A Review on Recent Development and Future Perspective of Nanofluid Utilization in Automotives

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A Review on Recent Development and Future Perspective of Nanofluid Utilization in Automotives

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Abstract: Nanofluids, have attracted considerable interest for their enhanced thermal properties, making them promising for automotive applications. This review examines recent advancements in nanofluid utilization within automotive systems, focusing on thermal management improvements in engine cooling, lubrication, and fuel efficiency. Studies have demonstrated that nanofluid-based coolants can increase thermal conductivity by 15–40%, leading to an increase in heat transfer efficiency and a reduction in engine operating temperatures by 5–10°C. Experimental results indicate that using Al_2O_3-water nanofluids in radiators improves OHTC by up to 25% compared to conventional ethylene glycol-water coolants. Additionally, nanolubricants infused with CNTs or graphene oxide has shown a 10–20% reduction in engine friction and wear, prolonging component lifespan. The integration of nanofluids as fuel additives has demonstrated a brake thermal efficiency improvement of up to 11.56%, while also reducing specific fuel consumption by approximately 8–10%. However, challenges remain in stability, compatibility, and large-scale feasibility. This paper provides a comprehensive overview of key achievements, highlights comparative performance metrics, and identifies future research directions for optimizing nanofluid applications in the automotive industry.

Keywords: automotive; heat transfer; nanofluids; nanolubricant; radiator coolant; thermal conductivity

1. Introduction

Enhancing the thermal performance of engine cooling systems is one of the modifications that can help reduce energy consumption while improving automotive performance. The radiator, a small heat exchanger, is the most essential component of the cooling system. Increases in flow rate, heat transfer surface area, and the temperature difference between cold and hot fluids are all known techniques that can be employed to enhance heat transmission in a compact heat exchanger, further study of fluid suspensions and caused clogging and abrasion in the flow channel. The concept of enhancing heat transfer in small-scale heat exchangers through traditional techniques, like expanding the surface area with added fins, is believed to have reached its limits. However, these methods have both advantages and drawbacks[1–2]. The heat transfer fluids used in car radiators have poorer heat transfer characteristics by nature. This creates restrictions on the usage of smaller engineering tools for performance enhancement. As a result, the most effective enhancement for a cooling system emphasizes the thermal properties of the fluids used in the heat exchanger rather than its design characteristics. In light of this, using nanofluids to enhance the thermal performance of automotive radiators appears to be a viable alternative[3–4]. The automotive industry has not been an exception among the many potential uses; the use of nanofluids in automotive has received extensive research. It is primarily suggested that nanofluids can replace the traditional radiator coolant, which is a blend of ethylene glycol and water[5–6].

The use of nanofluids as radiator coolants for vehicles has long been a subject of discussion because of their widely recognized heat-absorbing properties. However, nanofluids have many more uses in the automotive industry besides just heat transfer. These include the use of nanofluid as braking fluid, engine fuel, shock absorber fluid, and lubricant for automotive air conditioning systems[7–8]. The various application of utilization of nanofluid in automotive system is shown in Figure 1.

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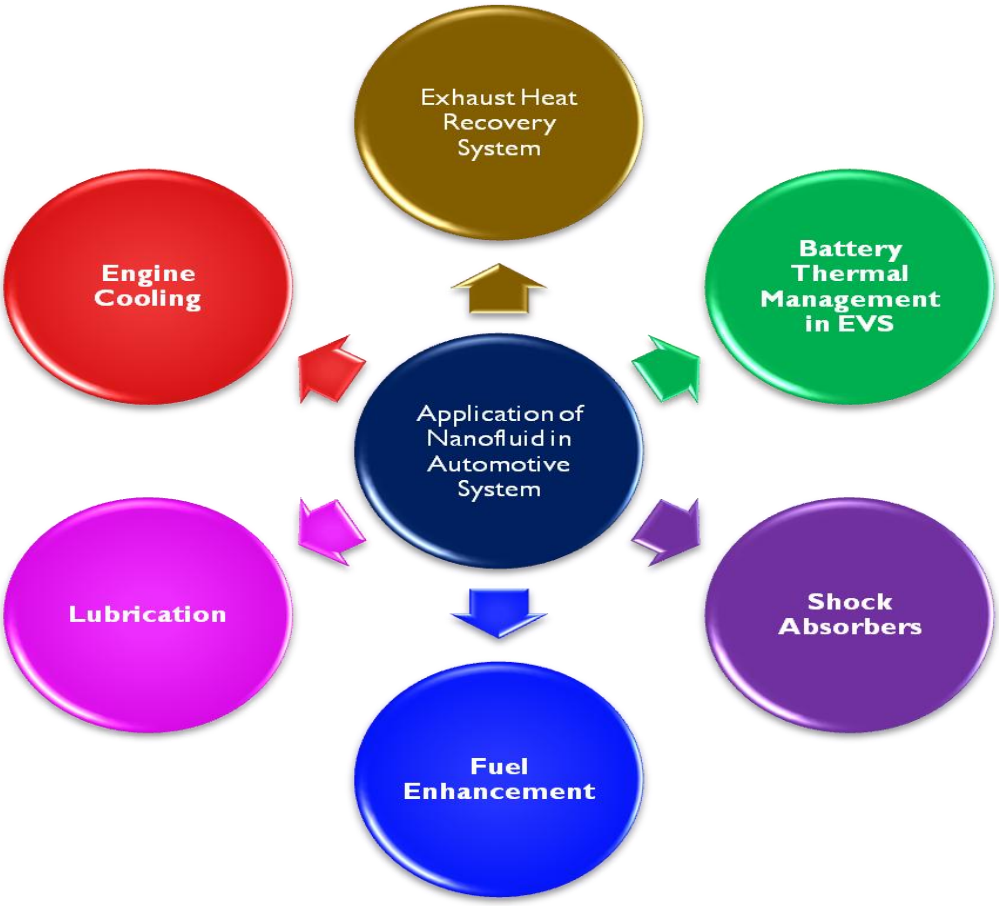

Fig. 1: Application of nanofluid in automotive system

A new technology for use in numerous mass and heat transport processes is provided by nanofluids. The commercialization of these mechanisms has been hampered by people's ignorance of the mechanisms' workings and the scope of their potential applications[9–10]. Since the last ten years, review articles on the many uses of nanofluids have been increasingly common. The use of nanofluids in the cooling system of vehicles has been studied in certain literature. Nanoparticles have been used with conventional coolants to boost the effectiveness of heat evacuation from the engine, and several studies have praised their efficacy[11–14]. The published findings, however, contain several inconsistencies, particularly in regards to the ideal amount of nanoparticles, the percentage of improvement, the innovative type of nanoparticles, and other issues.

Despite significant advancements in the application of nanofluids in the automotive industry, several critical research gaps remain. Existing studies highlight inconsistencies in the optimal nanoparticle concentration, improvement percentages, and the most effective nanoparticle types for enhancing thermal performance. While nanofluids have demonstrated improved heat transfer properties, their long-term stability, cost-effectiveness, and environmental impact under real-world conditions are still not well understood. Moreover, challenges related to large-scale production, standardization, and compatibility with existing automotive components hinder their widespread adoption. This review provides a comprehensive and systematic analysis of nanofluids in automotive applications, addressing key challenges, advancements, and future perspectives. While numerous studies have explored the benefits of nanofluids, several inconsistencies remain, particularly concerning the ideal nanoparticle concentration, percentage improvements in thermal performance, and the innovative use of new nanoparticle types. The novelty of this review lies in its structured approach to consolidating and critically analyzing the latest findings while bridging the gap between laboratory-scale experimentation and real-world automotive applications.

The study focuses on bridging the gap between laboratory-scale experimentation and practical implementation of nanofluids in automotive systems, such as engine cooling, lubrication, and heat transfer enhancement. While significant progress has been made in understanding the thermal and rheological properties of nanofluids, there remains limited insight into their long-term stability, cost-effectiveness, and environmental impact under real-world

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conditions. Additionally, challenges in scalability, compatibility with automotive components, and standardization hinder widespread adoption. The integration of nanofluids in automotive systems aligns with global sustainability goals. This review emphasizes how nanofluids contribute to reducing emissions, improving fuel efficiency, and minimizing energy losses in automotive operations.

2. Nanomaterials and Nanofluid

Nanomaterials and nanofluids have revolutionized the automotive industry by leveraging the unique properties of nanoscale structures to enhance performance, efficiency, and sustainability[15)]. Nanomaterials are materials with structures at the nanometer scale (1–100 nm), exhibiting unique physical, chemical, and mechanical properties due to their high surface-to-volume ratio and quantum effects[16)]. The size of different nanoscale materials is shown in Figure 2. Examples include nanoparticles, nanofibers, and carbon nanotubes, which are incorporated into automotive materials to improve strength, reduce weight, and enhance durability[17)]. For instance, lightweight nanocomposites reinforced with carbon nanotubes or graphene are used in vehicle frames and body panels, significantly reducing weight and improving fuel efficiency. Nanostructured coatings, such as titanium dioxide (TiO_2) and nanoceramics are applied to protect surfaces against corrosion, scratches, and wear while improving aesthetic finishes. These coatings also offer self-cleaning and anti-fogging properties, enhancing vehicle maintenance and safety[18–19)].

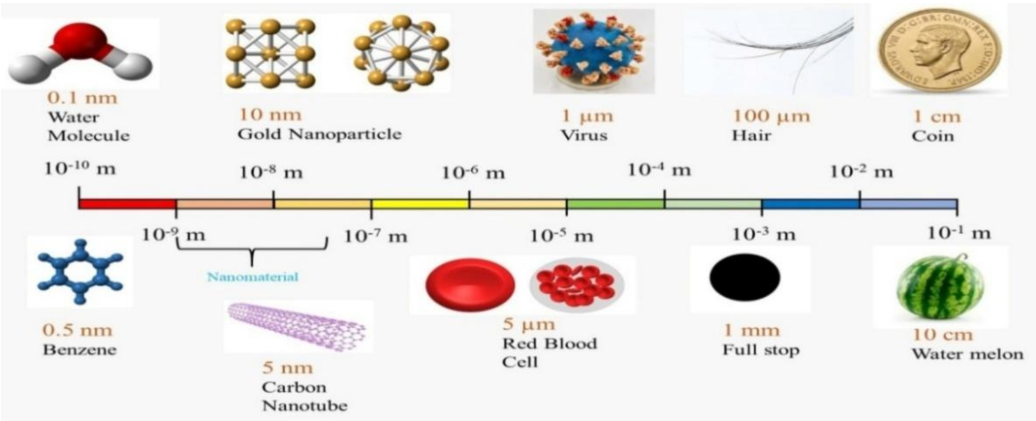

Fig. 2: Size of different nanostructured materials (1-100 nm)

Nanofluids, on the other hand, are fluids infused with nanoparticles like metals, oxides, or carbon-based materials, offering superior thermal and physical properties. The different types of nanomaterials used to enhance the performance of automobiles are shown in Figure 3

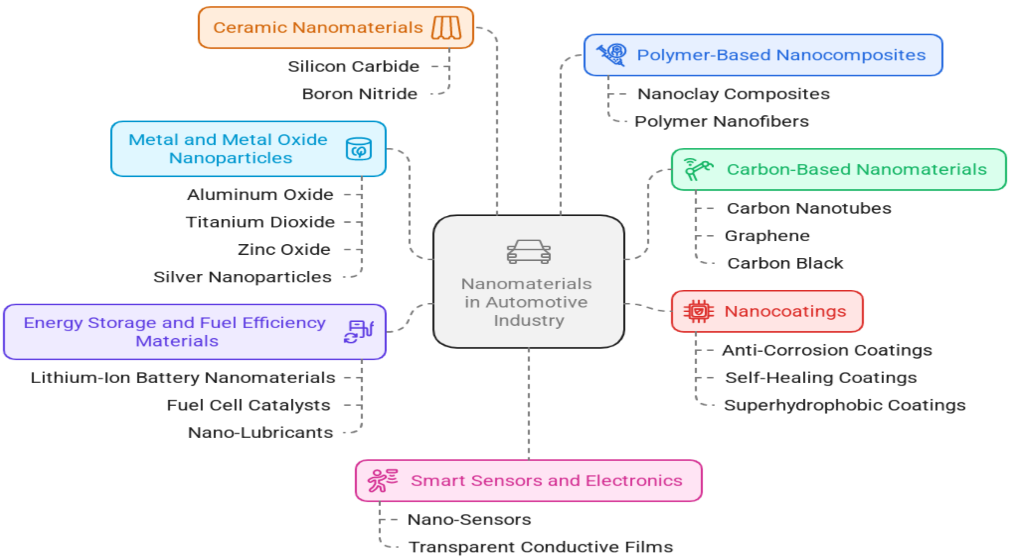

Fig. 3: Different types of nanomaterials used to enhance the performance of automobiles

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Nanomaterials play a crucial role in enhancing the performance of automobiles by improving strength, efficiency, and durability. Carbon-based nanomaterials like carbon nanotubes (CNTs) and graphene are used in lightweight composites, increasing fuel efficiency while maintaining structural integrity. Metal oxide nanoparticles, such as aluminum oxide and titanium dioxide, enhance wear resistance, reduce friction, and provide UV protection. Ceramic nanomaterials like silicon carbide and boron nitride improve brake pad durability and thermal conductivity in engine components[20]. Polymer-based nanocomposites strengthen plastics, making vehicles lighter yet more resilient. Nanocoatings, including self-healing and hydrophobic layers, protect exteriors from scratches and dirt, while nano-lubricants reduce engine friction, improving fuel economy. In energy systems, nanomaterials boost lithium-ion battery performance and hydrogen fuel cell efficiency. Additionally, nano-sensors enhance safety and monitoring systems. These advancements collectively contribute to better vehicle performance, longevity, and environmental sustainability in the automotive industry[21].

Choi and Eastman originally referred to these liquids as nanofluids. Nanofluids are base fluid-based colloidal suspensions of 10 nm–100 nm nanoscale particles[22]. In automobiles, nanofluids improve thermal management systems, which are critical for both internal combustion engines (ICEs) and electric vehicles (EVs). Coolants enhanced with nanoparticles such as aluminum oxide (Al_2O_3) or copper exhibit higher thermal conductivity, facilitating efficient heat dissipation from radiators and engines. This not only prevents overheating but also prolongs engine life and ensures optimal performance. For EVs, nanofluids are essential for cooling batteries and power electronics, ensuring safety and extending battery lifespan under high-energy demands[23].

The integration of nanomaterials into energy storage systems, such as lithium-ion batteries and super capacitors, has also enhanced the performance of EVs by improving energy density, charge rates, and durability. However, challenges such as cost-effective production, stability, and environmental impacts remain barriers to widespread adoption[24].

3. Nanofluid Preparation Technique and Factors Affecting its Stability

3.1. Nanofluid Preparation Technique

The primary steps in nanofluid preparation include the selection of appropriate nanoparticles and base fluids, followed by dispersing the nanoparticles into the fluid using specific techniques. Common nanoparticles used include metals (e.g., copper, silver), metal oxides (e.g., aluminum oxide, titanium dioxide), and carbon-based materials (e.g., graphene, carbon nanotubes), while base fluids range from water and oils to glycols and refrigerants[25].

Two widely used approaches for nanofluid preparation are single-step and two-step methods. The single-step method involves simultaneous synthesis and dispersion of nanoparticles directly into the base fluid. This method minimizes the chances of nanoparticle agglomeration since the particles are introduced in their nascent state. Techniques like chemical vapour deposition (CVD) and plasma-assisted synthesis are commonly employed in this approach. However, this method is limited by high costs and complexity in large-scale production[26].

The two-step method is more commonly used for large-scale applications. It involves first synthesizing nanoparticles through conventional techniques, such as sol-gel, ball milling, or chemical reduction, followed by their dispersion into the base fluid. To achieve uniform dispersion and prevent aggregation, mechanical methods like ultrasonication, high-shear mixing, and magnetic stirring are employed. Additionally, surfactants or stabilizing agents are often added to enhance the stability of the suspension by reducing inter-particle forces[27]. The two-step process for producing nanofluids is shown in Figure 4.

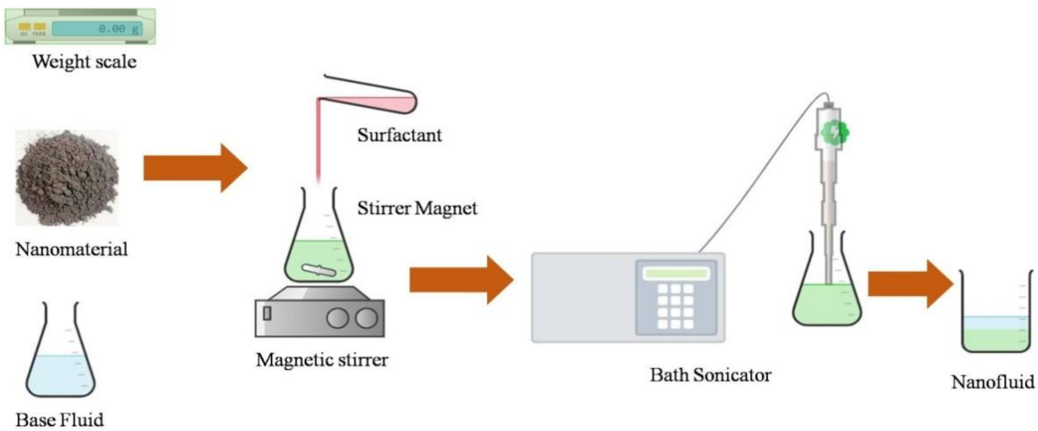

Fig. 4: Nanofluid preparation technique by 2-step method

Post-preparation, ensuring the stability of the nanofluid is critical. Techniques such as pH control, surfactant addition, and surface functionalization are applied to prevent sedimentation and clustering of nanoparticles over time[28]. Characterization methods, including zeta potential analysis and particle size distribution measurements, are used to assess stability and dispersion quality. The choice of preparation technique depends on the desired application, cost constraints, and required properties of the nanofluid. Properly prepared nanofluids exhibit enhanced thermal conductivity, heat transfer, and stability, making them indispensable in advanced cooling systems, energy devices, and industrial applications[29].

Preparing nanofluids presents several challenges, primarily related to nanoparticle dispersion, stability, and uniformity. Nanoparticles tend to agglomerate due to strong van der Waals forces, leading to poor dispersion and reduced heat transfer efficiency. Stability is another major issue, as suspended nanoparticles tend to settle over time, causing sedimentation and clogging in cooling systems. Achieving uniformity is difficult, as inconsistent nanoparticle distribution can result in localized hotspots and inefficient thermal performance[30]. Various strategies have been devised to overcome these challenges. Surfactants and surface modification techniques can help enhance nanoparticle dispersion by reducing attractive forces between particles. Additionally, adjusting the pH of the base fluid and using electrostatic or steric stabilization techniques can improve suspension stability. Ultrasonic agitation and high-shear mixing are effective in breaking up agglomerates and ensuring uniform dispersion. Furthermore, selecting appropriate nanoparticle concentrations and base fluids can optimize the thermal conductivity and viscosity of the nanofluid while maintaining stability. Advanced methods like nanocoating and functionalization of nanoparticles can also enhance their compatibility with base fluids. By implementing these solutions, nanofluids can achieve better stability, uniformity, and efficiency in coolant systems, making them more viable for industrial and automotive applications[31].

3.2. Factors Affecting Nanofluid Stability

Nanofluids lose their capacity to conduct heat because of their propensity to agglomerate. For the evaluation of nanofluids that can alter their thermophysical properties for applications, their stability is in fact a crucial factor. The long-term stability and thermal characteristics of the nanofluids were enhanced using chemical and physical techniques[32]. The various techniques to enhance the stability of nanofluid are illustrated in Figure 5. The base fluid's dielectric constant directly relates to the repulsive potential, hence the higher the dielectric constant, the more stable the base fluid will be. Among other base fluids, water has the highest dielectric constant, which suggests that it has a high repulsive potential[33].

Fig. 5: Techniques to enhance the stability of nanofluid

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As particle concentration rises, the average distance between particles decreases. A stronger Van der Waals attractive force is indicated by the reduced separation distance. Particle agglomeration occurs when electrostatic repulsive potential prevails over Van der Waal attractive potential. As a result, the effect of particle concentration is very important in determining the stability of nanofluids. Poor stability of nanofluid at greater particle concentrations has been noted by several researchers[34].
There is a correlation between the zeta potential value and the pH value of the suspension. The stability of nanofluid is influenced by the pH value, which also affects the electrical charge density on the surface of nanoparticles leading to stronger electrostatic repulsion between them. This repulsion counteracts Van der Waals attractive forces that cause agglomeration, thereby enhancing dispersion stability[34]. Furthermore, the optimal pH varies depending on the type of nanoparticle; for instance, metal oxide nanofluids exhibit enhanced stability when their zeta potential is maximized, typically at extreme acidic or basic conditions. Figure 6[34] depicts the variance in pH values for several nanoparticles that correlate to their zeta potential. When nanoparticles are created, the pH level also affects the size and form of the particles, which affects the stability of the nanofluid.

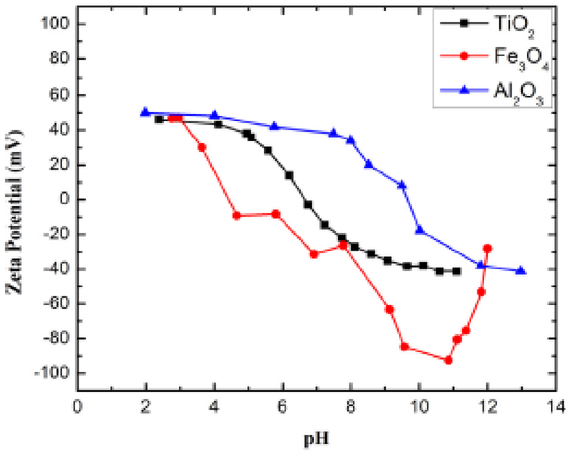

Fig. 6: Variation of Zeta potential with pH value of different nanofluid[34]

Ultrasonication is a widely used technique to improve the dispersion of nanoparticles by breaking down agglomerates through high-frequency sound waves. The process generates acoustic cavitation, which involves the rapid formation, growth, and collapse of microbubbles in the liquid medium. The intense shear forces produced during bubble collapse effectively separate nanoparticle clusters, ensuring uniform dispersion and reducing the average particle size[35]. Moreover, prolonged sonication can lead to a stable dispersion where the particle size no longer decreases with time, as observed in various studies. The effectiveness of ultrasonication depends on factors such as the duration of exposure, the intensity of the ultrasonic waves, and the type of sonicator used[36]. Ultrasonication allows for the management of nanofluid stability. By separating the nanoparticle cluster, ultrasonication creates a stable nanofluid. Sonication bath and probe sonicator are used for ultrasonication. The probe sonicator outperforms the other two procedures in terms of breaking up particle clusters and reducing average cluster size. Particle size is unaltered after an appropriate ultrasonication time, according to Chen and Wen[37]. Surfactants are used to stabilize nanofluids by lowering the surface tension of the base fluids and increasing particle immersion. Additionally, the surfactants weaken the improvement in thermal conductivity by raising the thermal resistance between the nanoparticles and the base fluids[38]. The technique that is most frequently used to evaluate stability is the sedimentation process. This method is based on the idea that sediment forms at the liquid column's bottom due to gravity. An alternative sedimentation technique called centrifugation takes a much less time to evaluate the stability of the nanofluid. The principle of the sedimentation method was utilised by Zhu et al.[39] in their experimental apparatus to gauge the stability of the graphite suspension.
The stability of nanofluids remains a significant challenge due to issues such as nanoparticle agglomeration, sedimentation, and changes in thermophysical properties over time. These factors reduce their thermal performance and reliability for prolonged applications[40]. Various factors, including particle concentration, pH levels, and the dielectric constant of the base fluid, influence nanofluid stability. To enhance stability, researchers employ techniques such as ultrasonication, which disperses clusters of nanoparticles, and the addition of surfactants or stabilizing agents, which reduce inter-particle forces and prevent agglomeration. Surface functionalization and pH control further improve dispersion quality and minimize sedimentation. Additionally, zeta potential analysis is commonly used to assess stability; ensuring nanoparticles remain well-dispersed in the fluid. These methods collectively contribute to enhancing the long-term effectiveness of nanofluids in industrial and automotive applications[41].
Nanoparticle clogging in coolant systems occurs due to particle agglomeration and sedimentation, leading to blocked channels and reduced heat transfer efficiency. Additionally, prolonged nanoparticle exposure can cause abrasive wear on system components, accelerating material degradation. To mitigate these issues, optimizing nanoparticle size, using stabilizing agents, and employing effective filtration systems are essential. Advanced coatings on components can also reduce wear, ensuring prolonged operational efficiency and reliability in nanofluid-based cooling applications[42].

4. Thermophysical Properties of Nanofluid

The thermophysical properties change as a result of the integration of nanoparticles in the base fluid. The degree to which different nanomaterials alter their parameters varies. The behaviour of heat transport is significantly improved by the thermophysical characteristics of nanofluids. It is quite important for managing industrial and energy-saving potential. The industry has showed a lot of interest in nanofluids. Nanoparticles, in contrast to ordinary particle-fluid suspension, have a considerable capacity to improve the thermal transfer qualities. Due to their capacity to enhance thermal characteristics, nanofluids have drawn considerable attention in the past ten years. Different properties of nanofluid are discussed in this section. Table 1 represents the different nanofluid properties on the performance of an automotive engine.

Table 1: Different nanofluid properties on the performance of an automotive engine

Property	Effect on Nanofluid	Impact on Engine Performance	Overall Consideration
Thermal Conductivity	Higher in nanofluids compared to base fluids (like water or conventional coolants).	Positive: Enhances heat transfer, allowing faster cooling of engine components. Prevents overheating, improves fuel efficiency, reduces wear, and allows for smaller cooling systems.	Benefit: Improved cooling performance and engine efficiency.
Viscosity	Can increase or decrease based on nanoparticle concentration, size, and shape.	Negative if too high: Increases pumping power, leading to more energy consumption and wear on the cooling system. Positive if optimized: Enhances heat transfer without excess energy use.	Balance needed: Excessive viscosity increases energy usage, while lower viscosity may reduce cooling efficiency.
Specific Heat	Typically lower in nanofluids compared to base fluids, meaning faster heat absorption.	Positive: Rapid heat absorption and dissipation improve cooling performance, stabilize engine temperatures, and prevent overheating. Negative: Risk of hotspots if not managed properly.	Balance required: Must be managed avoiding excessively high temperatures in localized areas of the engine.
Density	Generally higher due to the presence of nanoparticles.	Negative: Increases the fluid's weight, requiring more energy to circulate, which can reduce engine efficiency and increase fuel consumption.	Optimization required: Need to balance enhanced heat capacity with increased energy demands for fluid circulation.

4.1. Thermal Conductivity

The enhanced thermal conductivity of nanofluids is a game-changer in automotive thermal management systems, including radiators, engines, and battery cooling in electric vehicles (EVs)[43]. The high thermal conductivity of nanoparticles, combined with their increased surface area and mechanisms like Brownian motion, allows efficient energy transport within the fluid. This results in improved heat dissipation, keeping engines and batteries within optimal temperature ranges, even under high-performance conditions. In EVs, nanofluids efficiently cool batteries and power electronics, enhancing safety and extending component lifespan. By enabling smaller and lighter cooling systems, they contribute to vehicle weight reduction and improved fuel efficiency. Research continues to optimize formulations for maximum thermal performance, ensuring a balance between heat transfer, stability, and energy consumption[44].

The increased thermal conductivity of nanofluids allows for more efficient heat transfer in the engine's cooling system, helping to dissipate heat more effectively. This improvement prevents engine overheating, stabilizes operating temperatures, and reduces thermal stress on engine components. As a result, the engine can operate more efficiently, prolonging its life, improving fuel efficiency, and reducing emissions due to optimized combustion. Moreover, the use of nanofluids can potentially reduce the size of radiators and cooling systems, leading to more compact and lightweight engine designs in modern vehicles[45].

4.2. Viscosity

The viscosity of nanofluids is a critical parameter that significantly impacts their performance and efficiency in automotive thermal management systems. Viscosity influences the flow characteristics, pumping power requirements, and overall heat transfer efficiency of nanofluids used in components such as radiators, engine cooling systems, and battery thermal management units. Nanofluids are base fluids (e.g., water, ethylene glycol) containing suspended nanoparticles like metal oxides, metals, or carbon-based materials. While these nanoparticles enhance thermal conductivity, they also affect the viscosity of the fluid, which can either improve or hinder its performance, depending on the formulation[46]. An increase in viscosity due to nanoparticle addition is typically observed and depends on factors like particle size, shape, concentration, and suspension stability. Higher concentrations of nanoparticles, especially with irregular or larger shapes, tend to increase the fluid's viscosity. This, in turn, raises the pumping power required to circulate the nanofluid through automotive systems, potentially offsetting the thermal performance gains. Hence, achieving an optimal balance between thermal conductivity and viscosity is crucial[47].

Low-viscosity nanofluids are desirable for minimizing energy consumption during fluid circulation, which is especially important for fuel efficiency in internal combustion engine vehicles and energy conservation in electric vehicles (EVs). Advanced techniques, such as the use of smaller, spherical nanoparticles and surfactants, help reduce viscosity while maintaining stability and preventing particle agglomeration. In electric vehicles, where thermal management is vital for cooling batteries and power electronics, nanofluids with carefully tuned viscosity ensure effective heat transfer without excessive energy demands. Similarly, in internal combustion engine vehicles, optimizing viscosity reduces wear and tear on pumps and other components, enhancing system longevity[48].

Ongoing research focuses on developing nanofluids with adjustable viscosity through smart additives and hybrid nanoparticle systems, enabling tailored performance for specific automotive applications. By fine-tuning viscosity, nanofluids offer a promising solution for efficient, reliable, and sustainable automotive cooling systems.

4.3. Specific Heat

One of the crucial characteristics, the specific heat, has a significant impact on the pace at which heat is transferred in nanofluids. The experiment used two specific heat models to determine the specific heat of nanofluids. Pak and Cho[49] presented the first model, which is based on the volume concentration of nanoparticles.

$$C_{P_{nf}} = \phi(C_P)_P + (1-\phi)(C_P)_{bf} \qquad (1)$$

The specific heat of nanofluids is a critical property influencing their suitability for automotive thermal management systems, such as radiators, engines, and battery cooling units. Specific heat determines the fluid's capacity to absorb and store heat, impacting the efficiency of heat transfer and temperature regulation. In automobiles, nanofluids are engineered to enhance heat dissipation while maintaining manageable energy consumption. However, the addition of nanoparticles, such as metal oxides (e.g., Al_2O_3, TiO_2), metals (e.g., copper, silver), or carbon-based materials (e.g., graphene), typically reduces the specific heat of the base fluid because the specific heat of most solid nanoparticles is lower than that of common base fluids like water or ethylene glycol[50].

In thermal management systems, a reduced specific heat means that the nanofluid may reach higher temperatures more quickly, potentially requiring increased flow rates to maintain effective cooling. This trade-off necessitates careful optimization of nanoparticle concentration and type to achieve the desired balance between specific heat and thermal conductivity. While thermal conductivity improvements often offset the reduction in specific heat, overly high nanoparticle concentrations can lead to diminished thermal capacity and increased viscosity, reducing overall system performance[51].

In electric vehicles (EVs), specific heat is especially critical for battery thermal management, where precise temperature regulation is vital for safety and efficiency. Advanced nanofluids, such as those incorporating hybrid nanoparticles or composite materials, are designed to optimize both specific heat and thermal conductivity, ensuring effective heat absorption without excessive energy use[52].

For internal combustion engine vehicles, nanofluids with tailored specific heat properties allow for efficient engine cooling, enabling better heat absorption from hot surfaces while preventing overheating. Future research aims to develop nanofluids with enhanced specific heat using innovative particle compositions, surface functionalization, or hybrid nanostructures to maximize thermal storage capacity. By balancing specific heat with other properties, nanofluids continue to advance the efficiency, reliability, and sustainability of automotive thermal management systems[53].

4.4. Density of Nanofluid

The density of a nanofluid depends on several factors, including the properties of the base fluid and the concentration and type of nanoparticles used. Generally, adding nanoparticles to a base fluid increases its density due to the additional mass contributed by the nanoparticles. Keep in mind that the density of nanoparticles can vary depending on their material and characteristics, so it is essential to know the specific density value for the nanoparticles you are using[54].

The density of nanofluids plays a crucial role in determining their effectiveness in automobile engine cooling systems. When nanoparticles are added to base fluids, the overall density of the nanofluid increases, depending on the type and concentration of the nanoparticles. A higher density can improve the thermal capacity of the nanofluid, enhancing its ability to absorb and transport heat away from engine components. However, increased density also means that the fluid becomes heavier, requiring more energy to circulate through the cooling system, which can lead to higher pumping power and increased mechanical stress on the system. If not managed properly, this can negatively affect engine efficiency and fuel consumption. Therefore, the density of nanofluids must be optimized to strike a balance between improved heat transfer and the energy required for fluid circulation, ensuring that the cooling system operates efficiently without compromising the engine's overall performance.

5. Recent Development of Nanofluid Utilization in Automotive Industry

The utilization of nanofluids in the automotive industry attracted considerable interest in recent years. Nanofluids offer several potential benefits that can enhance various aspects of automotive systems. Here are some recent developments in the utilization of nanofluids in the automotive industry:

Heat Transfer Enhancement: Nanofluids have been extensively studied for their improved heat transfer properties. By dispersing nanoparticles in engine coolant or transmission fluid, nanofluids can boost heat dissipation and enhance the overall thermal efficiency of automotive systems. This can lead to better engine performance, reduced emissions, and increased fuel efficiency.

Lubrication Enhancement: Nanoparticles can be added to lubricating oils to improve their tribological properties. Nanofluid-based lubricants can diminish friction and wear between moving parts, thereby prolonging the lifespan of engine components and reducing energy losses. This can result in lower maintenance costs and improved fuel economy.

Engine Cooling: Nanofluids have shown potential for improving engine cooling systems. By incorporating nanoparticles into the coolant, nanofluids can boost the heat transfer rate and provide better thermal stability. This can help prevent engine overheating and improve overall engine performance.

Nanofluids have the potential to reduce emissions in automotive engines. By improving heat transfer and lubrication, nanofluids can optimize engine combustion and reduce the formation of harmful pollutants. This can contribute to lower emissions and improved air quality.

Battery Thermal Management: With the rise of electric vehicles (EVs), efficient thermal management of batteries has become crucial. Nanofluids can help enhance the heat dissipation of battery packs, preventing overheating and improving their performance and longevity. This is particularly important for fast charging and high-power applications.

Coatings and Surface Treatments: Nanofluids are also being explored for their potential in surface coatings and treatments. Nanostructured coatings can enhance the durability, corrosion resistance, and wear resistance of automotive components, leading to longer lifespan and improved performance.

It's worth noting that while nanofluids show great promise in various automotive applications, further research and development are still needed to optimize their performance, address potential challenges, and ensure their long-term reliability and safety in real-world automotive environments. In this section brief description of recent development of nanofluid utilization in automotive industry is provided.

5.1. Nanofluid used as Coolant in Automobile Radiator

Nanofluids have been studied and proposed as potential coolants for automobile radiators. Nanofluids are fluids composed of a base liquid, like H_2O or EG, with nanoparticles uniformly dispersed throughout. These nanoparticles are typically metallic or non-metallic particles with sizes in the nanometer range. Adding nanoparticles to the base fluid can improve the coolant's thermal properties, such as thermal conductivity and efficiency of heat transfer. This means that nanofluids have the potential to improve the cooling performance of radiators in automobiles.Nanofluids can be designed to work with existing cooling systems, allowing for seamless integration into automobile radiators. Nanofluids can be formulated to be compatible with existing cooling systems, making it easier to integrate them into automobile radiators. It's worth noting that while there is ongoing research and development in this area, the widespread adoption of nanofluids as coolants in automobile radiators is not yet common. More studies and advancements are needed to address the challenges and optimize the performance and reliability of nanofluid-based coolant systems. The summary of utilization of nanofluid as a coolant in automotives is provided in Table 2.

Table 2: Summary of utilization of nanofluid as a coolant in automotive radiator

Ref. No.	Nanofluid	Concentration	Remark
55	MWCNT	0.1% to 1.5 %	Thermal conductivity is enhanced by 4.2% at 30^0 C
56	SiC-MWCNT	0.04% to 0.4%	On 0.4 vol. %, there was a maximum improvement in thermal conductivity of 32.01%.
57	Graphene	0.1% to 0.5%	The heat transfer improved by 50% at an inlet temperature of 45°C.
58	Graphene	0.1% to 0.5%	The greatest increase in OHTC in relation to concentration is approximately 104% at 35°C
59	TiO_2/H_2O	0.1%to 0.3%	0.2% concentration of TiO_2/H_2O nanofluid can boost the efficiency of an automobile radiator by 47%.

60	Al_2O_3 and CuO	0.05% to 1%	Al_2O_3 nanofluids offer superior heat transfer performance and stability compared to CuO.
61	Graphite/water, and Graphite/ethylene glycol	0.05% to 0.1%	The heat transfer coefficient achieves a maximum enhancement of 11.7% at a lower Reynolds number.
62	ZnO/PG, α- Al_2O_3/PG, γ-Al_2O_3/PG	0.2% to 0.5%	The ZnO/PG nanofluid achieves a maximum heat transfer coefficient enhancement of 46.4% at a 0.2% volume fraction.
63	ZnO/H_2O-EG	0.01% to 0.04%	Maximum increase in rate of heat transfer of up to 36% at 0.04% volume concentration
64	TiO_2/EG- H_2O	0.3%to 2%	11.094% maximum enhancement in thermal conductivity at 2% concentration doping with Ag
65	SiO_2/H_2O	0.04% to 0.12%	The maximum recorded increase in heat transfer rate was 36.92%.
66	ZnO/H_2O	0%to 0.3%	A 0.2% concentration led to a 41% enhancement in heat transfer and a 50% rise in the OHTC.

Kole and Dey[55] used alumina nanofluid as engine coolant to improve the performance of the engine by improving the thermal conductivity. The volume concentration varied from 0.1% to 1.5%. Their results revealed that the thermal conductivity is enhanced by 4.2% at 300 C. They also concluded that the MWCNT posses higher thermal conductivity as compared to other nanofluids. Li et al.[56] used Sic-MWCNT nanofluid in the radiator of a car for enhancement of heat transfer and its thermophysical properties. Nanoparticle saturation had a clear correlation with concentration and a beneficial effect on the TC of Sic-MWCNT nanofluids. The variation of thermal conductivity at different concentration with temperature is shown in Figure 7. Upon hybrid nanofluids containing 0.4 vol. %, the greatest augmentation of TC has been determined to be 32.01%. Furthermore, the TC benefited much from the temperature.

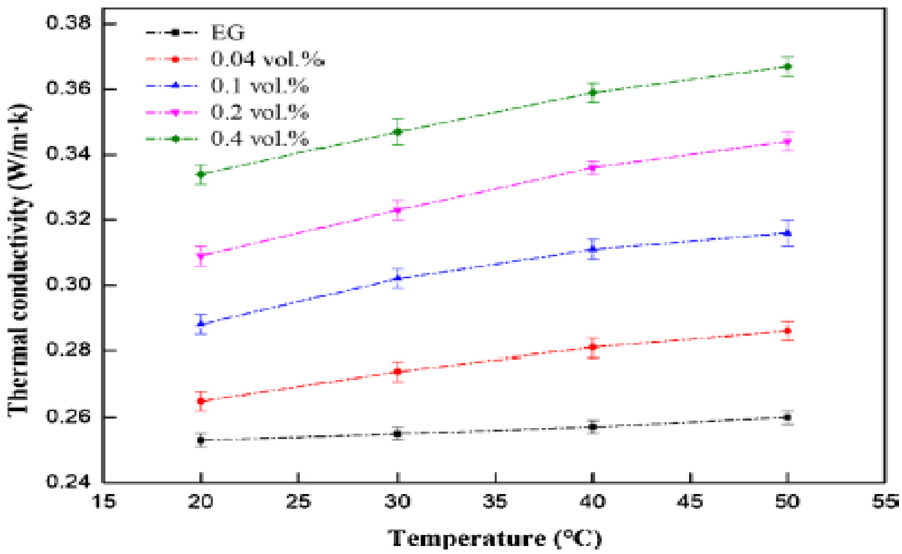

Fig. 7: Variation of thermal conductivity of SiC-MWCNT nanofluid with temperature[56]

Selvam et al.[57] used graphene in automobile radiator to enhance the performance of heat transfer. Their results revealed that the convective heat transfer ability of nanofluids improves as more graphene nanoplatelets are added, and as the inlet temperature and flow rate increase. At the 0.5 vol% and 100 g/s flow rate, the heat transfer improved by 20% at an inlet temperature of 35°C and by 51% at 45°C. Selvam et al.[58] once more documented that employing a nanofluid constructed with nanoplatelets of graphene as the coolant improved the overall heat transfer coefficient of an automotive radiator. The greatest increase in OHTC in relation to concentration is approximately 104% at 35°C and 81% at 45°C for maximum volume concentration. Additionally, as the flow rate of mass and graphene deposition rises, so does the pressure reduction of nanofluids. The flow rate of mass has a greater impact on the rise in pressure reduction than does the amount being loaded of graphene nanoplatelets. Ahmed et al.[59] used TiO_2/H_2O nanofluid in car radiator as coolant to improve its performance. The findings demonstrate that increasing the volume fraction lowers the friction factor. Furthermore, contrasted with 0.1 and 0.3% concentrations and H_2O as a coolant, a 0.2% concentration of TiO_2/H_2O nanofluid can enhance the efficiency of an automobile radiator by 47%. The variation of average heat transfer coefficient with Reynolds number at different concentration is shown in Figure 8. It is observed from Figure 8 that the average heat transfer coefficient increases with rise in Reynolds number and volume concentration and found maximum 2050W/m2K at 0.3% concentration.

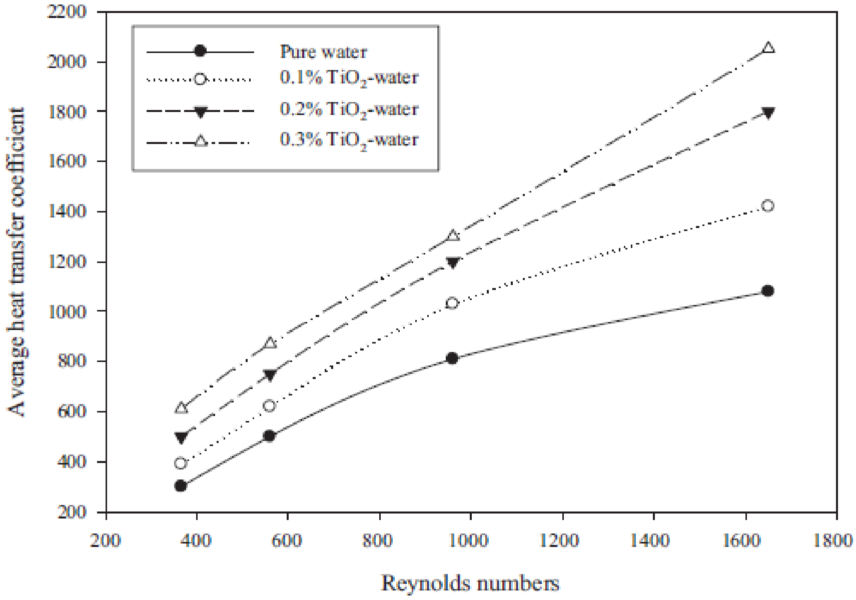

Fig. 8: Variation of average heat transfer coefficient with Reynolds number at different concentration[59)]

Alosious et al.[60)] used two different nanofluid Al_2O_3 and CuO nanofluid with varied concentration mentioned in Table 2 for enhancement of radiator as coolant experimentally as well as numerically. A 1% concentration of CuO and Al_2O_3nanofluids improved the internal heat transfer coefficient by up to 13.2% and 16.4%, respectively. However, increasing the concentration further raises viscosity and density, thereby increasing pumping power requirements. For the same cooling performance as water, using a 1% concentration of CuO and Al_2O_3 nanofluids allows for radiator area reductions of 2.1% and 2.9%, respectively. The optimal volume concentration range for balancing heat transfer enhancement and pumping power increase is 0.4% to 0.8%. Al_2O_3 nanofluids offer greater heat transfer enhancement and stability than CuO.

Akash et al.[61)] used graphite nano coolant having water or ethylene glycol as base fluid to enhance the performance of automobile radiator. It is observed that graphite nanocoolant demonstrates a higher heat transfer coefficient than the base fluid, achieving up to an 11.7% improvement at lower Reynolds numbers and air mass flow rates. Performance indices show that at reduced coolant and air flow rates, graphite nanocoolant outperforms the base fluid. However, as flow rates rise, the nanocoolant's performance diminishes, potentially increasing the pumping power required in high-flow scenarios and adversely impacting vehicle performance. Zhou et al.[62)] used three different nanofluid at different concentration mentioned in Table 2 to enhance the performance of car radiator. The findings showed that when the volume proportion increased, the coefficients of heat transfer of all nanofluids first rose and subsequently fell. The ZnO/PG nanofluid achieved its highest heat transfer coefficient at a 0.3 vol% concentration, with a 25.6% reduction observed when the concentration increased to 0.5 vol%. Smaller particles improved cooling performance, as the 0.1 vol% γ-Al_2O_3/PG nanofluid demonstrated a 19.9% higher heat transfer coefficient compared to α- Al_2O_3/PG. Additionally, a rise in flow rate enhanced the heat transfer coefficient of the 0.5 vol% α- Al_2O_3/PG nanofluid by 10.5%. Within a temperature range of 40–60°C, the HTC of the 0.2 vol% ZnO/PG nanofluid increased by 46.4%.

Khan et al.[63)] utilized ZnO/H_2O-EG nanofluid in a car radiator to enhance its heat transfer performance experimentally. Experimental results have shown that a maximum increase in rate of heat transfer of up to 36% can be achieved at a volume fraction of 0.04% nanofluid. Soylu et al.[64)] used TiO_2 nanofluid considering EG/H_2O as base fluid and doped with Cu and Ag to investigate the performance of radiator of automotive. The experimental findings indicated that introducing 0.3% silver (Ag) into TiO_2 nanofluids led to notable enhancements in thermal conductivity, with the greatest improvements observed at 1% and 2% nanoparticle concentrations, achieving increases of 5.615% and 11.094%, respectively. A theoretical analysis further suggested that Ag-doping optimizes heat transfer in these nanofluids and that the degree of enhancement grows with higher doping levels. Specifically, convection heat transfer coefficients rose by 26.15% for a 1% concentration and by 27.72% for a 2% concentration in the 0.3% Ag-doped TiO_2 nanofluids, highlighting the potential for improved thermal

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performance without operational issues. Shah et al.[65] used SiO_2/H_2Onanocoolant aluminum tube automotive radiator to enhance its convective thermal performance. The highest observed increase in heat transfer rate reached 36.92%, with the Nusselt number improving by 45.53% under optimal operational conditions. However, as nanoparticle volume rose from 0.04 to 0.12%, the rate of heat transfer improvement declined from 5% to 3.5%. This decrease was attributed to nanoparticle agglomeration and clustering, which limited further gains in heat transfer efficiency. The highest efficiency improvement of 7.57% was achieved.Qasim et al.[66] conducted experimental study on ZnO/H_2O nanofluid with varying volume concentration in a Suzuki Mehran radiator. A 0.2% concentration resulted in a 41% improvement in heat transfer, a 50% increase in the overall heat transfer coefficient. Higher concentrations (0.3%) led to a decline in performance as the increased viscosity and density restricted efficiency improvements.

5.2. Nanofluid used as Engine Fuel in Automotives

Nanofluids are gaining attention as potential enhancers of fuel performance in automotive engines, offering benefits such as improved combustion efficiency and enhanced thermal properties. By incorporating nanoparticles into conventional fuels, nanofluids help achieve a more complete burn, increasing fuel energy output and reducing emissions. This efficiency can contribute to better fuel economy and lower greenhouse gases, aligning with environmental goals. Additionally, nanofluids enhance heat transfer within the engine, which aids in cooling and helps prevent overheating, particularly beneficial for high-performance and heavy-duty vehicles. The summary of utilization of nanofluid as engine oil in automotives is provided in Table 3.

Table 3: Summary of utilization of nanofluid as engine oil in automotive

Ref. No.	Nanofluid	Type of Engine	Remark
67	CeO_2/lemongrass oil	Diesel	When compared to pure LGO emulsified and pure diesel fuel, the LGO nano emulsified fuel reduced smoke by 6.4% and 19.8%, respectively.
68	$Ce_xZr_{(1-x)}O_2/H_2O$	Diesel	At a 17.5 PPM concentration, diesel engines' exhaust smoke is reduced by 31%
69	TiO_2/MOME	Biodiesel in Diesel Engine	TiO_2 nanofluid provides a considerable reduction in NOx emissions for MOME.
70	MgO and SiO_2	Compression Ignition Engine	Highest NOx reduction of 7.2% occurring at a 50 ppm dosage of MgO.
71	Graphene oxide	Biodiesel in Diesel Engine	Adding GO nanoparticles increases brake power by approximately 15.81% for B10G90.
72	Graphite oxide and SWCNT	Light duty diesel engine	Maximum 15.4% increase in NO_X using SDD fuel compared to diesel
73	Graphene oxide	Compression Ignition Engine	Maximum 11.56%increase in BTEby adding GO nanoparticlesto DSOB
74	MWCNT	4 Stroke Diesel Engine	At the maximum capacity, greenhouse gas emissions for WFOME25MWCNT is 0.075%
75	Ce-ZnO	Single Cylinder Diesel Engine	25% rise in BTE using 50 ppm Ce-ZnO nanoparticles in SBME 25
76	Al_2O_3 and ZnO	CI engine	NOx emissions rose by 10% due to higher combustion temperatures

Annamalai et al.[67] used CeO2/LGO nanofluid in diesel engine to access the performance of the engine. Their result revealed that the LGO nano-emulsion fuel, enhanced with cerium oxide nanoparticles, significantly reduces emissions compared to standard LGO and diesel fuels. Specifically, it decreases unburned hydrocarbon (HC) emissions by 35.5% compared to LGO and 15.69% compared to diesel, while carbon monoxide (CO) emissions drop by 16.03% and 26%, respectively. This is largely due to the oxidative properties of the cerium oxide. Figure 9 illustrates how NOx emissions change with brake power. Additionally, NOx emissions decrease by 24.8% compared to LGO and 20.3% compared to diesel, supported by water's high latent heat of vaporization in the fuel and the reduction effect of CeO_2.

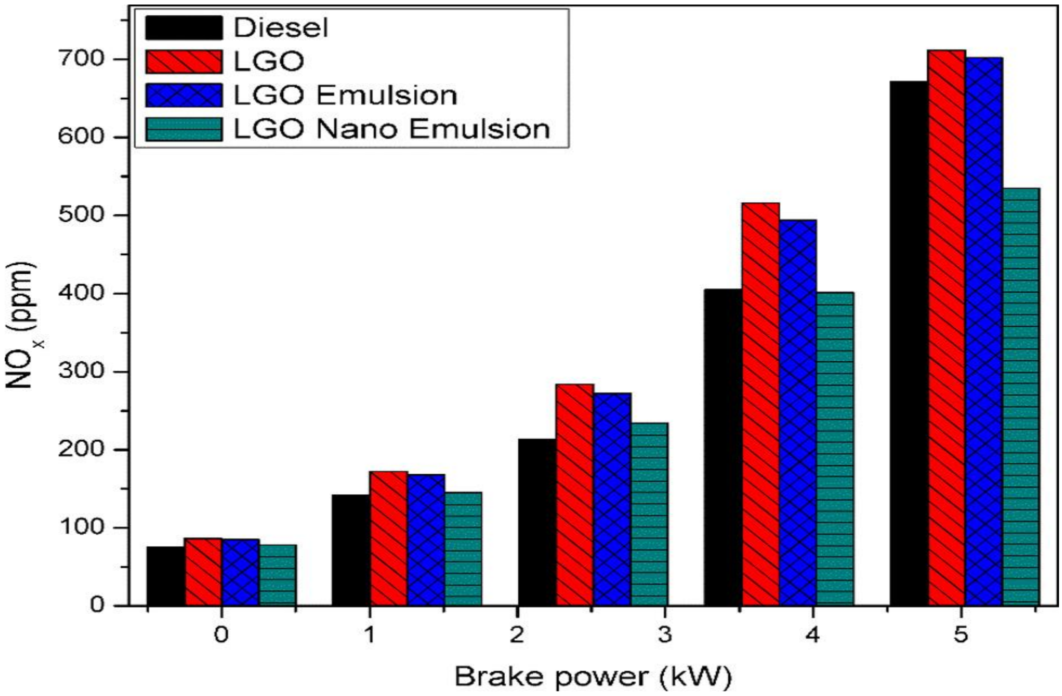

Fig. 9: Variation of NOx emission with Brake power[67)]

Sanjeevan and Sajith[68)] concentrated on creating a secure suspension of $Ce_xZr_{(1-x)}O_2$ nanoparticles in diesel and examining how these nanoparticles affected the effectiveness of diesel engines, fuel characteristics, and combustion smoke. According to research examinations, at a 17.5 PPM concentration, diesel engines' exhaust smoke is reduced by 31%, and their braking thermal efficiency is increased by 3%. Yuvarajan et al.[69)] examined experimentally how TiO_2 nanofluid affect the way biodiesel emissions appear in diesel engines. From their investigation, it is observed that TiO_2 nanofluid's better oxidation abilities, increased thermal conductivity,and catalytic impact reduce HC, CO, and emissions of smoke at all loads when added to MOME (base fuel).

ÖZGÜR et al.[70)] looked into the effects of adding MgO (25 PPM) and SiO_2 (50 PPM) nanoparticle additions to biodiesel on fuel attributes as well as impacts on diesel engine efficiency and emissions from the exhaust.The addition of MgO and SiO_2 nanoparticles to biodiesel fuel led to an increase in CO_2 emissions, with a maximum average rise of 7% observed at a 25 ppm dosage of MgO. In contrast, NO_x emissions decreased with the addition of these nanoparticles, with the highest reduction of 7.2% occurring at a 50 ppm dosage of MgO. Hoseini et al.[71)] looked into how GO nanoparticles, which are new fuel components, affected a diesel engine's emission properties and engine efficiency. For diesel-biodiesel combinations, adding GO nanoparticles increases brake power by approximately 15.81% for B10G90. The current study's findings suggest that biodiesel from Ailanthus altissima can be utilized as a sustainable fuel substitute. Additionally, the findings demonstrate that GO nanoparticles are appropriate additives for enhancing a diesel engine's efficiency and emission properties.

Ooi et al.[72)] used two different nanofluid graphite oxides and SWCNT as additive of diesel to evaluate the performance of LDDE. In comparison to diesel, the significant exothermic emission of heat of SWCNTs and graphite oxide additions in SDD and GDD fuels led to stronger in-cylinder temperatures and greater heat emission rates, which in turn produced increased NOx concentrations. When comparing GDD and SDD fuels to diesel, the total NOx rise is 9.2% and 15.4%, correspondingly. Nevertheless, lean NOx traps and targeted catalytic reduction might be used to mitigate the harmful effects of elevated NOx. Soudagar et al.[73)] investigated how GO nanoparticles affected the emission levels as well as effectiveness of a CI engine running on DSOB. The variation in BTE with brake power is shown in Figure 10. While changing the braking power and load conditions, the tests were conducted at a steady speed. For the nanofuel blend DSOME2040, the findings showed significant improvements in performance as well as emission features, including an 11.56% increase in BTE, an 8.34% decrease in BSF consumption, a 21.68% decrease in unburned hydrocarbon, a 24.88% decrease in smoke, a 38.662% decrease in CO, and a 5.62% decrease in NOx emissions.

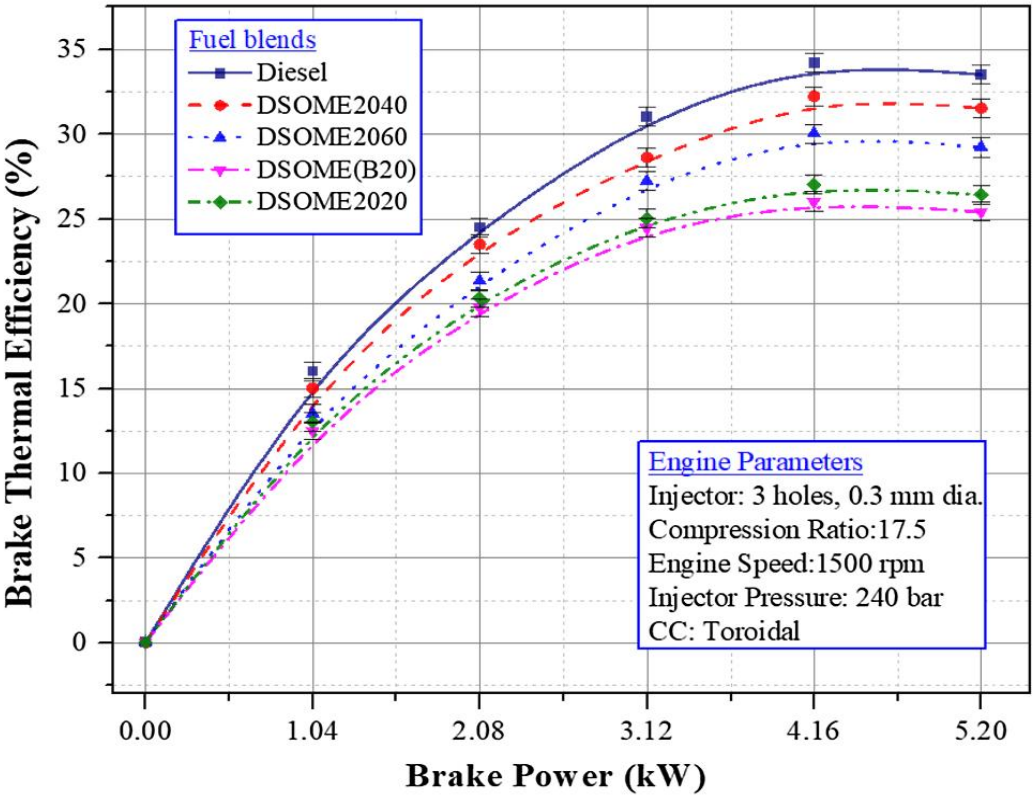

Fig. 10: Variation of BTE with Brake power[73)]

Sulochana and Bhatti[74)] used MWCNT nanotube blended in WFOME to investigate the performance of twin cylinder four stroke diesel engines.At the maximum capacity, greenhouse gas emissions for WFOME50MWCNT are 0.054%, while those for WFOME25MWCNT are 0.075%, and 0.1 for diesel with no additives. Consequently, compared with the other fuels, WFOME50MWCNT is found to have lower CO emissions. The effects of diesel-soybean biodiesel mixtures containing 3% Ce-ZnO nanocrystals on the efficiency, emissions, and combustion properties of a single-cylinder CI engine were examined by Hussain et al.[75)]. When 50 ppm Ce-ZnO nanoparticles were added to SBME25 (SBME25Ce-ZnO50), the BSFC dropped by 21.81%, the BTE and HRR rose by 20.66% and 18.1%, accordingly, and the CO, smoke, and HC reduced by 30%, 18.7%, and 21.5%, accordingly, in comparison to SBME25 fuel functioning. Dhahad and Chaichan[76)] added Al_2O_3 and ZnO nanoparticles in Iraqi diesel to predict the performance and pollutants emitted from the CI engine. Adding nanoparticles to diesel fuel was found to enhance engine performance and lower emissions, with improvements scaling with higher nanoparticle doses. Specifically, the addition of 100 ppm nano-alumina led to a notable reduction in BSFC by 8% and an increase in BTE by 6%. Emission reductions included a 17% decrease in carbon monoxide (CO) and unburned hydrocarbons (HC), a 26% reduction in total particulate matter, and 19% decreases in both sulphur dioxide (SO_2) and hydrogen sulphide (H_2S). However, nitrogen oxides (NOx) emissions rose by 10% due to higher combustion temperatures. These findings suggest that incorporating nanoparticles could play a significant role in optimizing diesel engine efficiency and minimizing emissions without modifying the engine, especially when using Iraqi diesel.

5.3. Nanofluid used as Shock Absorber Automotives

Nanofluids are emerging as a powerful alternative to conventional damping fluids in automotive shock absorbers, with the potential to significantly enhance vehicle performance, comfort, and safety. Traditional shock absorbers often use hydraulic oils, but their capacity to absorb shock and dissipate energy can be limited, particularly under intense or fluctuating driving conditions. Nanofluids, containing nanoparticles suspended within base fluids, introduce advanced properties like higher thermal conductivity, variable viscosity, and enhanced stability, making them ideal for automotive shock absorption. When incorporated into shock absorbers, nanofluids deliver superior damping performance by efficiently managing kinetic energy transfer and mitigating road-induced vibrations, which in turn reduces strain on the vehicle’s suspension and other components[77)].

The unique properties of nanofluids make them well-suited to automotive applications. The inclusion of nanoparticles like aluminum oxide, copper oxide, and carbon nanotubes amplifies the fluid's energy absorption capabilities, allowing for more precise and consistent damping. These nanoparticles enhance the fluid's heat dissipation ability, a critical factor during long drives or challenging road conditions when shock absorbers can become overheated. As a result, nanofluids enable shock absorbers to maintain their effectiveness over extended periods and a broader range of temperatures, ultimately improving reliability and preventing component fatigue. Moreover, nanofluids can dynamically adjust their viscosity in response to changes in pressure or temperature, providing a more adaptable damping response under varying load conditions. This property is especially beneficial in high-performance and off-road vehicles, which frequently experience shifts in stress and impact loads[78].

In practical terms, the use of nanofluids in automotive shock absorbers enhances driving comfort and stability by reducing the transmission of shocks and vibrations to the vehicle's cabin. This leads to a smoother ride, even on uneven or rough terrain, which is essential not only for passenger comfort but also for the longevity of vehicle parts. Reduced vibrations mean less wear and tear on components like tires, axles, and chassis, which ultimately lowers maintenance costs and prolongs the life of the vehicle. Additionally, nanofluids have shown promise in improving the fuel efficiency of vehicles. Since these fluids are more effective at damping, they minimize the energy lost to excessive vibrations and jolts, potentially contributing to fuel savings, particularly in heavy vehicles and fleets[79].

Environmental and economic factors further underscore the potential of nanofluids in automotive shock absorbers. Their enhanced stability and efficiency can reduce the frequency of fluid replacement, thereby decreasing the waste associated with disposal of traditional oils. This aligns well with the automotive industry's growing emphasis on sustainable practices and reducing its environmental footprint. Additionally, as nanotechnology progresses and the production costs of nanoparticles decrease, the widespread adoption of nanofluids is expected to become more feasible across a range of automotive models, from luxury to mass-market vehicles[80].

Ali et al.[81] investigated ways to improve the viscous damping in oil-based shock absorbers by incorporating fumed silica nanoparticles in varying concentrations (from 1% to 5%) into the hydraulic oil. Additionally, they experimented with hybrid nanoparticles by combining functionalized multi-walled carbon nanotubes (MWCNTs) and fumed silica, maintaining a total nanoparticle concentration of 5%. The study found that the introduction of these nanoparticles, both single-phase and hybrid, reduced energy loss due to viscous damping friction in the dashpot mechanism. Notably, using a 5% concentration of MWCNTs alone (without silica) significantly improved response parameters like maximum overshoot and settling time in the system's steady-state performance. Bahiraei and Mashaei[82] conducted a three-dimensional analysis of the flow and heat transfer behaviour of an Al_2O_3/H_2O nanofluid within channels containing discrete heat sources, incorporating variable thermophysical properties in their simulations. The study found that the thermal conductivity of the nanofluid increased significantly near the heat sources, enhancing heat removal in these regions. This property suggests that Al_2O_3/H_2O nanofluid could be effectively applied as a smart cooling solution for high-temperature areas. Pawar et al.[83] explored the effectiveness of adding copper oxide (CuO) nanoparticles to shock absorber oil to enhance its viscosity and vibration-damping abilities. Testing various concentrations from 0.25% to 1.5%, they observed that a 1% CuO concentration resulted in a 20% rise in viscosity at 25°C relative to the base oil, suggesting greater load support and potential friction reduction. Using a shock absorber test rig, they further found that the CuO-enhanced oil reduced vibration acceleration, achieving a 15% enhancement in damping performance at the optimal nanoparticle concentration.

Yeh et al.[84] developed a micro-nano fluid damper that uses a polymer-based fluid containing hydrophobic particles smaller than 1 μm. This damper converts vibrations into heat, which can then be released, enhancing its ability to absorb impacts. The micro-nano fluid also showed high viscosity and thermal conductivity, contributing to improved impact absorption. Zhang et al.[85] developed a method to stabilize carbon nanostructure dispersions, specifically to enhance shock absorber fluids by improving their viscosity index.

5.4. Nanofluid used as Engine Lubricants in Automotives

Nanofluids have emerged as promising engine lubricants in automotive applications, offering significant advantages in enhancing engine performance and efficiency. By incorporating nanoparticles into traditional lubricants, these fluids improve thermal conductivity, viscosity, and lubrication properties, which are critical for reducing engine wear and friction[86]. The high thermal conductivity of nanofluids aids in effective heat dissipation, preventing overheating and extending engine life. Moreover, the enhanced viscosity provided by nanofluids ensures stable lubrication across a wide temperature range, particularly under high-stress conditions, which is essential for reliable performance in demanding automotive environments[87]. Nanoparticles like copper, aluminum oxide, and carbon nanotubes are commonly used for their superior heat transfer capabilities and low wear rates. With these attributes, nanofluids contribute to fuel efficiency and reduced emissions by minimizing frictional losses and optimizing thermal management, marking them as an

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innovative solution for sustainable and high-performance automotive lubrication[88]. The summary of utilization of nanofluid as engine lubricant in automotives is provided in Table 4.

Table 4: Summary of utilization of nanofluid as engine lubricant in automotive

Ref. No.	Nanofluid	Volume Fraction	Remark
89	MWCNT-ZnO	0.05% to 1%	At 5°C, a 9% decrease in viscosity was noted with a solid volume percentage of 0.05%.
90	CuO	0.1% to 0.5%	A 0.1 wt. % concentration of nanolubricants improved thermal conductivity by 3%.
91	Cu-engine oil	0.2% to 1%	Thermal conductivity increased from 27% to 49%
92	MWCNT/diesel oil and GNP/diesel oil	0.05% to 0.5%	Nanofluids generally exhibit a performance index greater than one, except in cases involving the MWCNT and GNP hybrid.
93	MoS_2/ engine oil	0.1% to 2%	A 0.9% reduction in combustibility in comparison to the conventional lubricant without nanoparticles.
94	Cr_2AlC/5W-30 engine oil	0% to 0.5%	The coefficient of friction (COF) is reduced by approximately 22%.
95	Al_2O_3/engine oil, TiO_2/engine oil	0.05% to 0.5%	Maximum 50% frictional power loss was observed using TiO_2nanolubricants
96	Al_2O_3/TiO_2- 5W-30 engine oil	0.1%	The warm-up phase is accelerated by 24% by Al_2O_3/TiO_2 hybrid nanolubricant.
97	CNC/SAE 40 engine oil	0.1% to 0.9%	Maximum 69% reduction in wear rate value was observed at 0.1% volume fraction
98	CuO-MWCNT/10W-40	0.05% to 1%	About 43.52% is the highest possible dynamic viscosity boost that nano-lubricant may achieve

Esfe et al.[89] investigated the rheological properties of MWCNT-ZnO (20%-80%)/5W50 nano-engine oil with solid volume fractions up to 1% and temperatures ranging from 5°C to 55°C. The research highlighted that using nanoparticles in volume fractions below 0.25% optimizes engine oil viscosity. Notably, a 9% viscosity reduction was observed at 5°C with a solid volume fraction of 0.05% and a shear rate of 666.5 (1/sec). This improvement facilitates easier pumping and faster lubrication during cold starts, reducing potential engine damage. Additionally, nanoparticles enhance heat transfer from engine components. At temperatures between 35°C and 55°C, the nano-oil exhibited better high-temperature performance due to its lower viscosity dependence on temperature compared to standard 5W50 engine oil, making it more suitable for such conditions.

Ettefaghi et al.[90] examined the effects of adding copper oxide (CuO) nanoparticles to engine oil at concentrations ranging from 0.1% to 0.5%. Their findings showed that a 0.1 wt. % concentration of nanolubricants improved thermal conductivity by 3% and increased the flash point by 7.9% compared to the base oil. Additionally, at lower concentrations, the oil's viscosity remained largely unchanged, ensuring its suitability for lubrication. Aberoumand and Jafarimoghaddam[91] used Cu-engine oil nanofluid to investigate the performance of engine. The variation of thermal conductivity with temperature using Cu-engine oil nanofluid at different concentration is shown in Figure 11. When applied nanofluids were used at temperatures between 40 and 100 degrees Celsius, their thermal conductivity increased from 27% to 49% for volume fractions of 0.2% and 1%.

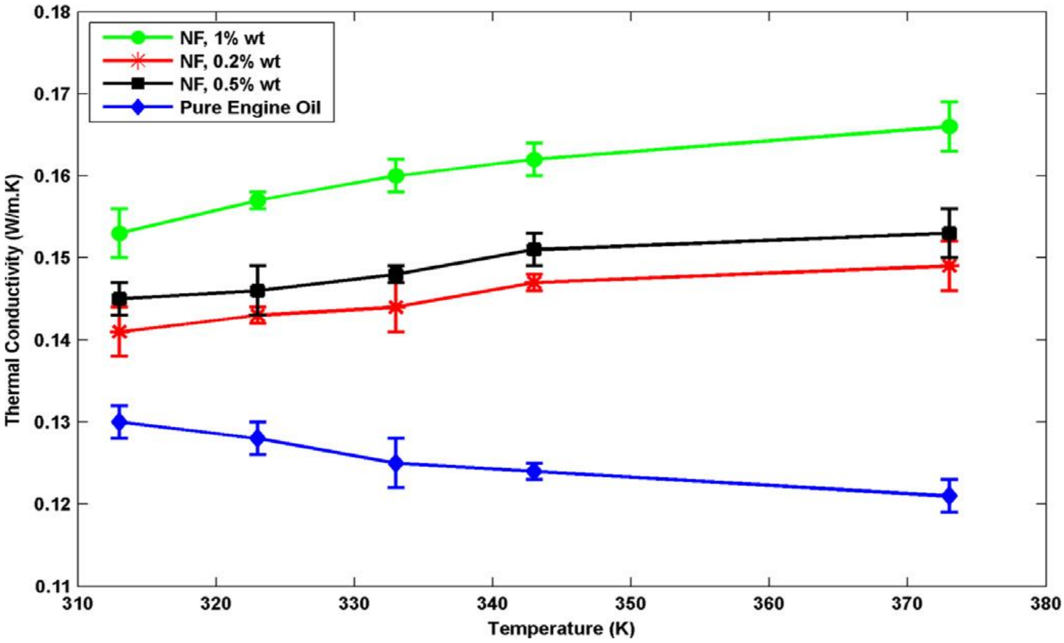

Fig. 11: Variation of thermal conductivity with temperature at different volume fraction of nanofluid[91)]

Naddaf et al.[92)] used MWCNT/diesel oil and GNP/diesel oil to investigate the engine performance experimentally. The findings showed that, in comparison to base oil, the heat transfer characteristics of nanofluids enhanced. Additionally, the findings show that raising the motion of the nanofluid raises the CCHT for all weight coefficients of nanoparticles, and that there is no discernible rise in pressure drop for nanofluids compared to pure oil. With the exception of the two situations involving the MWCNT and GNP hybrid, the performance index of nanofluids is greater than one in all other situations. Thus, employing nanofluids is appropriate for usage in industrial units since it increases the HTC more than it improves the pressure drop.

Sgroi et al.[93)] reported the findings of tests conducted on completely prepared engine oil that included MoS_2 nanoparticles. On the NEDC, the nano-lubricant made it possible to show a 0.9% decrease in combustibility compared to the standard lubricant devoid of nanoparticles.

Davis et al.[94)] concentrated on adding Cr_2AlC nanolamella to 5W-30 engine oil in order to improve its tribological characteristics. Cr_2AlC -based nanofluids outperform h-BN and MoS_2-based alternatives in tribological and anti-wear properties. The coefficient of friction (COF) is reduced by approximately 22%, and the tribofilm's oil film strength is enhanced nearly threefold with Cr_2AlC nanolamella. These nanofluids deliver 2.2 to 2.6 times higher oil film strength compared to h-BN and MoS_2 nanoparticles. The lubricating oils maintain stability throughout testing, and the use of Cr_2AlC nanoparticles increases flash and fire points by 17.9% and 17.8%, respectively, offering a safer and more efficient alternative to conventional lubricants.

Ali et al.[95)] used Al_2O and TiO_2 nanomaterials in engine oil as additive to enhance the tribological features of piston ring arrangement in an automobile engine. The variation of friction coefficient with the concentration of nanolubricant is shown in Figure 12. Blending Al_2O_3 and TiO_2 nanoparticles with engine oil at an optimal concentration of 0.25 wt% improves performance. Adding oleic acid as a solvent enhances nanoparticle suspension while reducing the friction coefficient by 11% and wear rate by 2.6%. These improvements are linked to chemical interactions on the friction surfaces.

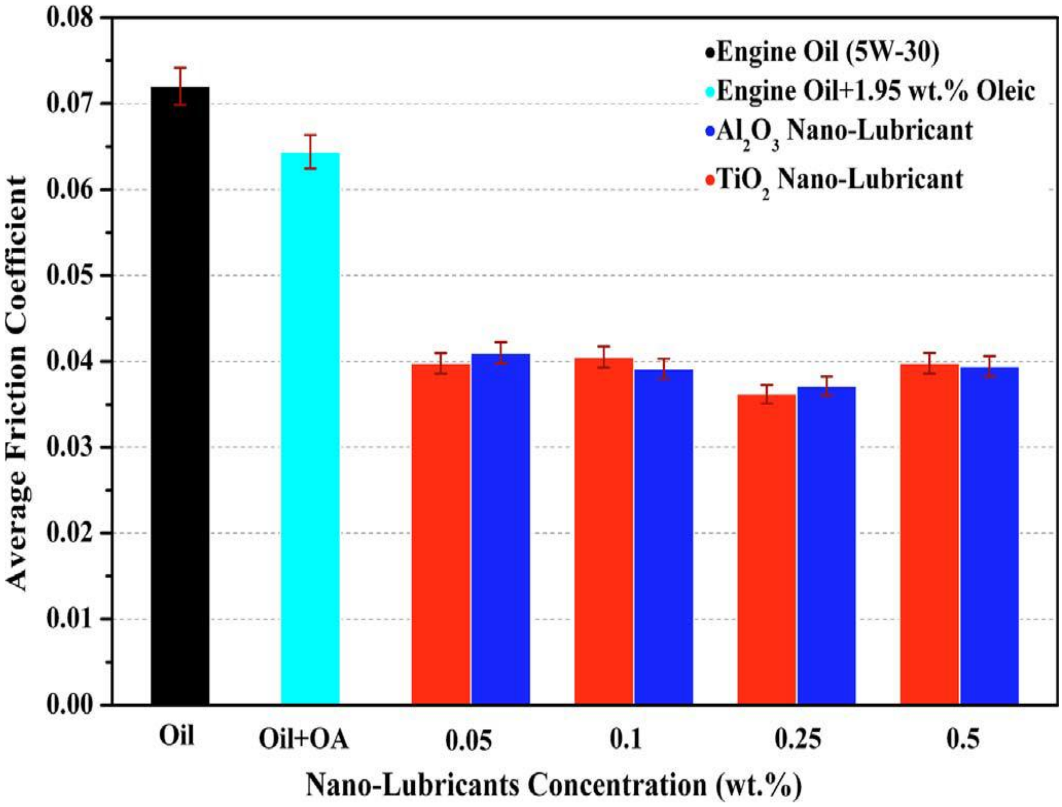

Fig. 12: Variation of friction coefficient with the concentration of nanolubricant[95)]

Ali et al.[96)] used Al_2O_3/TiO_2 hybrid nanomaterials in engine oil as additive to improve the economy of fuel in a gasoline engine. The variation of fuel consumption with vehicle speed using hybrid nanolubricant is shown in Figure 13. Around 16–20% less gasoline was used when Al_2O_3/TiO_2 hybrid nanolubricants were used. Therefore, a fuel economy of roughly 4 L/100 km in an urban area is implied by the decrease in consumption of gasoline noted during the NEDC assessment. Using Al_2O_3/TiO_2 hybrid nanolubricants enhances engine performance by increasing brake power and torque under various operating conditions compared to standard 5W-30 oil. This improvement is due to a 5–7% reduction in frictional power losses, leading to a mechanical efficiency boost of 1.7–2.5%.

Awang et al.[97)] used CNC/SAE 40 engine oil nanolubricant to investigate the frictional as well as wear performance of engine. According to this research, adding CNC nanoparticles to oil for engines greatly lowers wear and friction, improving the lubricating qualities of the fluid. Considering all lubrication circumstances, base oil with 0.1% CNC exhibits the best wear protection and the least coefficient of friction, among other outstanding tribological characteristics. Esfe and Sarlak[98)] used CuO-MWCNT/10W – 40 nanolubricants in IC engine to investigate the rheological features. The most significant percentage of dynamic viscosity improvement in volume fraction of 1% is around 43.52 %, as evidence from experiments indicates that as the volume fraction grows, the magnitude of nanolubricant viscosity rises in comparison to unadulterated lubricant.

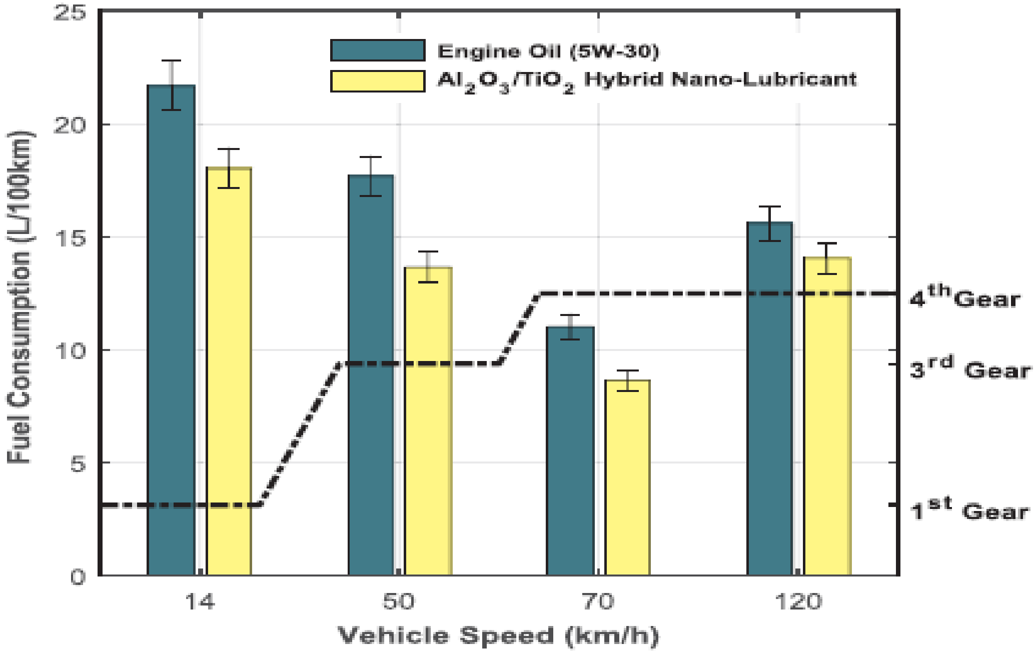

Fig. 13: Variation of fuel consumption with vehicle speed using hybrid nanolubricant[96]

6. Challenges and Limitation of Utilization of Nanofluid in Automotive Industry

The utilization of nanofluids in the automotive industry presents promising potential for enhanced heat transfer, fuel efficiency, and reduced emissions[99]. However, significant challenges and limitations hinder widespread adoption. Nanofluids often suffer from stability issues, where nanoparticles tend to agglomerate and settle, reducing their thermal efficiency over time[100]. High production costs, especially for quality-controlled synthesis, add to the economic burden, making them less competitive compared to traditional coolants. Material compatibility is another concern, as some nanoparticles can corrode engine metals like aluminum and copper, potentially decreasing component lifespan[101]. Additionally, the environmental and health risks posed by nanoparticle exposure during use or disposal raise regulatory and safety concerns. The lack of industry-wide standards complicates efforts to ensure consistent performance and safety, and the complex heat transfer mechanisms and increased viscosity associated with nanofluids can lead to unpredictable outcomes and increased energy demands[102]. Finally, automotive systems designed for traditional fluids may require costly modifications to accommodate nanofluids, making this technology challenging to implement on a large scale[103]. The challenges and limitations of utilization of nanofluid in automotive industry according to the various factors factor are presented in Table 5

Table 5: Challenges and limitations of utilization of nanofluid in automotive

Factor	Challenges	Limitations
Stability of Nanofluids	Nanofluids tend to agglomerate, leading to sedimentation and instability over time. This can decrease their thermal performance and make them unreliable for prolonged use	The instability can reduce the life of the nanofluid, require frequent maintenance or replacement, and potentially clog cooling channels or other fine components in automotive systems.
High Production Costs	The synthesis of nanofluids, particularly high-quality and uniform nanoparticles, can be costly. Processes like surface modification or dispersion of nanoparticles add to these expenses.	High production costs make nanofluids economically unfeasible for many automotive applications where traditional coolants are significantly cheaper.
Material Compatibility and Corrosion	Nanofluids may cause corrosion or interact negatively with materials like aluminum, copper, and steel used in automotive components. Some nanoparticles can accelerate wear or corrosion when in contact with these metals.	This can reduce the lifespan of parts, increase maintenance costs, and necessitate the development of special corrosion-resistant materials, further increasing the cost.

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Health and Environmental Concerns	Some nanoparticles, especially metals and metal oxides, may be hazardous to human health and the environment if released during accidents or disposal.	The potential toxicity and environmental risks require strict handling protocols and disposal methods, limiting the practicality and scalability of nanofluids in the automotive industry.
Lack of Standardization	The automotive industry currently lacks standardized protocols for testing, evaluating, and utilizing nanofluids. Different types of nanoparticles behave uniquely under similar conditions, leading to inconsistent results across tests.	Without standardized testing, it's difficult to reliably assess performance and safety, making adoption challenging for manufacturers who rely on predictable, regulated standards.
Complex Heat Transfer Mechanisms	Nanofluids enhance thermal conductivity, but the relationship between nanoparticle concentration, flow properties, and heat transfer rates is complex and not fully understood.	This complexity makes it difficult to optimize formulations and predict outcomes, leading to inconsistent cooling performance, especially under varying engine loads or environmental conditions.
Viscosity and Flow Challenges	The addition of nanoparticles increases the viscosity of the base fluid, which can hinder flow and result in higher pumping power requirements.	Higher viscosity negatively impacts energy efficiency, as engines must work harder to pump the fluid, potentially negating the energy savings from improved thermal properties.
Thermal Degradation and Long-Term Performance	Nanoparticles may degrade over time under high thermal loads, reducing their heat transfer capabilities and potentially generating unwanted byproducts.	Long-term exposure to engine heat and pressure cycles may reduce the effectiveness of nanofluids, necessitating frequent replacement or supplementation, which is not ideal for regular automotive use.
Challenges in Scaling Up	Scaling up nanofluid production for mass use in vehicles requires large quantities of high-quality nanomaterials and precise mixing technology.	he large-scale production is challenging due to the complexity of maintaining particle uniformity and fluid stability, making it difficult to produce consistent, cost-effective nanofluids for commercial automotive applications.
Impact on Existing Engine and Cooling System Design	Automotive engines and cooling systems are designed for traditional fluids, and the shift to nanofluids may require re-engineering components to accommodate changes in thermal properties, viscosity, and material compatibility.	Redesigning or retrofitting existing systems to accommodate nanofluids would incur substantial costs, making the adoption of nanofluids less attractive for manufacturers and consumers alike.

7. Environmental and Safety Aspects of Nanofluid Utilization in Automotive Systems

The utilization of nanofluids in automotive systems presents both environmental benefits and safety challenges. Environmentally, nanofluids improve thermal conductivity and heat dissipation in cooling systems, leading to enhanced engine efficiency and reduced fuel consumption. This directly lowers greenhouse gas emissions and contributes to a reduction in fossil fuel dependency. Additionally, nanofluids can extend the lifespan of engine components by reducing thermal stress, which minimizes material degradation and waste generation[104)]. However, concerns exist regarding the environmental fate of nanoparticles, as their small size and high reactivity may lead to bioaccumulation and toxicity in ecosystems. Proper disposal and recycling strategies are necessary to prevent potential contamination of soil and water sources[105)].

From a safety perspective, nanofluid utilization introduces potential health risks due to nanoparticle exposure during manufacturing, handling, and accidental leaks. The inhalation of nanoparticles can pose respiratory hazards, while skin contact may lead to irritation or other health effects. In automotive systems, ensuring nanoparticle stability is crucial to preventing aggregation, which can cause clogging or damage to heat exchangers and radiators[106)]. Moreover, the flammability and reactivity of certain nanomaterials raise concerns about their behavior under extreme conditions, such as high temperatures or accidental spills. To mitigate these risks, stringent safety protocols, protective measures, and rigorous testing must be implemented during nanofluid production and application[107)]. By addressing these environmental and safety challenges, nanofluids can offer a sustainable and efficient solution for improving automotive performance while minimizing potential hazards.

8. Energy and Cost-Effectiveness of Nanofluid Applications

While nanofluids exhibit enhanced thermal properties that contribute to improved heat dissipation and energy efficiency in automotive cooling and lubrication systems, their adoption comes with several trade-offs. High production costs remain a major barrier, as the synthesis of nanoparticles and the processes required to ensure stable dispersions contribute to increased expenses compared to traditional coolants. Additionally, the increased viscosity of nanofluids can lead to higher pumping power requirements, potentially offsetting the energy savings gained from improved thermal performance[108].

From an economic standpoint, lifecycle cost analysis is crucial in determining the feasibility of nanofluids in commercial automotive applications. While improved heat transfer can extend engine and component lifespans by reducing thermal stress and wear, additional costs may arise due to material compatibility issues, potential corrosion, and the need for specialized formulations[109]. Moreover, stability concerns, such as nanoparticle sedimentation and long-term degradation under high thermal loads, necessitate frequent monitoring and potential replacement, further impacting maintenance costs[110].

Lifecycle cost analysis must weigh these production and operational expenses against potential fuel savings, reduced emissions, and extended component lifetimes. Future research should focus on scalable production methods, cost-efficient nanoparticle synthesis, and long-term stability improvements to ensure that nanofluids become a viable and economically feasible alternative in the automotive industry.

9. Regulatory Challenges and Standardization Issues in Nanofluid Adoption

While nanofluids demonstrate significant potential in enhancing thermal performance in automotive applications, their widespread implementation is hindered by the lack of standardized testing protocols and regulatory frameworks. Unlike conventional automotive coolants and lubricants, nanofluids exhibit complex behavior due to variations in nanoparticle composition, stability, and dispersion techniques. The absence of universally accepted testing methodologies makes it difficult to evaluate their safety, efficiency, and long-term performance across different automotive systems.

Additionally, certification of nanofluid-based systems remains a critical challenge, as current automotive standards are primarily designed for traditional coolants. The unpredictability of nanoparticle interactions with engine materials raises concerns about corrosion, sedimentation, and potential environmental hazards. Regulatory bodies have yet to establish industry-wide safety benchmarks for nanofluids, making it difficult for manufacturers to integrate them into commercial vehicle systems without extensive independent validation.

To ensure safe and reliable deployment of nanofluids in automotive applications, the development of globally recognized industry standards is imperative. Establishing performance benchmarks, testing guidelines, and certification protocols will facilitate regulatory compliance while ensuring that nanofluids meet stringent safety and performance criteria before widespread adoption.

10. Conclusion and Future Scope

The application of nanofluids in the automotive industry has demonstrated significant potential for enhancing vehicle performance, energy efficiency, and sustainability. These advanced fluids, engineered with nanoparticles, offer superior thermal conductivity, improved lubrication properties, enhanced shock absorption, and better combustion efficiency compared to conventional fluids. Their integration as coolants in radiators enables efficient heat dissipation, while their role as engine fuels improves combustion and reduces emissions. Nanofluids as lubricants minimize friction and wear, prolonging engine life. Additionally, their utilization in shock absorbers optimizes vibration dampening, ensuring smoother rides. Despite these promising advancements, challenges such as production costs, long-term stability, and compatibility with existing systems need to be addressed. Future research should focus on large-scale applications, cost-effectiveness, and environmental impacts to maximize the benefits of nanofluids in the automotive sector. In summary, nanofluids hold great promise to revolutionize automotive technology and contribute to a more sustainable and efficient transportation industry. The important conclusion drawn from this review article is mentioned below:

Nanofluids have demonstrated exceptional thermal conductivity, making them effective in improving heat dissipation in automotive systems, particularly in radiators.

Nanofluids used as additives in engine fuels result in better combustion efficiency, leading to reduced fuel consumption and lower emissions.

Nanofluid-based lubricants reduce engine wear and friction, contributing to increased engine lifespan and smoother operation.

Utilizing nanofluids in shock absorbers enhances damping properties, resulting in better vibration control and ride comfort.

The use of nanofluids in automotive applications directly supports lower emissions, aligning with environmental regulations and sustainability goals.

Components exposed to nanofluids experience reduced wear and thermal stress, improving overall durability and reliability.

By optimizing heat transfer and reducing energy losses, nanofluids contribute to energy-efficient vehicle operations.

Nanofluids exhibit adaptability across various automotive systems, offering potential for multi-functional use.

Only limited research has been performed on utilization of nanofluid in automotive industry. Therefore lot works are required to be performed in future to predict the exact

behaviour of nanofluid utilization in automobiles. Some are listed below:
Research on cost-effective and scalable methods for nanoparticle production to make nanofluids more economically viable for large-scale automotive applications.
Development of stable nanofluid formulations to prevent sedimentation or degradation over time, ensuring consistent performance in automotive systems.
Investigation into compatibility between nanofluids and existing automotive materials to avoid corrosion or adverse chemical reactions.
Tailoring nanofluid compositions for specific automotive applications, such as radiator coolants, engine lubricants, or fuel additives, to maximize performance.
Focus on biodegradable or environmentally friendly nanoparticles to reduce the ecological impact of nanofluid usage.
Exploring nanofluids for thermal management in electric vehicle batteries and enhancing efficiency in hybrid engines.
Utilization of advanced computational tools to model nanofluid behavior and optimize designs before implementation in vehicles.
Establishing safety and performance benchmarks for nanofluids to facilitate their adoption and meet industry regulations.

Nomenclature

ϕ	Volume fraction of nanofluid
b_f	Base fluid
C_P	Specific heat
n_f	Nanofluid
p	Solid particle
Abbreviations	
BTE	Brake thermal efficiency
BSF	Brake specific fuel
BSFC	Brake specific fuel consumption
CNC	Cellulose nanocrystals
CCHT	Coefficient of convective heat transfer
CO	Carbon monoxide
COF	Coefficient of friction
$Ce_xZr_{(1-x)}O_2$	Cerium zirconium mixed oxide
DSOB	Dairy scum oil biodiesel
DSOME	Dairy scum oil methyl ester
DSOME2040	Dairy scum oil methyl ester 20% blended with diesel with 40 ppm Graphene nanoparticles
EG	Ethylene glycol
GNP	Graphene nanoplatelets
GDD	Graphite Oxide dosed in Diesel at 25 ppm dosing ratio
HTC	Heat transfer coefficient
HRR	Heat release rate
HC	Hydrocarbons
hBN	Hexagonal boron nitride
LGO	Lemongrass oil
LDDE	Light duty diesel engine
MQL	Minimum quality lubrication
MQCL	Minimum quality cooling lubrication
MOME	Mustard oil methyl ester
NEDC	New European Driving Cycle
OHTC	Overall heat transfer coefficient
GO	Graphene oxide
PG	Propylene glycol
SWCNT	Single walled carbon nanotubes
SDD	Single-walled Carbon Nanotubes dosed in Diesel at 25 ppm dosing ratio
SBME 25	25% soybean biodiesel in diesel
WFOME	Waste fry oil methyl ester

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