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Thermophysical Properties and Heat Transfer Performance in Nanofluids: A Comprehensive Review and CFD Analysis

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***Abstract:** This study offers a thorough analysis of the thermophysical characteristics and heat transfer performance in nanofluids using computational fluid dynamics (CFD). Nine different nanofluids are studied with a heat flow of 5000 W/m^2. The study looks at the differences between nanofluids and water in terms of density, viscosity, and thermal conductivity. The findings reveal increased densities, viscosities, and thermal conductivities in nanofluids, providing fresh insights on these improvements. Their greater heat transfer ability, as seen by higher outlet temperatures and better thermal energy exchange, is confirmed by the CFD study. The research advances knowledge of nanofluids' potential for use in diverse heat transfer systems.*
***Keywords:** Thermophysical properties, Heat transfer performance, Nanofluids, Heat flow, Density, Viscosity, Thermal conductivity, Nanofluid characteristics, Heat transfer ability, Outlet temperatures, Thermal energy exchange, CFD analysis, Heat transfer systems, Nanofluid applications*

I. INTRODUCTION

The utilization of nanofluids, which are colloidal suspensions of nanoparticles in base fluids, has shown great potential in enhancing heat transmission in diverse applications. Extensive research has focused on investigating the unique characteristics of nanofluids and their ability to address heat dissipation challenges across industries.

A study conducted a comprehensive review of nanofluids, specifically examining their increased thermal conductivity compared to base fluids, with a focus on enhancing heat transfer rates [1]. Another investigation centred on the properties of nanofluids' pool boiling, revealing their superior performance compared to pure fluids [2]. It is evident that nanofluids have the potential to improve heat transfer even in heat exchange systems involving water. The impact of nanoparticle concentration on heat transmission was explored, demonstrating that raising the concentration enhances convective heat transfer efficiency [3]. Furthermore, the use of Al2O3-water nanofluids in electronic liquid cooling systems showcased their potential for efficient thermal management [4].

Nanoparticle size and shape were found to significantly influence the thermal conductivity of nanofluids, emphasizing the importance of these factors in enhancing heat transfer performance [5]. The rheological behavior of nanofluids was investigated, revealing changes in fluid viscosity upon nanoparticle introduction, crucial for optimizing their flow behavior in heat transfer devices [6]. Stability studies addressed concerns such as sedimentation and agglomeration of nanoparticles in base fluids, offering suggestions to enhance nanofluids' stability for long-term heat transfer applications [7].

Research on the impact of nanoparticle material on heat transfer demonstrated the improvement in thermal conductivity achieved by various nanoparticles in diverse base fluids [8]. Theoretical models were developed to predict the thermal conductivity and convective heat transport of nanofluids, providing valuable insights for understanding and optimizing their dynamics [9]. Additionally, the application of nanofluids in solar thermal systems was explored, highlighting their potential to enhance energy absorption and promote renewable energy usage [10].

The comprehensive study on nanofluids signifies their promising role in improving heat transfer efficiency and addressing thermal management challenges across a range of applications. Based on these findings, nanofluids offer opportunities to develop more effective and sustainable heat exchange systems.

The objective of this study is to conduct a meticulous assessment of the thermophysical characteristics and heat transmission capabilities of nanofluids. We will investigate the influence of nanoparticle composition and concentration on the thermal conductivity, viscosity, and specific heat of nanofluids. Moreover, we will compare the enhancement of convective heat transfer in nanofluids with conventional fluids.

Computational fluid dynamics (CFD) simulations will be employed to analyze heat transfer in electronic devices at constant heat flux of 5000 w/m^2, providing insights into the effectiveness of nanofluids in various metals. These CFD analyses will deliver essential information regarding heat transmission properties and the practical application of nanofluids in real-world scenarios.

II. LITERATURE REVIEW

A. Overview of nanofluids and their composition

Nanofluids, suspensions of solid nanoparticles in base fluids, exhibit remarkable changes in thermophysical characteristics, including thermal conductivity, viscosity, and specific heat capacity. These alterations are a direct result of introducing nanoparticles with sizes ranging from 1 to 100 nanometres into the base fluid.

The choice of nanoparticles significantly influences the thermophysical properties of nanofluids. Metal nanoparticles like copper (Cu) and aluminium (Al) are commonly utilized due to their superior thermal conductivity and stability within nanofluids [1,11-14]. Moreover, metal oxide nanoparticles, including titanium dioxide (TiO2) and aluminium oxide (Al2O3), are extensively investigated for their stability and compatibility with various base fluids [9],[15]-[18].

The concentration of nanoparticles in nanofluids is a significant factor affecting their performance. In experimental study, a wide range of concentrations have been explored, from extremely low concentrations (like 0.1 vol%) to moderate concentrations (10 vol%). The optimal heat transfer enhancement varies with nanoparticle concentration, base fluid, and application, according to numerous studies [16],[19]-[23].

Several methods, including sonication, surfactant addition, and surface modifications, have been used to assure effective dispersion of nanoparticles. The stabilization and dispersibility of nanoparticles in the base fluid are improved by surface alterations, such as functionalization and coating techniques. To improve dispersion and avoid agglomeration, silanization, polymer grafting, and chemical surface treatments have been investigated [20],[24]-[27].

In the formulation of nanofluids, the base fluid selection is crucial. Due to their outstanding heat transfer capabilities and environmental friendliness, water-based nanofluids have received a lot of research attention [14],[16],[20],[23],[28]-[29]. In systems needing freeze protection, such as automotive cooling [16,30-32], ethylene glycol-based nanofluids are used. Oils, including mineral oils and synthetic oils, have also been investigated by researchers as base fluids for high-temperature applications [18],[19],[29],[33]-[36].

Nanoparticle surface changes are essential for improving nanoparticle stability and dispersibility in the base fluid. The surface of nanoparticles has been altered using a variety of methods, including functionalization, coating, and chemical treatments. The compatibility and dispersibility of nanoparticles are enhanced by functionalization with organic molecules, such as amino acids and polymers [20],[24],[26],[17],[29],[37]. Silica coating and polymer encapsulation are two coating techniques that create a protective layer around nanoparticles to reduce agglomeration and increase stability [32],[38]-[41].

The stability and dispersion of nanofluids are influenced by the surface charge of nanoparticles and the presence of surfactants [13],[20],[24],[36],[42]. Surface charge change, accomplished through surface functionalization or pH adjustment, can increase the electrostatic repulsion between nanoparticles and avoid aggregation. To enhance dispersion stability and prevent particle agglomeration, surfactants, such as non-ionic, anionic, and cationic surfactants, are frequently added to nanofluids [23],[27],[29],[40],[43]. Additionally, the size and shape of nanoparticles play a crucial role in influencing the thermal conductivity and heat transfer properties of nanofluids. Non-spherical nanoparticles like nanowires and nanotubes have been employed to enhance thermal conductivity and heat transmission [20],[37],[44]-[46]. Numerous studies have investigated the relationship between thermal conductivity and nanoparticle size, revealing that smaller nanoparticles yield significantly greater increases in thermal conductivity [14],[17],[26],[30],[47].

Furthermore, the choice of base fluid, nanoparticle concentration, surface modifications, and base fluid selection all contribute to the thermal properties and heat transfer characteristics of nanofluids. A comprehensive understanding of these characteristics is essential for the efficient design and optimization of nanofluids in diverse heat transfer applications, as indicated by the extensive research cited.

B. Review of recent advancements in nanofluids research

There have been several developments in the study of nanofluids in recent years. A novel type of nanofluid with copper oxide nanoparticles coated in graphene oxide had good thermal conductivity and stability. In a different investigation, Haddad et al. created a unique nanofluid by mixing multi-walled carbon nanotubes with a base fluid, which enhanced thermal conductivity and heat transfer performance [49].

The creation of novel techniques for the production and characterisation of nanofluids has also been a research priority. A unique method for the manufacture of copper oxide nanoparticles was created by Liu et al., and it was utilised to create a high-performance nanofluid with improved thermal conductivity [50]. Al-Sammarraie et al. created a completely novel method for making silver nanoparticles, which they then mixed with a base fluid to create a nanofluid with enhanced thermal conductivity and stability [48].

Another focal point of research revolves around investigating the impacts of different parameters on the thermal properties and heat transfer efficiency of nanofluids. For instance, researchers examined the influence of nanoparticle concentration on the thermal conductivity and viscosity of alumina-water nanofluids. The findings revealed that as the concentration of nanoparticles increased, the thermal conductivity of the nanofluid exhibited an upsurge, while its viscosity decreased. Additionally, Naji et al. conducted a study to explore the effects of temperature and concentration on the thermal conductivity and viscosity of a water-and-carbon nanotube nanofluid [51].

Recent breakthroughs in nanofluid research, in general, have resulted in the development of new and improved nanofluids with improved thermal characteristics and heat transfer ability. As a result of these advances, nanofluids can now be used in a variety of heat transfer processes, and our understanding of the underlying mechanisms that regulate nanofluid thermal behaviour has improved.

C. Thermophysical properties of nanofluids

Understanding the performance of nanofluids' heat transport requires knowledge of their thermophysical properties. Here are some of the thermophysical characteristics of nanofluids that are frequently reported:

1) *Thermal conductivity*: The thermal conductivity of nanofluids surpasses that of the base fluid due to the remarkable thermal conductivity of nanoparticles and their capacity to enhance thermal coupling at the solid-fluid interface [52],[14].
2) *Specific heat capacity*: Nanofluids exhibit a slightly higher specific heat capacity compared to base fluids, primarily due to the superior performance of nanoparticles in this aspect [53]–[54].
3) *Viscosity*: Introducing nanoparticles to the base fluid leads to an increase in nanofluid viscosity. This can be attributed to nanoparticle aggregation and cluster formation, resulting in effective size enlargement [55]-[56].
4) *Density:* The density of nanofluids may experience slight variations depending on the type and quantity of nanoparticles employed in the base fluid [57]– [58].
5) *Surface tension*: Research suggests that the presence of nanoparticles in base fluids can reduce the surface tension of nanofluids. This decline in surface tension arises from nanoparticle adsorption at the fluid interface [59]-[60].
6) *Boiling heat transfer*: Nanofluids demonstrate enhanced boiling heat transfer compared to base fluids. This improvement is attributed to the nanoparticles' role as active sites for bubble nucleation and growth [58],[61].
7) *Critical heat flux*: Studies indicate that nanofluids exhibit higher critical heat flux (CHF) than the base fluid. The inclusion of nanoparticles enhances interfacial thermal contact between the solid and fluid phases, leading to the observed CHF improvement [62]-[63].
8) *Thermal diffusivity*: Nanofluids are proposed to possess higher thermal diffusivity compared to conventional fluids. This rise in thermal diffusivity can be attributed to the nanoparticles' high thermal conductivity and their ability to facilitate thermal coupling at the solid-fluid interface [54],[52].
9) *Heat capacity rate*: The addition of nanoparticles to the base fluid enhances the heat capacity rate of nanofluids, attributed to the nanoparticles' higher specific heat capacity compared to the base fluid [53],[64].
10) *Thermal expansion coefficient*: Nanofluids exhibit distinct thermal expansion coefficients compared to the base fluid, influenced by the effect of nanoparticles on the fluid's thermal expansion behaviour and volume changes with temperature [65]-[66].
11) *Electrical conductivity*: Nanofluids have the potential to exhibit enhanced electrical conductivity compared to the base fluid, stemming from the presence of conductive nanoparticles within the fluid [67]–[68].
12) *pH level*: Nanofluids can experience changes in pH level due to the inclusion of nanoparticles, introducing new chemical species into the fluid stream [69]-[70].
13) *Zeta potential*: Nanofluids can exhibit a wide range of zeta potential values in comparison to the base fluid. The surface charge alteration caused by nanoparticles affects the stability and dispersion characteristics of the nanofluids [69],[71].
14) *Sedimentation stability*: Over time, nanofluids may experience sedimentation as nanoparticles settle out. Several factors, such as nanoparticle size, concentration, and surface modification, influence the sedimentation stability of nanofluids [72]-[73].

15) *pH stability*: The pH level of the fluid plays a role in the dispersion and stability of nanofluids, known as pH-dependent stability. The interaction between fluid molecules and nanoparticles leads to variations in stability based on the pH level [70],[74].
16) *Rheological behaviour*: The viscosity of nanofluids exhibits non-Newtonian behaviour, where viscosity varies with shear rate or shear stress. Nanoparticles introduce complex flow properties, resulting in non-Newtonian rheological behaviour of the fluid [75]–[76].

D. Heat transfer enhancement mechanisms in nanofluids

1) *Brownian motion and bigger surface area*: The small size of nanoparticles produces a bigger surface area, which boosts convective heat transmission. Additionally, the fluid is better dispersed due to the Brownian motion of nanoparticles, which might result in more even heat transfer throughout the system [43],[77]-[78].
2) *Better thermal conductivity*: The fact that nanoparticles have a higher thermal conductivity than the base fluid improves heat transfer efficiency. Nanofluids can boost the thermal conductivity of a base fluid by up to tenfold [79]-[81].
3) *Formation of a boundary layer*: At the fluid-solid interface, nanoparticles can form a thin layer that minimises the heat resistance between the fluid and the solid surface. As a result, the efficacy of heat transfer is increased [9],[28].
4) *Fluid characteristics* can be altered by nanoparticles, which can impact the performance of heat transfer by changing the viscosity and density of the base fluid [66],[82].
5) *Enhancement of phase change*: The performance of heat transfer during the phase change process can be improved by the inclusion of nanoparticles in phase change materials. The nucleation sites provided by the nanoparticles can increase the efficiency of the phase shift [83]-[84].
6) *Thermophoresis*: By allowing nanoparticles to move in a temperature gradient, thermophoresis can improve the efficiency of heat transfer. In the case of natural convection, this mechanism is very important [85]-[86].
7) *Electrophoresis*: By manipulating the nanoparticles in the fluid using electric fields, it is possible to improve heat transfer efficiency. This method is especially important when forced convection is involved [87]-[88].
8) *Interfacial layer*: Heat transfer efficiency may be improved by establishing an interfacial layer between nanoparticles and the base fluid. When the thermal resistance at the fluid-solid interface is decreased by the interfacial layer, convective heat transport is facilitated [89].
9) *Enhanced nucleate boiling*: Surface wettability can be changed by nanoparticles in nanofluids, which improves the heat transmission during boiling. By promoting bubble formation and growth, the modified surface properties can improve boiling's heat transfer coefficient [90].
10) *Enhanced forced convection*: The forced convection process of heat transmission can be improved by the inclusion of nanoparticles since it alters the base fluid's flow. Turbulence brought on by nanoparticles that disturb the boundary layer and generate turbulence can lead to higher heat transfer rates [91].
11) *Improved radiation heat transfer*: High emissivity nanoparticles can improve radiation heat transfer in nanofluids. As a result of the nanoparticles, the fluid has a higher effective emissivity, which facilitates heat transfer by radiation [92].
12) *Synergistic effects*: The augmentation of heat transmission in nanofluids can result from the combination of many mechanisms, such as improved thermal conductivity, modifications to the fluid's characteristics, and altered flow behaviour. The performance of heat transport can be enhanced even further by these integrated techniques [93].

E. Applications of nanofluids in heat transfer systems

1) *Electronic device cooling*: Nanofluids have received a lot of attention as a potential solution for cooling components like computer chips, LEDs, and power electronics. Nanofluids are efficient in dissipating heat produced by these devices due to their improved heat transfer capabilities, which improves device performance and reliability [94]-[95].
2) *Solar thermal systems*: Research is being done on the use of nanofluids in solar thermal systems to improve the efficiency of the heat transfer fluids and solar collectors. The system operates more effectively because nanofluids have a high thermal conductivity, which improves heat absorption and transfer in solar collectors [96]–[97].
3) *Automotive cooling systems*: Nanofluids' potential in automotive cooling applications is being investigated. Nanofluids' enhanced heat transfer and high thermal conductivity can increase the effectiveness of engine cooling systems, enhancing both engine performance and fuel efficiency [98]-[99].

4) *Heat exchangers*: Nanofluids are being investigated for use in heat exchangers to improve the efficiency of heat transmission. Circulating nanofluids in the heat exchanger tubes can improve heat transmission, resulting in improved energy efficiency and more compact designs [100]-[101].
5) *Air conditioning and Refrigeration*: The heat transfer capabilities of the working fluids in refrigeration and air conditioning systems may be improved by nanofluids. Cooler, more efficient systems can be created by using nanofluids as refrigerants or coolants [102]–[103].
6) *Nuclear reactors*: nuclear reactors may make use of nanofluids, particularly to increase the efficiency of cooling the reactor core. Due to their high thermal conductivity and stability, nanofluids are a good choice for improving heat transfer in nuclear cooling systems, leading to safer and more efficient reactor operation [104]–[105].
7) For application in *microfluidic systems*, where precise temperature control and heat dissipation are essential, nanofluids are currently being researched. To progress industries like biotechnology and microelectronics, the usage of nanofluids in microchannels can improve heat transmission and thermal management in microdevices [106]-[107].
8) *Industrial operations*: Nanofluids have the potential to be used in a range of industrial processes that call for effective heat transfer, including metal casting, chemical reactors, and heat treatment. Improved energy efficiency and process control are possible when nanofluids are used as heat transfer fluids [108]-[109].

III. EXPERIMENTAL METHODOLOGY

A. *Selection of Nanofluid Samples and Base Fluids*

For nanofluids used to cool electronic circuits, such CPU chip, LED, and many more choosing the base fluid is essential to achieve effective heat dissipation. The effectiveness of various base fluids in nanofluids for electronic chip cooling applications has been examined in several research articles. Here are a few base fluids that have been widely examined and reported on:

1) *Water:* Because of its outstanding thermal characteristics, high heat capacity, and low cost, water is frequently regarded as the best base fluid for cooling electronic chips. Due to its excellent thermal conductivity, it facilitates efficient heat transfer. It has been demonstrated that water-based nanofluids improve the cooling capacity of electronic chips [110]-[111].
2) *Engine oil*: Some engine oils, such as synthetic or mineral oil, have been investigated as base fluids for nanofluids in electronic chip cooling. Engine oils are compatible with chip materials and have excellent lubrication and thermal stability capabilities. They are capable of moving heat from the chip surface to the cooling system effectively [112]-[113].
3) *Synthetic esters*: Excellent thermal stability, low viscosity, and strong dielectric qualities are characteristics of synthetic esters. In dielectric cooling systems for electronic devices, they are frequently employed as base fluids. Nanofluids based on synthetic ester have shown potential heat transfer and electrical insulating abilities [114]-[115].
4) *Fluorocarbon liquids*: Perfluorocarbons (PFCs), one type of fluorocarbon liquid, has drawn interest for its potential use as the foundation fluid for nanofluids in the cooling of computer chips. Fluorocarbon liquids have excellent chemical stability, low viscosity, and high boiling temperatures. They provide efficient cooling for electronic devices with high temperatures [116]-[117].
5) *Dielectric liquids*: In electronic cooling applications, base fluids such as silicone oils or polyalphaolefins (PAOs) are frequently utilised. These liquids have a high thermal stability, strong dielectric characteristics, and low toxicity. Dielectric nanofluids have demonstrated better heat transfer capabilities for cooling electronic chips [118]-[119].
6) For analysis we have *choose water as base fluid* because Due to its superior thermal characteristics and large heat capacity, water is a frequently utilised base fluid. It is effective in distributing nanoparticles and promoting heat transfer.
7) According to the thermal conductivity and above findings we have choose 9 Nanofluid samples for this CFD analysis:
8) *Diamond nanofluids*: Due to their high thermal conductivity, diamond nanoparticles can considerably improve the efficiency of heat transmission when mixed with a base fluid [120].
9) *Carbon nanotube (CNT) nanofluids*: Due to their high thermal conductivity, carbon nanotubes can enhance the heat transfer capabilities of nanofluids [121].
10) *Nanofluids made of graphene*: Graphene is a two-dimensional substance that has exceptional thermal conductivity. Graphene nanofluids have high heat transfer performance when mixed with a base fluid [122].
11) *Nanofluids made of boron nitride (BN)*: For applications such as cooling electronic chips, boron nitride nanoparticles with high thermal conductivity can improve the heat transfer capabilities of nanofluids [123].
12) *AlN nanofluids*: Since aluminium nitride nanoparticles have strong thermal conductivity, adding them to nanofluids can increase the effectiveness of heat transfer for cooling electronic chips [124].

13) *Silicon carbide (SiC) nanofluids*: Silicon carbide nanoparticles have a high thermal conductivity, and they can improve heat transfer performance in electronic chip cooling applications when they are disseminated in a base fluid [125].
14) *Copper (Cu) nanofluids*: Copper nanoparticles have a high thermal conductivity, which can be used to enhance the heat transfer properties of nanofluids for cooling electronic devices [126].
15) *Nanofluids containing silver (Ag) nanoparticles* can improve the heat transfer capabilities for cooling electronic chips since they have great thermal conductivity [127].
16) *Zinc oxide (ZnO) nanofluids*: Zinc oxide nanoparticles have a relatively high thermal conductivity, therefore adding them to nanofluids might increase the efficiency of heat transfer for applications like cooling electronic chips [128].

B. Preparation and characterization of nanofluid samples

Nanoparticles must be dispersed into a base fluid to create a stable, uniform suspension to prepare nanofluid samples. Numerous academic articles have examined various approaches to making nanofluids. Here are a few approaches that are frequently cited:

1) *Two-step procedure*: This process involves synthesising nanoparticles separately before dispersing them in the base fluid. The nanoparticles are often produced by techniques including chemical precipitation, sol-gel, or thermal breakdown. The nanoparticles in the base fluid are dispersed by vigorous stirring, sonication, or high-energy mixing [129]-[130].
2) *One-step approach*: In this approach, the base fluid is used to directly synthesise nanoparticles. Techniques like co-precipitation, hydrothermal synthesis, or chemical reduction can be used to accomplish this. Throughout the actual synthesis process, the nanoparticles develop and disseminate in the base fluid [131]-[132].
3) *Method with the use of surfactants*: Surfactants are employed to keep nanoparticles from clumping together and to stabilise them in the base fluid. Surfactant molecules bind to the surfaces of nanoparticles to form a barrier that prevents particle aggregation. This technique guarantees greater nanoparticle stability and dispersion in the nanofluid [133]-[134].
4) *High-pressure homogenization*: High-pressure homogenization is a process in which a suspension of nanofluid is put under extreme pressure and shear forces in a device called a high-pressure homogenizer. The stability and heat transfer capabilities of the nanofluid are increased because of this method' assistance in attaining uniform dispersion and reducing particle size [135]-[136].
5) *Creating nanofluids with the use of microfluidics* is a precise and regulated process. It entails carefully blending base fluid with nanoparticles utilising microchannels or microreactors. This technique improves the homogeneity and stability of the nanofluid through effective mixing and concentration control [137]-[138].
6) *Electrochemical deposition*: Using this technique, metal ions are electrochemically reduced in a base fluid to create nanoparticles. The electrochemical technique provides for exact control of the nanoparticle size and morphology, with the base fluid serving as the electrolyte [139]-[140].
7) *Laser ablation*: In this technique, laser pulses are used to vaporise a target substance that is submerged in a base fluid, creating nanoparticles in the process. A nanofluid is created by dispersing the abated nanoparticles in the base fluid. The size of the nanoparticles can be controlled by laser ablation, and many different materials can be synthesised [141]-[142].
8) *Method of microemulsion*: Microemulsion is the formation of nanoparticles within nanometer-sized droplets in a surfactant-stabilized environment. The production of nanoparticles with homogeneous sizes is facilitated by the microemulsion, which offers a constrained environment for their synthesis. The generated nanofluid shows good stability and nanoparticle dispersion [143]-[144].
9) *Solvothermal synthesis*: Solvothermal synthesis is the reaction of precursors in a solvent under high pressure and high temperature. This process enables the controlled growth of nanoparticles inside the base fluid, producing particles with well-defined size and shape. For the creation of intricate nanoparticle architectures, solvothermal synthesis is especially effective [145]-[146].
10) *Co-precipitation technique*: Using this technique, precursor components are simultaneously precipitated in the base fluid to create nanoparticles. The co-precipitation approach enables an easy and affordable synthesis of nanoparticles. By changing the reaction settings, it offers control over the nanoparticle size [147]-[148].
11) Understanding the characteristics and behaviour of nanofluid samples requires their characterization. In research publications, many methods are used to characterise nanofluids. The following are some typical characterisation techniques mentioned in the literature:

12) *Investigation of particle sizes*: The average particle size and size distribution of nanoparticles in nanofluids can be determined using methods such as dynamic light scattering (DLS), nanoparticle tracking analysis (NTA), and scanning electron microscopy (SEM) [149]-[150].
13) *Measurement of zeta potential*: Zeta potential provides insights into the stability and surface charge of nanoparticles in nanofluids. Laser Doppler velocimetry (LDV) or electrophoretic light scattering (ELS) are commonly used techniques to measure zeta potential, which indicates the potential for nanoparticle aggregation or dispersion [151]-[152].
14) *Thermal conductivity measurement*: The thermal conductivity of nanofluids is a critical property that can be evaluated using methods such as the transient hot-wires method, thermal comparator, or differential scanning calorimetry (DSC) [153]-[154].
15) *Viscosity measurement*: Viscosity plays a significant role in the flow behavior and pumping power requirements of nanofluids. Techniques like rotating viscometry and capillary viscometry are commonly employed to determine the viscosity of nanofluids as a function of temperature and nanoparticle concentration [155]-[156].
16) *Stability analysis*: The long-term behavior and prevention of particle agglomeration or sedimentation in nanofluids are determined by their stability. Turbidity measurement, sedimentation analysis, or ultraviolet-visible spectroscopy (UV-Vis) are among the methods used to assess nanofluid stability [157]-[158].
17) *Surface morphology analysis*: Transmission electron microscopy (TEM) or scanning electron microscopy (SEM) can be used to analyze the surface morphology and distribution of nanoparticles in nanofluids, allowing for the study of particle shape and aggregation [159]-[160].
18) *X-ray diffraction (XRD)*: XRD analysis is employed to determine the crystal structure and phase composition of nanoparticles in nanofluids, providing information on crystallinity and potential chemical interactions with the base fluid [161]–[162].
19) *Spectroscopic analysis*: Techniques like Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy are utilized to investigate the chemical interaction between nanoparticles and the base fluid, aiding in the determination of nanofluid stability and compatibility [163]-[164].
20) *Ultrasonic spectroscopy:* Ultrasonic methods, including ultrasonic velocity and attenuation measurements, provide insights into the dispersion and interactions of nanoparticles in nanofluids, evaluating stability and homogeneity [165]-[166].
21) *Differential scanning calorimetry (DSC):* DSC analysis is used to understand the thermal behavior of nanofluids, assessing phase transitions, specific heat capacity, and thermal stability, which helps elucidate the influence of nanoparticles on the thermal characteristics of the base fluid [167]-[168].
22) *Transmission electron microscopy (TEM)*: TEM allows for the observation of the form, size, and distribution of nanoparticles in nanofluid samples through high-resolution imaging, facilitating research on nanoparticle dispersion and nanoscale experiments [169]-[170].
23) *Atomic force microscopy (AFM):* AFM is a method employed to examine the surface topography and roughness of nanofluid sample surfaces, providing details on nanoscale interactions between nanoparticles and the base fluid [171]-[172].
24) *X-ray photoelectron spectroscopy (XPS):* XPS analysis investigates the elemental composition and surface chemistry of nanoparticles in nanofluids, aiding in the identification of functional groups and surface modifications that may influence nanofluid properties [173]–[174].
25) *Electrokinetic analysis:* Electrokinetic techniques such as electrophoresis or electroosmotic flow can be used to determine the surface charge and zeta potential of nanoparticles in nanofluids, shedding light on their stability and dispersion behavior [175]-[176].
26) *Thermal stability analysis*: Thermal stability investigations involve subjecting nanofluid samples to high temperatures over time and monitoring changes in their physical characteristics. Thermogravimetric analysis (TGA) or isothermal ageing studies can be performed to evaluate thermal stability and degradation behavior of nanofluids [177]-[178].

C. Measurement of thermophysical properties

The optimal size of nanofluids' particles for applications requiring the highest heat transfer performance, such as cooling electronic device:

Using nanofluids to cool electronic device, showed that nanofluids containing nanoparticles between 20 and 100 nm demonstrated enhanced heat transfer capability. The study did point out that overly tiny nanoparticles might cause particle aggregation and increased viscosity, which would be detrimental to heat transfer [179].

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According to Murshed, who studied the thermal performance of nanofluids for electronic device cooling, nanoparticles between 10 and 100 nm in size offered improved heat transfer. Smaller particles, they discovered, provided better dispersion and interaction with the heat source, improving thermal conductivity [19].

According to Lee, when determining the appropriate particle size, it is important to consider the chip's specific heat flow and chip-to-fluid thermal resistance. For efficient heat transfer, they advised using nanoparticles with diameters ranging from 20 to 100 nm [180].

In a study by Kole, the effect of particle size on the thermal conductivity and heat transfer efficiency of nanofluids for electronic device cooling was investigated. It was hypothesised that nanoparticles between 30 and 50 nm in size offered the best thermal conductivity improvement, resulting in increased heat transfer performance [181].

According to Huminic, who studied the usage of nanofluids for CPU chip cooling, the performance of heat transmission was best for nanoparticles between 20 and 60 nm in size. They emphasised that the range of particle sizes offered a reasonable compromise between increasing thermal conductivity and preventing particle aggregation [182].

From given above studies we have choose **20 nm as size of nanoparticles** for making nanofluids.

Properties of different nanofluids used with different 5% Vol percentage.

Formula for Calculation of thermophysical properties of nanofluids

(General Equations)

Density (ρ):

$$\rho_{nf} = \rho_f(1-\varphi) + \rho_p.\varphi$$

, where ρ_f and ρ_p are the densities of the base fluid and nanoparticles, respectively.

Specific Heat Capacity (Cp):

$$C_{pnf} = \frac{\{(1-\varphi).(\rho_f.C_{pf}) + (\varphi.C_{pp})\}}{\rho_{nf}}$$

, where C_{pf}, ρ_f is specific heat capacity and density of the base fluid and C_{pp} is specific heat capacity of nanoparticles and ρnf from last equation.

Viscosity (μ):

$$\mu_{nf} = \mu_f.\{1 + (123\varphi^2) + (7.3\varphi)\}$$

, where μ_f is viscosity of base fluid.

Thermal Conductivity (k):

$$k_{nf} = \frac{k_f.\{k_f + 2k_p + 2(k_p - k_s)(1+b^3).\varphi\}}{\{k_f + 2k_p - 2(k_p - k_s)(1+b^3).\varphi\}}$$

, where k_p and k_f are thermal conductivity of nanoparticle and base fluid in this case take b=0.1.

Material	Density (g/cm³)	Specific Heat Capacity (J/g·K)	Thermal Conductivity (W/m·K)
Diamond	3.51	0.55	1750
Carbon Nanotube	1.7	1.2	4000
Graphene Oxide	1.9	0.65	100
Boron Nitride	2.7	0.7	125
Aluminium Nitride	3.3	0.75	180
Silicon Carbide	3.1	0.75	250
Copper	8.93	0.385	380
Silver	10.55	0.235	415
Zinc Oxide	5.64	0.45	30
Water	1	4.18	0.6

Table 1. Thermophysical Properties of various materials at 25 (°C)

D. Experimental setup for heat transfer performance analysis

Pipe Dimensions: *Diameter- 4.5mm, length – 600mm*

- Pump
- Flow Adjuster
- Electronic device
- Reservoir

The reservoir, where the nanofluid is kept, is the first component of the cooling system. The reservoir makes sure that there is always enough nanofluid available for cooling.

Pump: A pump is used to move the nanofluid between the pipe and the reservoir. To guarantee effective heat transfer, the pump creates the required flow rate.

Heat source: The nanofluid runs through the pipe, acting as a direct cooling path for the electrical gadget, absorbing and dispersing heat. But in this instance, the pipe itself acts as the main radiator of heat. To effectively transfer heat from the electrical device to the nanofluid, the pipe is engineered to have a high thermal conductivity. The pipe wall receives the boundary heat flux, which creates the essential heat source for the nanofluid to absorb. Due to the temperature difference, the nanofluid absorbs heat from the pipe wall as it passes through. Forced convection is used in the cooling system.

Nanofluid Cooling: The heat produced by the electronic device is absorbed by the nanofluid as it passes past the pipe.

Return to Reservoir: After it has cooled the pipe, it is returned to the reservoir. To continue cooling, the nanofluid can now be pushed back into the pipe. This closes the cooling loop.

Boundary Conditions:

Inlet: Velocity Inlet

Conditions: Velocity Magnitude: 1 m/s, Temperature: 298 K

Type: Wall

Conditions: Thermal BC Type: Heat Flux, Heat Flux: 5000 W/m^2

Wall Motion: Stationary Wall, Shear Boundary Condition: No Slip

IV. CFD Analysis

A. Overview of computational fluid dynamics (CFD)

A numerical approach called computational fluid dynamics (CFD) is used to address issues with fluid flow and heat transfer. It entails the application of computer methods to model and examine fluid flow phenomena in intricate geometries, such as velocity distribution, pressure change, and temperature distribution.

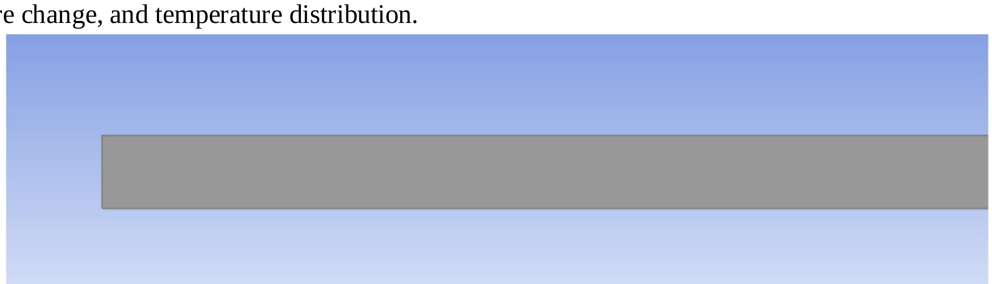

Fig 1. Model of pipe

B. Development of numerical models for nanofluid flow and heat transfer

1) The flow is laminar, steady state, and incompressible.
2) Body force's impact is disregarded.
3) Nanofluids' thermophysical characteristics never change.
a) Continuity Equation: $\nabla \cdot u = 0$
b) Navier-Stokes Equations: $\nabla \cdot (u \otimes u) = -\nabla p + \mu\nabla$^2u
c) Energy Equation: $\nabla \cdot (uH) = \nabla \cdot (k\nabla T) + Qgen$
d) Nanoparticle Volume Fraction Equation: $\nabla \cdot (up) = \nabla \cdot (Dp\nabla p) + Sp$

In these equations
u is the fluid velocity vector
p is the pressure
μ is the fluid dynamic viscosity
H is the total enthalpy of the fluid
k is the thermal conductivity of the fluid
T is the fluid temperature
Qgen is the heat generation rate (e.g., from the electronic device chip)
up is the nanoparticle velocity vector.
Dp is the diffusion coefficient of nanoparticles.
Sp is the source term related to the nanoparticle interactions.

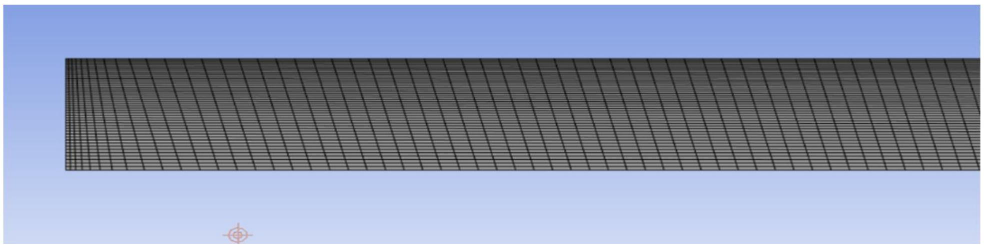

Fig 2. Meshed Model of pipe

V. RESULTS

A. *Thermophysical Properties of different nanofluids with varying vol%*

1.Diamond

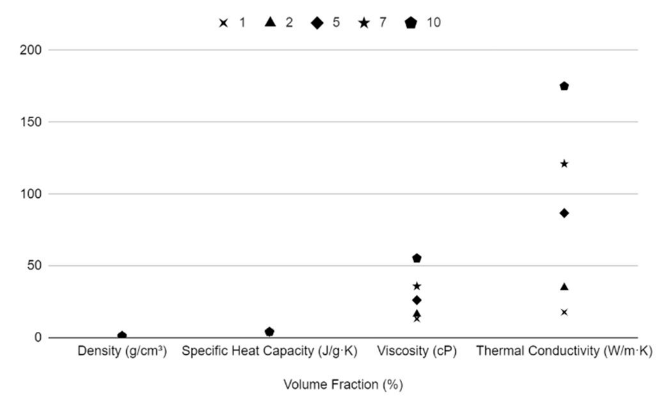

Fig 3. thermophysical properties of carbon nanotubes.

2. Carbon nanotube (multi-Walled)

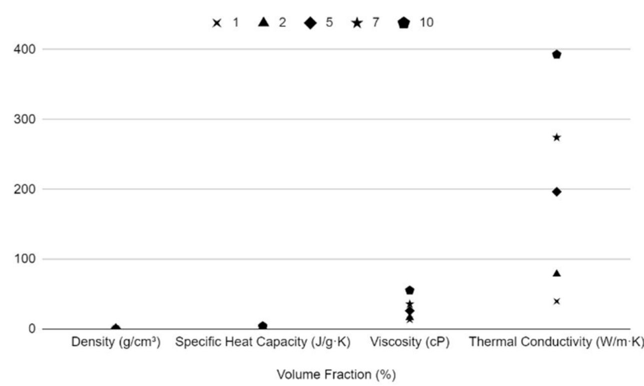

Fig 4. thermophysical properties of carbon nanotubes

3. Graphene oxide

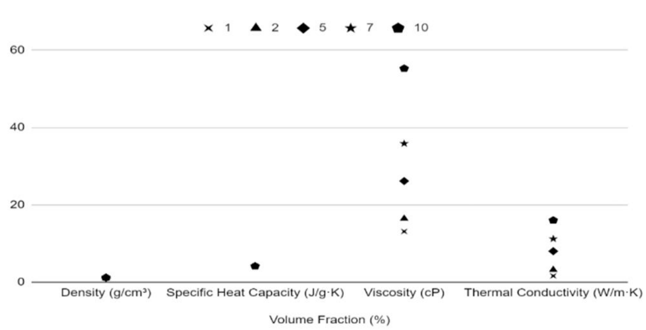

Fig 5. thermophysical properties of graphene oxide

4. Boron nitride

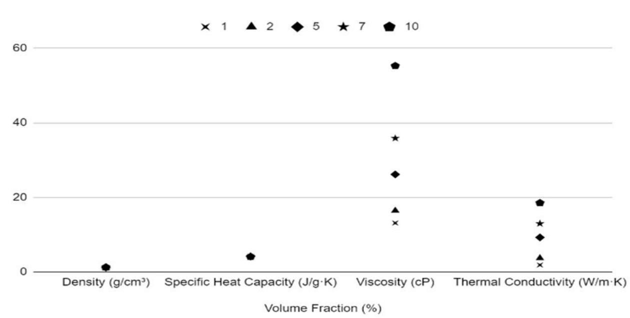

Fig 6. thermophysical properties of boron nitride

5. Aluminium nitride

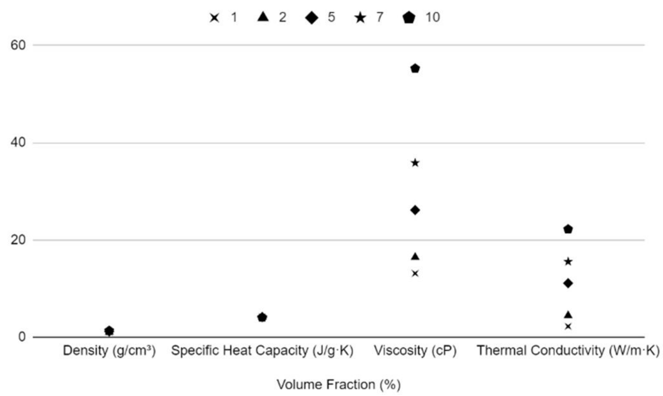

Fig 7. thermophysical properties of aluminium nitride

6. Silicon carbide

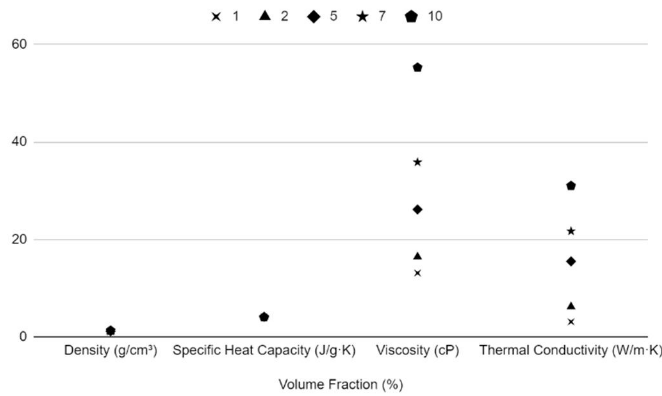

Fig 8. thermophysical properties of silicon carbide

7. Copper

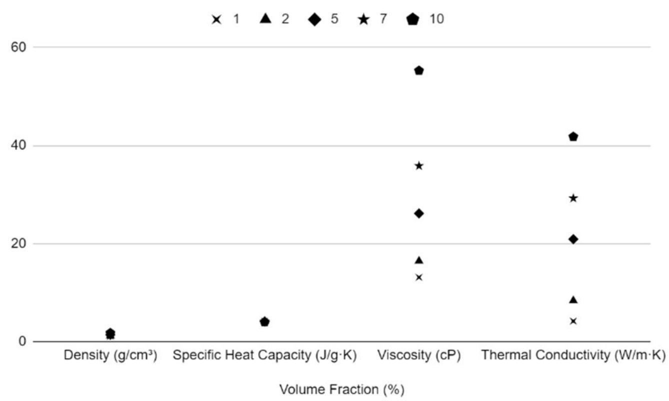

Fig 9. thermophysical properties of copper

8. Silver

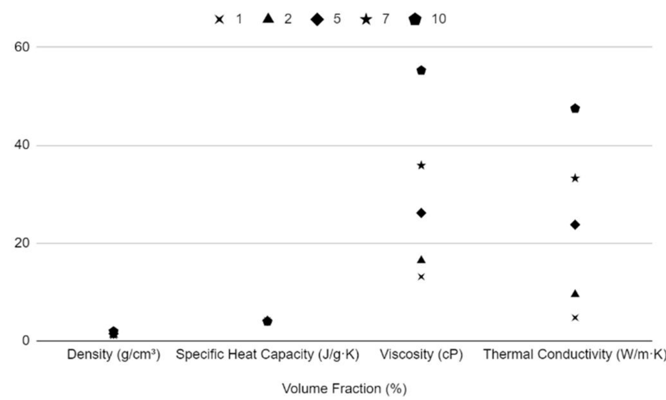

Fig 10. thermophysical properties of silver

9. Zinc oxide

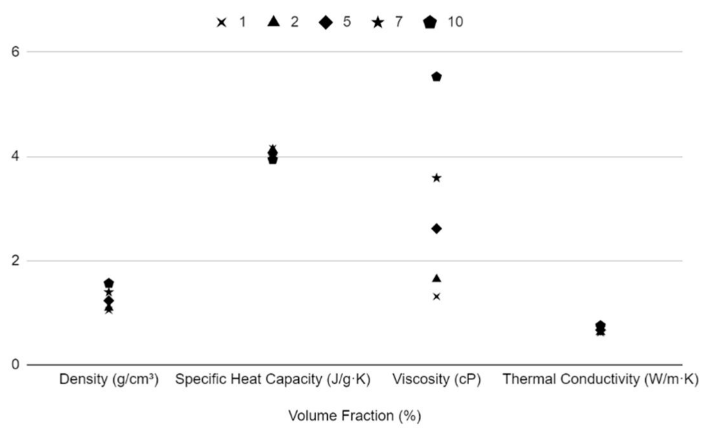

Fig 11. thermophysical properties of zinc oxide

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B. Comparison between nanofluids and Percentage of Enhancement

The enhancement (p%) depicted in density as a percentage variation in the density of the nanofluids relative to the base fluid is given by the formula $p\% = \left(\frac{p_{nf}-p_f}{p_{nf}}\right).100$, and values in the range of 0.8-49% are listed.

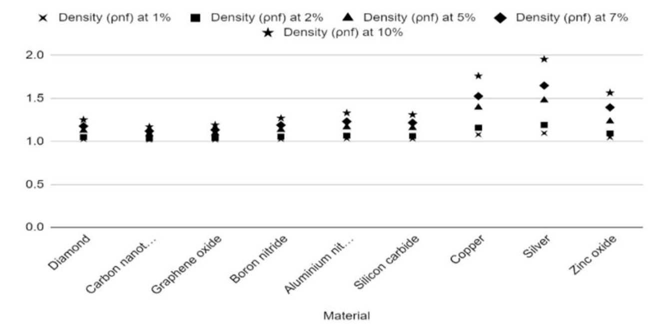

Fig 12. density of different nanofluids

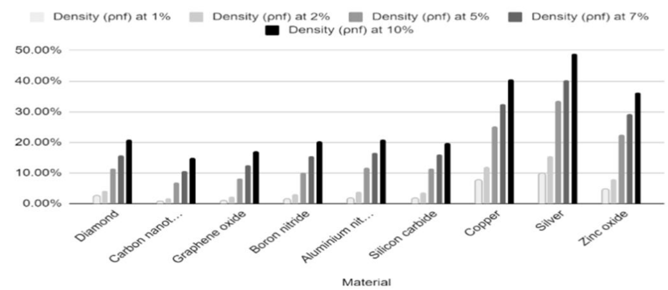

Fig 13. percentage enhancement of density of different nanofluids

The enhancement (u%) depicted in viscosity as a percentage variation in the viscosity of the nanofluids relative to the base fluid is given by the formula, $\mu\% = \left(\frac{\mu_{nf}-\mu_f}{\mu_{nf}}\right).100$, and values in the range of 1-55% are listed.

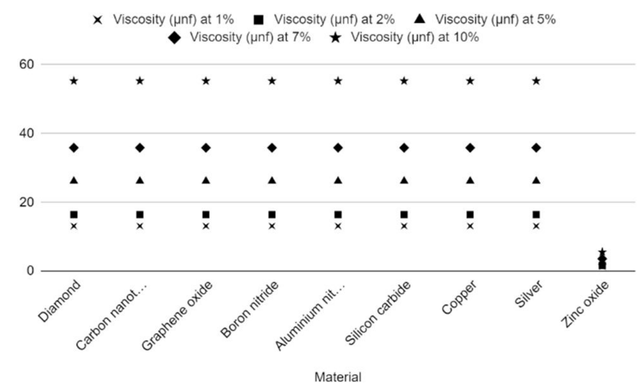

Fig 14. viscosity of different nanofluids

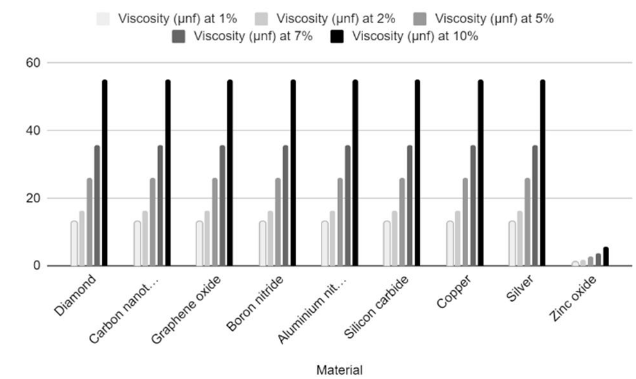

Fig 15. percentage enhancement of viscosity of different nanofluids

The enhancement (k%) depicted in thermal conductivity as a percentage variation in the thermal conductivity of the nanofluids relative to the base fluid is given by the formula, $k\% = \left(\frac{k_{nf}-k_f}{k_{nf}}\right).100$, and values in the range of 2.3-99.8% are listed.

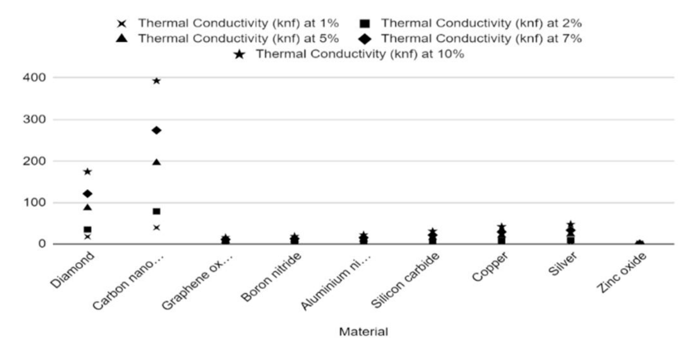

Fig 16. thermal conductivity of different nanofluids

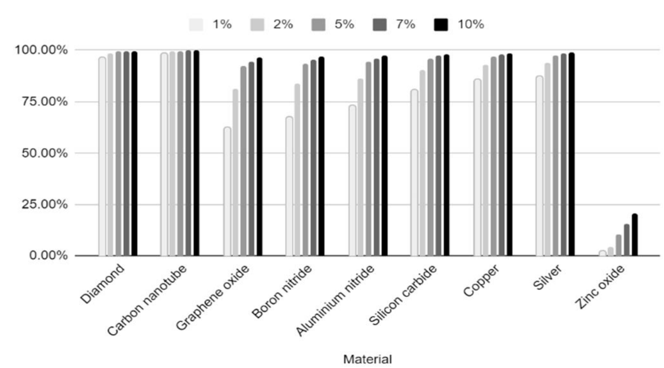

Fig 17. percentage enhancement of thermal conductivity of different nanofluids

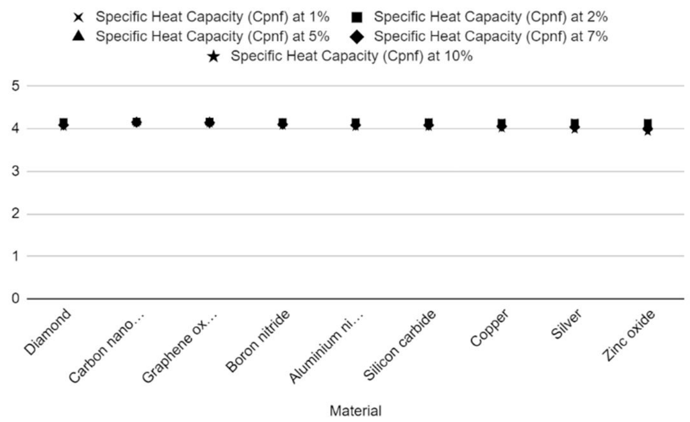

Fig 18. specific heat capacity of different nanofluids

C. *CFD analysis results*

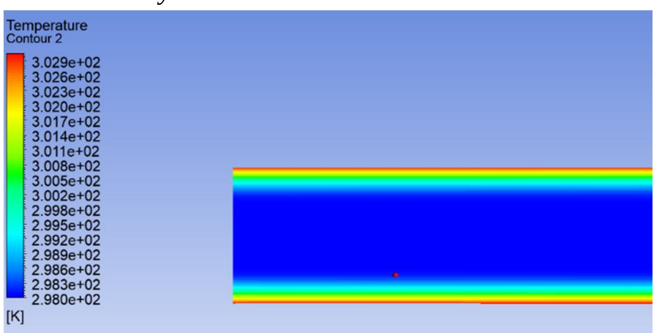

Fig 19. Skewness of model from outlet

Fig 20. Skewness of model from Inlet

Material	Outlet Temp.	Inlet Temp.	Pipe wall Temp.
Water	300.16	298.98	301.43
Diamond	300.49	298	298.5
Carbon nanotube	300.58	298	298.51
Graphene oxide	300.101	298.11	298.73
Boron nitride	300.189	298.095	298.71
Aluminium nitride	300.278	298.03	298.699
Silicon carbide	300.33	298	298.634
Copper	300.38	298	298.59
Silver	300.41	298	298.55
Zinc oxide	299.99	298.289	300.003

Table 2. 1% Vol

Material	Outlet Temp.	Inlet Temp.	Pipe wall Temp.
Water	300.16	298.98	301.43
Diamond	301.01	298	299.09
Carbon nanotube	301.23	298	299.004
Graphene oxide	300.58	298.2	299.401
Boron nitride	300.69	298.172	299.39
Aluminium nitride	300.81	298.153	299.32
Silicon carbide	300.89	298.12	299.254
Copper	300.9	298.09	299.187
Silver	300.95	298.07	299.13
Zinc oxide	300.58	298.578	299.867

Table 3. 2% Vol

Material	Outlet Temp.	Inlet Temp.	Pipe wall Temp.
Water	300.16	298.98	301.43
Diamond	303.02	298.1	300.26
Carbon nanotube	303.34	298	300.13
Graphene oxide	302.189	298.233	300.55
Boron nitride	302.254	298.228	300.49
Aluminium nitride	302.53	298.201	300.46
Silicon carbide	302.785	298.179	300.42
Copper	302.845	298.145	300.35
Silver	302.9	298.137	300.3
Zinc oxide	300.58	298.806	300.6

Table 4. 5% Vol

Material	Outlet Temp.	Inlet Temp.	Pipe wall Temp.
Water	300.16	298.98	301.43
Diamond	305.001	298.28	301.79
Carbon nanotube	305.1	298.13	301.74
Graphene oxide	303.86	298.68	301.945
Boron nitride	303.99	298.62	301.93
Aluminium nitride	304.12	298.589	301.899
Silicon carbide	304.267	298.456	301.88
Copper	304.375	298.399	301.83
Silver	304.5	298.367	301.81
Zinc oxide	301.12	298.89	300.89

Table 5. 7% Vol

Material	Outlet Temp.	Inlet Temp.	Pipe wall Temp.
Water	300.16	298.98	301.43
Diamond	307.98	298.48	303.224
Carbon nanotube	308.01	298.45	303.219
Graphene oxide	305.99	298.79	303.64
Boron nitride	306.128	298.71	303.599
Aluminium nitride	306.234	298.695	303.535
Silicon carbide	306.34	298.532	303.4124
Copper	306.57	298.509	303.389
Silver	306.87	298.49	303.265
Zinc oxide	301.57	298.99	301

Table 6. 10% Vol

With the outlet temperature representing the temperature at the fluid outlet, the inlet temperature representing the temperature at the fluid inlet, and the pipe wall temperature representing the temperature at the pipe wall, these numbers indicate the temperature distribution throughout the nanofluid.

VI. PRACTICAL IMPLICATIONS AND FUTURE DIRECTIONS

A. *Challenges and limitations of nanofluid utilization*

1) *Nanoparticle Dispersion*: It might be difficult to achieve a steady and uniform dispersion of nanoparticles in the base fluid. It is possible for nanoparticles to clump together and settle, which can cause non-uniform characteristics and poorer performance in nanofluids.
2) *Nanoparticle Sedimentation*: Because nanoparticles are much denser than the base fluid, they may eventually settle or sediment over time. As a result, the anticipated improvement in heat transfer characteristics may not be achieved.
3) *Nanoparticle Stability*: Chemical reactions or agglomeration may cause nanoparticles to vary in size, shape, and surface characteristics. The stability and long-term effectiveness of nanofluids may be impacted by this.
4) *Cost*: The creation and manufacturing of nanoparticles can be expensive, which may restrict the usage of nanofluids on a large scale. The cost of expanding the production process can also be a problem.
5) *Material compatibility*: Nanoparticles may interact with cooling system or device materials, causing corrosion or other material degradation. To prevent any negative consequences, it is essential to make sure that nanoparticles and system materials are compatible.
6) *Measurement and Characterization*: It can be difficult to quantify and characterise the characteristics of nanofluids, such as the concentration, size, and thermal conductivity, accurately. For a thorough analysis, standardised measuring procedures and trustworthy characterisation techniques are required.
7) *Safety and environmental concerns* include the possible toxicity of nanoparticles as well as how they may affect the environment. It is crucial to make sure that nanofluids are handled, disposed of, and their environmental impact is evaluated safely.
8) *Scaling Up*: It can be difficult to successfully deploy nanofluids at a larger scale, such as in industrial applications. It is necessary to consider aspects like production procedures, scalability, and economic viability.
9) *Limited Understanding*: The underlying principles driving the heat transfer increase in nanofluids are not well understood, despite intensive investigation. To fully understand how nanoparticles and the base fluid interact, more investigation is required.
10) *Application Specificity*: The best performance of nanofluids could vary depending on the application. It's possible that nanofluids that function effectively in one system or operating environment won't always perform similarly in other systems or circumstances.
11) *Extreme working circumstances*, such as high temperatures, high pressures, or hostile surroundings, can cause nanofluids to lose their stability and perform differently. It is essential to comprehend the limitations and behaviour of nanofluids under these circumstances.
12) *Uncertainty in Predictive Models*: The complexity of the interactions between nanoparticles and fluids makes it difficult to develop precise predictive models for nanofluid behaviour and performance. The accuracy of predictions can be impacted by the assumptions and model parameters that are uncertain.
13) *Limited Long-Term Stability*: Over time, some nanofluids may experience property changes or deterioration that impair their performance or make them unpredictable. To determine if nanofluids are suitable for long-term uses, studies of their stability over time are required.
14) *Energy Consumption*: The energy needed for the synthesis and dispersion of nanoparticles, as well as the extra energy required for the pumping and circulation of nanofluids, can influence the overall energy efficiency of cooling systems. It's crucial to strike a balance between energy usage and the advantages of improved heat transfer.

B. *Recommendations for the effective use of nanofluids in heat transfer applications*

1) *Enhance Heat Transfer Performance by Optimising Nanoparticle Concentration*: Conduct thorough research to identify the ideal nanoparticle concentration. The performance benefits of higher concentrations may not always outweigh the risks of increased viscosity and particle settling. It's important to strike the correct balance.
2) *Enhance Nanoparticle Dispersion*: Use efficient dispersion methods to make sure that nanoparticles are evenly distributed throughout the base fluid. To avoid nanoparticle aggregation and sedimentation, consider surface alterations or the application of surfactants.
3) *Enhance Stability*: Create plans to make nanofluids more stable over the long-term while being stored and used. To avoid agglomeration and settling, this may need the use of additives, surface treatments, or modifications to the surface chemistry of the nanoparticles.

4) *Examine the utilisation of novel nanoparticles* to investigate their improved thermophysical characteristics and stability. Look at substitute materials that have excellent thermal conductivity, good dispersibility, and little propensity to clump.
5) *Particle Size Effect*: Examine the impact of nanoparticle size on the efficiency of heat transfer. Due to their increased surface area, smaller nanoparticles may improve heat transfer, but they can also have higher viscosity and stronger agglomeration tendencies.
6) *Characterise Nanofluid Properties*: To properly forecast heat transfer performance, conduct thorough characterization of nanofluid properties, including thermal conductivity, viscosity, density, and specific heat capacity. This will aid in improving simulations and numerical models.
7) *Investigate the effects* of flow rate, flow pattern, and channel shape on the efficiency of heat transmission for nanofluids. To maximise heat transmission while reducing pressure drop, experiment with various cooling topologies, such as microchannel designs.
8) *Analyse Cost-Effectiveness*: Conduct cost-benefit analysis to see whether employing nanofluids for electronic device cooling is generally cost-effective. To evaluate the technology's economic viability, consider elements including the price of nanoparticles, synthesis techniques, system upkeep, and long-term performance.
9) *Address Material Compatibility*: Ensure that the cooling system's materials and nanofluids are compatible. To preserve the integrity and endurance of the system, consider potential corrosion problems and choose materials that are compatible with the nanofluid.
10) *Considerations for Safety and the Environment*: Thoroughly evaluate the safety of nanofluids and their potential effects on the environment and human health. Create safe handling and disposal procedures to reduce the risks of exposure to nanoparticles.

C. *Future research directions to further explore the potential of nanofluids.*

1) Investigate cutting-edge synthesis methods for nanoparticles with enhanced characteristics, such as regulated size, shape, and surface chemistry. Investigate scalable and affordable ways to generate lots of nanoparticles for useful applications.
2) To improve nanoparticle dispersion, stability, and compatibility with base fluids, investigate the impact of surface modification techniques such as functionalization and coating. Investigate techniques for surface engineering to modify the characteristics of nanoparticles for uses.
3) Investigate the usage of multi-component nanofluids by adding different kinds of nanoparticles or additives to them to produce synergistic effects on heat transfer performance. Examine how various nanoparticles behave and interact when combined in nanofluid compositions.
4) Hybrid Cooling Systems: To improve heat dissipation from electronic device chips, look at the combination of nanofluids with existing cooling technologies as heat pipes, vapour chambers, or thermoelectric coolers. Examine the beneficial interactions and potential increases in cooling effectiveness.
5) Enhanced Heat Transfer Mechanisms: Investigate the underlying processes causing the enhanced heat transfer seen in nanofluids. Investigate the roles that convection, conduction, and radiation play in the transmission of heat in nanofluids and create sophisticated models to predict their behaviour.
6) Develop sophisticated experimental procedures and characterisation techniques to precisely determine the thermophysical characteristics of nanofluids, such as their density, viscosity, thermal conductivity, and specific heat capacity. Boost the reliability and precision of your measurements.
7) Enhance numerical models and simulations to better forecast and analyse the behaviour of nanofluids in cooling applications. Computational Modelling and Simulation. To accurately depict the complicated nature of nanofluid flow and heat transfer, use cutting-edge turbulence models, particle tracking methods, and multi-phase flow simulations.
8) The best parameters for various cooling applications should be determined by examining the impact of nanoparticle size and concentration on heat transfer performance. Examine the trade-off between improved heat transmission and greater viscosity as well as size-dependent phenomena.
9) Assess the long-term stability and dependability of nanofluids under conditions of continuous operation. Examine how the accumulation, sedimentation, and fouling of nanoparticles affect the effectiveness and longevity of cooling systems.
10) Application-Specific Studies: Investigate the usage of nanofluids in different electronic devices, such as GPUs, power electronics, and LED lighting, by conducting application-specific studies. Examine the cooling efficiency, dependability, and affordability of cooling systems based on nanofluids in these applications.

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VII. CONCLUSION

The results of theoretical research offer important new understandings into the enhancements in density, viscosity, and thermal conductivity seen in nanofluids when compared to the base fluid. According to the density enhancement (p%) range of 0.8% to 49%, nanofluids typically have greater densities. The presence of nanoparticles, which add to the total mass of the fluid, is responsible for the rise in density. Depending on the kind of nanoparticles utilised, the degree of density improvement varies.

As shown by the range of viscosity enhancement (u%) values from 1% to 55%, nanofluids often have greater viscosities than the basic fluid. This is because nanoparticles increase flow resistance and viscosities by introducing new interactions and forces. Like density enhancement, the degree of viscosity augmentation varies based on the materials.

Nanofluids have thermal conductivities that are noticeably higher than the basic fluid, as indicated by thermal conductivity enhancement (k%) values between 2.3% and 99.8%. This enhancement is related to the nanoparticles' increased surface area, which enables more effective energy transmission and improves the fluid's capacity for heat transfer. Depending on the type of nanoparticles utilised, the degree of improvement in heat conductivity varies.

The computational fluid dynamics (CFD) with heat flux of 5000 w/m^2 investigation demonstrates that the outlet temperatures of nanofluids are typically higher than those of water, demonstrating their superior heat transfer performance. The greatest output temperature across all volume percentages is shown by diamond nanofluid among the materials examined, demonstrating its extraordinary improvement in heat transmission.

Nanofluids often have input temperatures that are on par with or slightly greater than those of water, demonstrating their effectiveness at collecting heat from the surrounding environment. When compared to water, nanofluids' pipe wall temperatures vary; some display lower temperatures, which indicates better heat dissipation, while others exhibit somewhat higher temperatures.

When the temperature differences between the input and output are analysed, nanofluids consistently display bigger temperature differences than water, indicating that they are more effective at transferring heat and transferring thermal energy.

Higher volume percentages often lead to higher output temperatures and wider temperature disparities, suggesting improved heat transfer performance, when comparing the various volume percentages of nanofluids. The ability of nanofluids to transport heat seems to be improved as the volume % of nanoparticles rises.

In conclusion, the data shows that under the measured conditions, the investigated nanofluids have improved heat transfer capabilities compared to water. Different materials exhibit varied degrees of improvement in heat transmission, including diamond, carbon nanotubes, graphene oxide, boron nitride, aluminium nitride, silicon carbide, copper, silver, and zinc oxide. Higher output temperatures and better heat transfer performance are typically associated with increasing the volume percentage of nanoparticles.

A. Nomenclature

□ - density[kg/m^3] □ - mass concentration

B. Subscript

k - thermal conductivity [W/m.C] P - Pressure [N/m^2]
u - velocity [m/s] □ -viscosity [N.s /m^2]
f - liquid phases p - solid particle
nf - nanofluid

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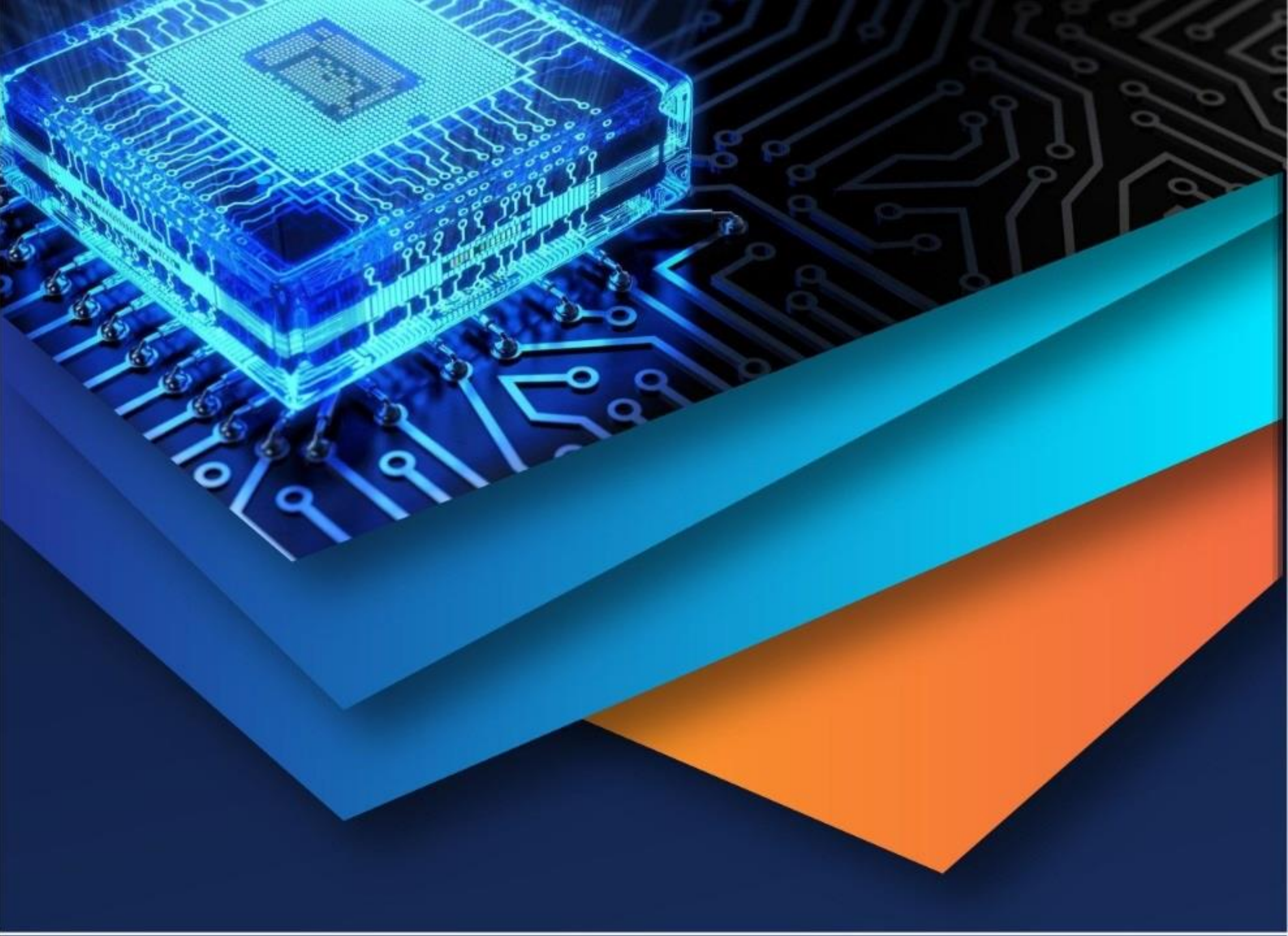

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