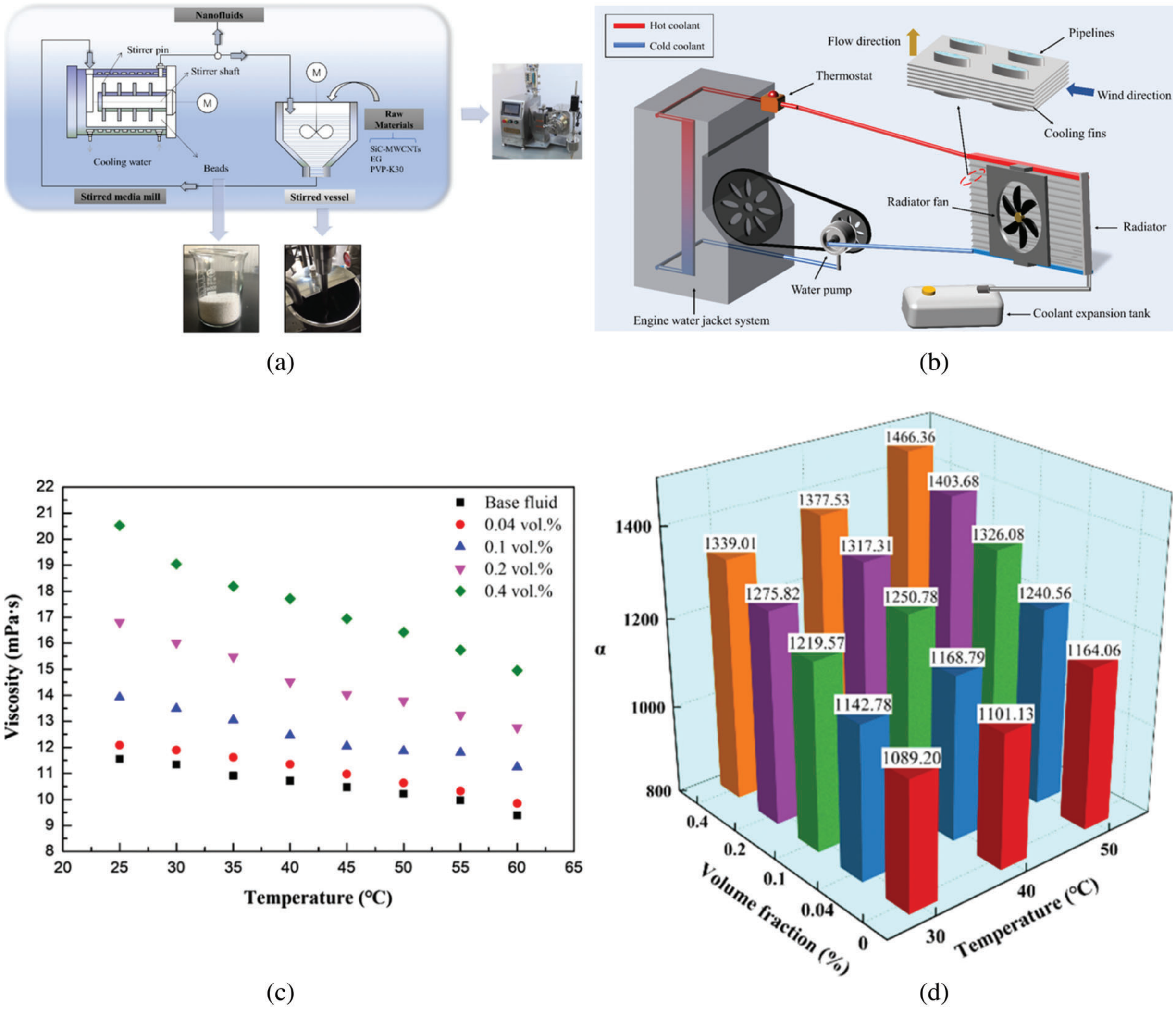



**Figure 4:** (a) Schematic diagram of the hybrid nanofluids preparation by sand mill machine; (b) The automobile engine cooling system; (c) The results of temperature's impact on SiC-MWCNTs/EG nanofluids' viscosity, measured from 25°C–60°C; (d) The impact of incorporating SiC-MWCNTs nanoparticles into the coolant at 30°C, 40°C, and 50°C compared to the pure coolant. Adapted with permission from Reference [76]. Copyright©2021, Elsevier

Leong et al. [79] studied the application of copper nanofluids based on ethylene glycol in automotive cooling systems, comparing their performance to pure ethylene glycol. They found substantial improvements in both the heat transfer coefficient and the overall heat transfer rate within the engine cooling system. The radiator referenced in their study, taken from Vasu et al. [80] and Kays et al. [81], is a cross-flow compact heat exchanger featuring 644 flat brass tubes and 346 uninterrupted copper fins. Flat tubes are chosen for their ability to enhance cooling rates and reduce flow resistance. The radiator was installed on a turbocharged diesel engine, model TBD 232V-12, highlighting the practical application of their findings in real-world automotive cooling systems. This research utilized copper nanoparticles, renowned for their high thermal conductivity, to enhance heat transfer under four different modeling conditions. Initially, with Reynolds numbers for air and coolant set at 4000 and 6000, respectively, a

3.8% heat transfer increment was observed with 2% copper particles. Increasing the air Reynolds number to 6000 while keeping the coolant at 5000 resulted in significant heat transfer improvements of 42.7% for pure ethylene glycol and 45.2% for the nanofluid. Conversely, the Reynolds number of the coolant was raised to 7000, while the air Reynolds number was kept at 4000, yielding minimal enhancements. Another phase showed a 18.7% decrease in the air frontal area with specific Reynolds numbers for air and coolant. Finally, varying the copper nanoparticle volume fraction at a constant coolant flow rate resulted in a 12.13% rise in pumping power for the nanofluid compared to pure ethylene glycol. All these cases are illustrated in Fig. 5.

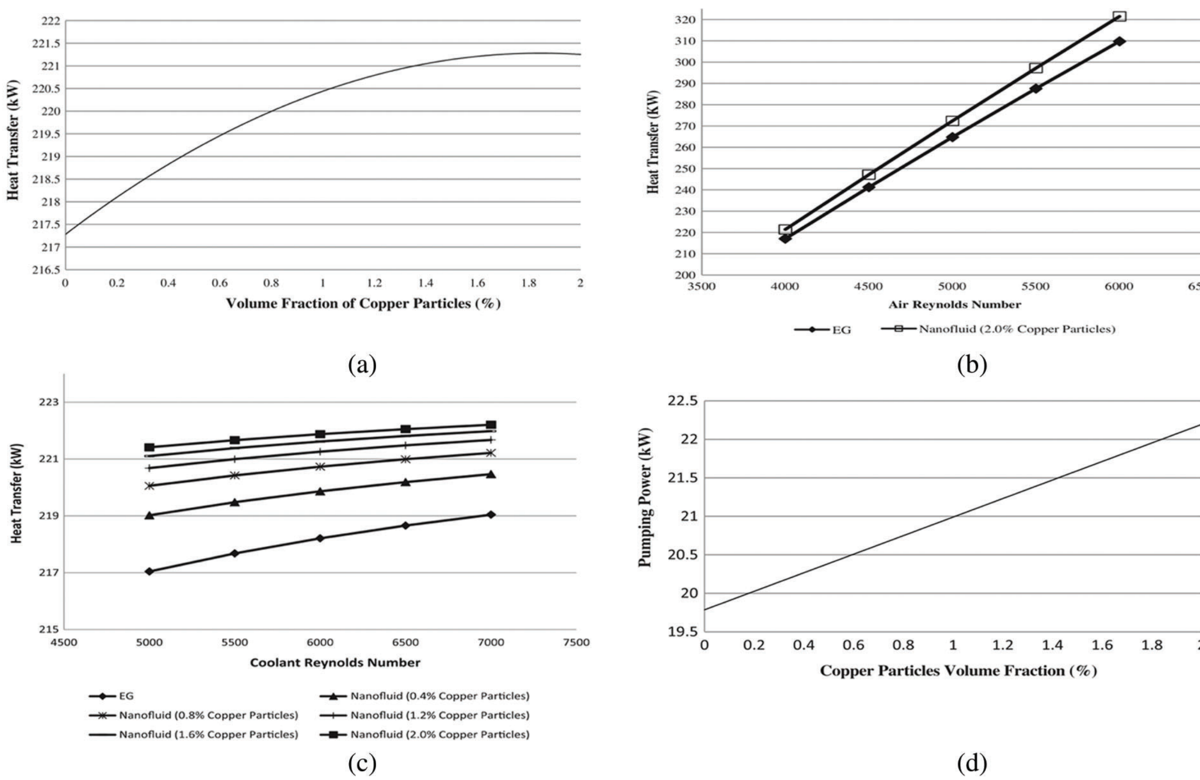
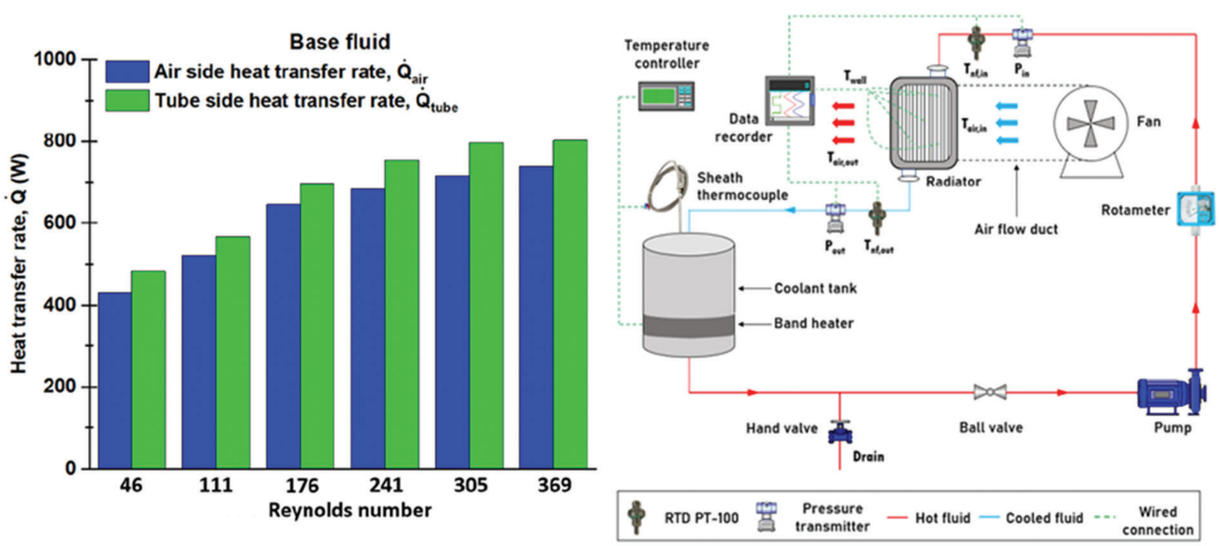



**Figure 5:** (a) The increase in volume fraction of copper nanoparticles from 0% to 2%; (b) Comparison between ethylene glycol and nanofluid at constant coolant Reynolds number and varying air Reynolds numbers from 4000 to 6000; (c) The effect of coolant Reynolds number, ranging from 5000 to 7000, on heat transfer rate enhancement with an increase in copper nanoparticles from 0% to 2% compared to pure ethylene glycol; (d) Influence of copper volume fraction varied from 0% to 2% on pumping power at a fixed coolant rate. Adapted with permission from Reference [79]. Copyright©2010, Elsevier

Xian et al. [82] performed an experimental investigation on hybrid nanoparticles and their impact on engine cooling. The base coolant used was ethylene glycol, and the nanoparticles investigated were $TiO_2$ and graphene nanoparticles (GnP). The research concluded that an optimal combination ratio should be determined to enhance efficiency. GnP-$TiO_2$ nanoparticles (70:30) were mixed with 0.1 wt% coolant, resulting in improvements of 4.94% to 35.87% in the heat transfer coefficient, Nusselt number, and also in radiator efficiency [83,84]. These findings are shown in Fig. 6a. A real aluminum radiator (Perodua Kancil) with 31 tubes and 32 fins was used in this experiment. The test device employed 304 stainless steel pipes, insulated to prevent heat transfer, for coolant liquid transfer. Additionally, a thermocouple model SRS 10A was used for temperature measurement, with an industrial fan positioned 20 cm from the radiator, and a Sanso PMD pump was employed to circulate the coolant. A schematic representation of the setup is provided in Fig. 6b. The coolant flow rate was controlled between 100 and 600 L per hour, while the fan speed was adjusted to 1.7, 1.9, and 2.1 m per second. Considering the errors, the Reynolds number varied from 50 to 368. In this experiment, hybrid nanoparticles 10G, 5G-5T, 3G-7T, and 7G-3T were investigated. With a Reynolds number of 50, an airspeed of 1.7 m/s, and a nanoparticle concentration of 0.075 wt%, the overall heat transfer coefficient (OHTC) saw increases of 20%, 25.1%, 28.7%, and 29%, respectively [85]. The information for this part is shown in Fig. 6c. The mixing ratio was a key factor affecting the Nusselt number [86,87]. The highest Nusselt number for nanoparticles, 6.19, was observed for 7G–3T with a mixing ratio of 70:30, a flow rate of 600 L per hour, Reynolds number of 259, and an airspeed of 2.1 m/s, with a 0.1 wt% concentration of this nanoparticle. Conversely, the 10 G nanoparticles at a concentration of 0.025 wt%, an airspeed of 1.7 m/s, and a Reynolds number of 50 achieved a Nusselt number of 3.03, which was 1.88% lower than the base coolant. Xian et al. [82] evaluated the radiator's performance by varying the concentration of nanoparticles in the base coolant. At an airspeed of 1.7 m/s and a Reynolds number of 50, incorporating 0.025 wt%, 0.05 wt%, 0.075 wt%, and 0.1 wt% of GnP-$TiO_2$ (70:30) into the base coolant led to increases in radiator efficiency of 7.93%, 13.5%, 15.8%, and 18.9%, respectively [88,89]. Enhancement in heat transfer can be seen in this pattern, a result of the increased nanoparticle content [90,91]. Refer to Fig. 6d for relevant information.

Finally, Table 5 is presented, which summarizes the research works analyzed in this section and helps the readers to easily compare these works. This table contains all the important key points related to the researches of Section 6. One can easily understand the differences at a glance.




(a) (b)

**Figure 6:** (Continued)

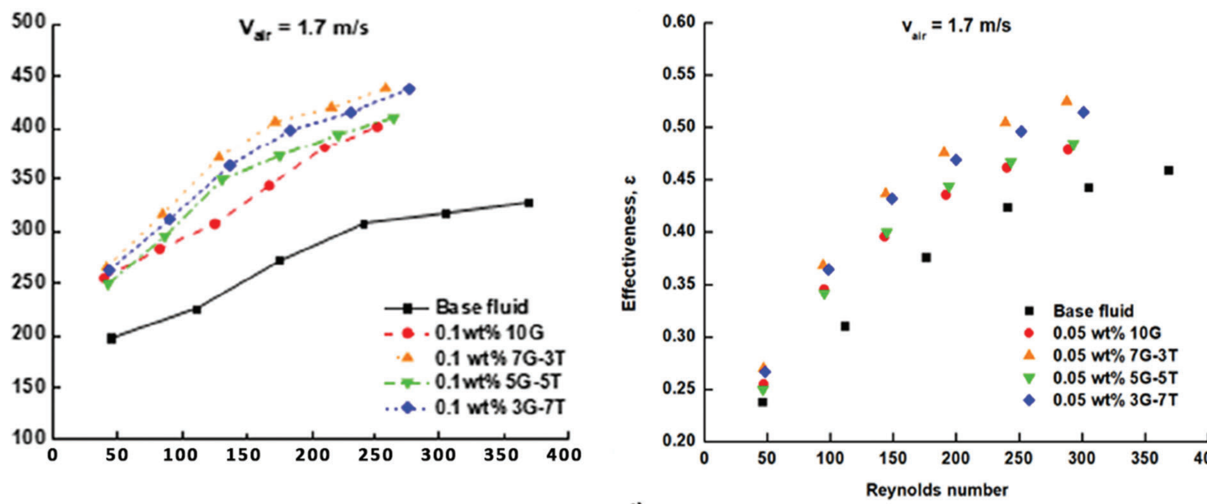



**Figure 6:** (a) Verification of experimental data: assessment of heat transfer rate error across various Reynolds numbers; (b) Schematic representation of experimental setup; (c) OHTC and Reynolds diagram at a speed of 1.7 m/s and a concentration of 0.1 wt%; (d) Comparison of nanoparticle effects (10G, 5G-5T, 3G-7T, 7G-3T) at 0.005 wt% on Reynolds number and effectiveness, measured against ethylene glycol. Adapted with permission from Reference [82]. Copyright©2022, Elsevier

**Table 5:** Summary of research works reviewed in Section 6

| Study | Nano coolant | Experimental setup | Main findings | Description |
|---|---|---|---|---|
| [71] | $Fe_2O_3/TiO_2$ nanoparticles in water with SDBS surfactant | Radiator system with electric heater, centrifugal pump, flow rate: 11–15 LPM, fan speed: 700–800 rpm | Heat transfer rate increased by 26.7%, Nusselt number up 21% at 0.009% concentration and 15 LPM flow rate | Hybrid nanofluids show promise in enhancing heat transfer in automotive radiators, potentially allowing for smaller radiators and improved fuel efficiency |
| [72] | CuO in water with SDS surfactant, pH 10.1 | Car cooling system mimic with 0.6 $m^3/h$ flow rate, 35°C air | Optimal conditions: 0.5 $m^3/h$ nanofluid flow, 1009 $m^3/h$ air flow; 0.4 vol % concentration increased heat transfer | Stabilization techniques are critical for effective use of nanofluids; optimized conditions increase heat transfer efficiency in automobile cooling systems |
| [74] | CuO and $Al_2O_3$ in 60:40 ethylene glycol-water mix | Numerical study using developed thermophysical correlations for CuO and $Al_2O_3$ | 61% heat transfer enhancement at 4% CuO; reduced pumping power at higher particle concentration | Nanofluids improve heat transfer efficiency while reducing pumping power, benefiting energy efficiency in automotive applications |

(Continued)

**Table 5 (continued)**

| Study | Nano coolant | Experimental setup | Main findings | Description |
|---|---|---|---|---|
| [76] | SiC-MWCNTs in ethylene glycol with PVP-K30 | Aluminum radiator with steady flow, 1.5 m/s; temperature range: 25°C–60°C | Max 32% thermal conductivity increase at 0.4 vol.% concentration; viscosity inversely related to temperature | SiC-MWCNTs hybrid nanofluids improve thermal conductivity and show potential for high-temperature operations in vehicle cooling systems |
| [79] | Copper nanoparticles in ethylene glycol | Cross-flow heat exchanger with flat tubes, turbocharged diesel engine | 45.2% heat transfer increase at 2% copper concentration and air Reynolds number of 6000 | Copper nanofluids substantially enhance heat transfer rates, showing potential for real-world engine cooling system improvements |
| [82] | $TiO_2$ and graphene (GnP) in ethylene glycol, 70:30 GnP-$TiO_2$ ratio | Aluminum radiator with adjustable fan speeds, various nanoparticle concentrations | Heat transfer coefficient increased up to 35.87%; Nusselt number improved with 7G–3T nanoparticles | Optimal nanoparticle mixing ratios significantly improve radiator efficiency and heat transfer rates, supporting radiator performance enhancement in automotive systems |

## 7 Challenges of Nanofluids for Automotive Cooling Systems

Future research in nanofluids for automotive cooling systems faces several key challenges to maximize their practical application and effectiveness. Long-term stability is a primary concern, as maintaining consistent nanofluid performance over time is essential for sustained use in vehicle radiators. Without this stability, sedimentation or clustering could reduce heat transfer efficiency and compromise the nanofluid's reliability [92]. Another challenge is compatibility with radiator materials. Prolonged exposure to nanoparticles may lead to corrosion or degradation of standard radiator materials, necessitating comprehensive studies on material compatibility to prevent damage and ensure optimal performance [93]. Additionally, pumping power and operational costs pose potential barriers; some nanofluids can increase system viscosity [94–96], requiring higher pumping power and potentially driving up energy consumption [97,98]. Addressing these factors is crucial to make nanofluids a viable solution in practical automotive systems. Furthermore, optimizing nanoparticle concentrations is needed to balance thermal conductivity with manageable viscosity levels. Higher concentrations improve heat transfer but may also increase viscosity, causing higher pressure drops and energy costs. Fine-tuning these concentrations to achieve maximum thermal benefits without adverse effects remains an open research area [99]. Finally, external factors such as electric or magnetic fields could influence nanofluid performance, as certain nanoparticles exhibit unique responses to these stimuli [100]. Understanding these effects could open new avenues for controlled performance adjustments in specific operational conditions. Addressing these challenges will enhance the long-term feasibility of nanofluids, guiding future research toward more stable, efficient, and cost-effective applications.

## 8 Conclusions

Here, a review is performed about the role of nanofluids and hybrid nanofluids in enhancing the efficiency of flat tube car radiators. Key points and findings of the present work can be summarized as follows:

- *This review highlights the significant potential of nanofluids and hybrid nanofluids in enhancing the performance of flat tube car radiators, particularly as traditional coolants begin to reach their limits in modern vehicles*.
- *By improving heat transfer capabilities, these advanced fluids could lead to more efficient, compact, and lightweight radiator designs, contributing to better fuel efficiency and overall vehicle performance*.
- *The effects of using nanofluids extend beyond thermal efficiency; they also impact engine performance, pressure drop, and pumping power, raising important cost considerations*.
- *We acknowledge the challenges associated with the adoption of nanofluids, such as ensuring their long-term stability and compatibility with radiator materials, and addressing potential increases in pumping power and operational costs*.
- *This review synthesizes current research, offering a comprehensive overview of the types of nanofluids and their applications in automotive cooling systems*.
- *Specific improvements regarding the application of nanofluid/hybrid nanofluid in flat tube car radiators are discussed, including the exploration of nanoparticle combinations that optimize thermal and hydraulic performance*.
- *While the potential benefits are clear, further research is needed to address existing challenges, such as the optimization of nanoparticle concentrations and the effects of external factors like electric fields*.
- *Challenges for future work include improving the cost-effectiveness of nanofluids, ensuring their stability over time, and evaluating their long-term effects on engine performance and radiator materials*.

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**Availability of Data and Materials:** The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Ethics Approval:** Not applicable.

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