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Volume Fraction Effect on the Thermal Conductivity of Metals and their Oxide-Based Nanofluids: A Review

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ABSRTACT

Due to their enhanced thermal properties, nanofluids, which are colloidal suspensions of nanoparticles in a base fluid, have been gaining a lot of attention recently. The volume fraction of nanoparticles is one of the key variables influencing an upsurge in thermal conductivity of nanofluids. This review wants to deliver an in-depth review of the research on the consequences of volume fraction on the thermal conductivity of metals and the oxide-based nanofluids around them. The examination of the synthesis, characterization, and measurement of the thermal conductivity of nanofluids are addressed thoroughly in this article. It also investigates the effects of numerous variables on the impact of the volume fraction, including particle size, shape, and surface modification. The review sheds light on the problems in the area and suggests potential uses for further study.

Keywords: nanofluids, characterization techniques, thermal conductivity.

INTRODUCTION

Background

Determining how the concentration of nanoparticles in a fluid medium affects that medium's ability to conduct heat is the primary objective of research on the volume fraction effect on the thermal conductivity of metals and their oxide-based nanofluids [1]. Because it can shed light on how to create and improve nanofluids for usage in a variety of systems, including cooling systems, heat exchangers, and electrical devices, this work is crucial. The capability of a material to conduct heat can be measured by its thermal conductivity. Because of the existence of free electrons, which are readily able to transport thermal energy, metals frequently exhibit high thermal conductivity. However, the addition of nanoparticles can enhance or modify the heat conductivity of a metal or a fluid.

Colloidal suspensions of nanoparticles, usually ranging in size from one to one hundred nanometers, known as nanofluids, are disseminated in a base fluid like water, oil, or ethylene glycol. Copper, aluminium, titanium dioxide, or alumina are just a few examples of the metal or oxide-based nanoparticles that may exist. Colloidal suspensions of nanoparticles, usually one to one hundred nanometers in size, are dissolved in a base fluid, such as water, oil, or ethylene glycol.

The volume fraction of a nanofluid refers to the concentration or proportion of nanoparticles in a fluid media. It usually appears as a percentage or a fraction. The volume fraction effect on thermal conductivity is the term for the variation in the nanofluid's thermal conductivity that occurs with varied nanoparticle concentrations [2].

Experimental research has looked at how volume fraction affects the thermal conductivity of metal- and oxide-based nanofluids. These investigations often involve the synthesis of nanofluids with different nanoparticle volume fractions and the measurement of their thermal conductivities by means of techniques like the transient hot wire method, the hot plate method, or the laser flash method. The findings of these investigations could provide insight into the relationship between the volume fraction and the rise in thermal conductivity of nanofluids [1, 2].

The volume fraction influence on thermal conductivity depends on the type, size, and shape of the nanoparticles as well as on their stability and dispersion in the base fluid. The thermal conductivity can alter as the volume fraction of nanoparticles increases due to the interparticle interactions and the effective thermal pathways inside the nanofluid.

By increasing the volume percentage of nanoparticles, nanofluids often exhibit better thermal conductivity. Better phonon transport across the nanoparticle-fluid interface and greater particle-particle interaction are two of the reasons that are responsible for this improvement. However, at high volume fractions, nanoparticles may aggregate or cluster, which may result in the formation of thermal bridges, reducing thermal conductivity [3].

Volume fraction effect on the thermal conductivity of metals and their oxide-based nanofluids is a complicated phenomenon that is influenced by a wide range of variables. More study is required to better comprehend the mechanisms underlying this relationship and to develop nanofluids with superior compositions for particular uses.

In this review paper, we will present a synopsis of the published research, assess the experimental designs and methodologies, and explore the applications [6] and implications. We also note the areas of science needing more investigation.

Synthesis and Characterization of Nanofluids

The development and evaluation of nanofluids are essential steps in comprehending the impact of volume fraction on metals and the thermal conductivity of their oxide-based nanofluids. This section's primary topics revolve with developing and analyzing nanofluids containing various nanoparticle volume fractions. Below is a list of the key steps in this procedure.

Nanoparticle Selection

The first step is to select appropriate nanoparticles that will mix with the underlying fluid. Common choices include metals such as copper, aluminum, or silver, and oxide-based nanoparticles like alumina, titanium dioxide, or zinc oxide. The selection depends on factors such as thermal conductivity enhancement [8], stability, and cost.

Nanofluid Preparation

There are numerous ways to make nanofluids, such as

- one-step processes
- two-step processes.

Nanoparticles are immediately created in the base fluid during the one-step procedure. Pre-synthesized nanoparticles are disseminated in the fluid throughout the two-step procedure. Techniques like sol-gel, co-precipitation, and chemical reduction are used for nanoparticle synthesis. The dispersion can be achieved through mechanical stirring, ultrasonication, or high-shear mixing to avoid agglomeration.

Base fluid Selection

For the best result of thermal conductivity, we have to use such a base fluid which enhances the required result. Mostly water [6], oils, ethylene glycol [5] is used as a base fluid which disperses the nanoparticles uniformly throughout the fluid by different techniques.

Characterization Techniques

Beyond thermal conductivity, other relevant properties of nanofluids can be characterized. Nanoparticles are investigated using technologies like scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR), as well as their appearance, crystal structure, and chemical makeup.

Measurement Techniques for Thermal Conductivity

A few of the approaches used to measure the thermal conductivity of nano composites are listed below.

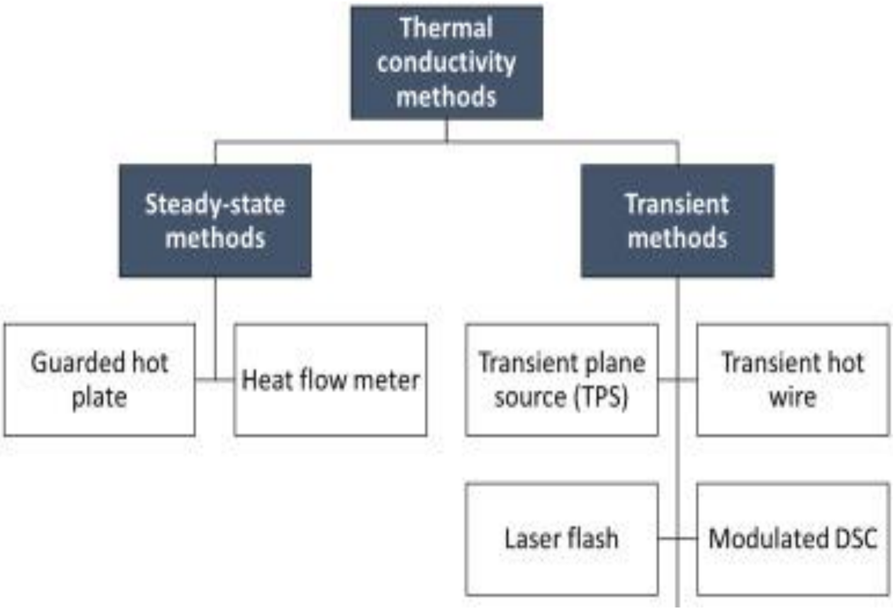

Figure 2: Methods to find thermal conductivity

Transient Hot Wire Method

A common approach for determining the thermal conductivity of fluids, including nanofluids, is the transient hot wire method.

It involves a small wire, typically made of platinum, which is heated using an electric current. The rise and decay of the wire are recorded, and the thermal conductivity is calculated based on the wire's dimensions and the response. Formula use to find thermal conductivity is

Thermal conductivity (λ) = ($Q \times l$) / ($A \times \Delta T$)

Hot Plate Method

Another frequently used method for determining the thermal conductivity of nanofluids is the hot plate method. This technique involves sandwiching a nanofluid sample between two heated surfaces. Measurements are made of the heat flow through the sample as well as the differential across it. The sample's dimensions and thermal characteristics are then used to compute the thermal conductivity. The formula to calculate thermal conductivity is

Thermal conductivity (λ) = ($Q \times d$) / ($A \times \Delta T$)

Laser Flash Method

The thermal diffusivity of materials, which can be translated to thermal conductivity, is measured using the laser flash method as a non-contact method. An infrared detector measures the increase after a laser pulse is delivered onto a thin disc-shaped sample. The response and the sample's size are examined to estimate the thermal conductivity.

Thermal diffusivity (α) = (s^2) / ($4 \times \pi^2 \times t \times \Delta T$)

Thermal conductivity (λ) = $\alpha \times \rho \times Cp$

Guarded Hot Plate Method

A steady-state approach for determining the thermal conductivity of solids and fluids is the guarded hot plate method. The sample is sandwiched between two regulated plates, one of which is heated and the other is cooled. Based on the difference, size, and rate of heat transfer through the sample, the thermal conductivity is estimated. The formula to calculate thermal conductivity is

Thermal conductivity (λ) = ($Q \times d$) / ($A \times \Delta T$)

Differential Scanning Calorimetry (DSC)

The widely used DSC method is used for an array of objectives, notably assessing thermal conductivity [4]. In DSC, as the is altered, the heat flow between a sample and a reference material is measured. The thermal conductivity can be calculated by examining the heat flow data and taking the sample geometry into account.

Comparative Methods

Comparative approaches entail contrasting a nanofluid's thermal conductivity with that of a base fluid or reference fluid. These techniques involve comparing the heat flow through the nanofluid and the reference fluid under identical circumstances while utilizing a conventional fluid as a reference. By contrasting the data, The increase in conductivity of heat put on by nanoparticles is capable of being identified.

Formula use to find thermal conductivity is

$\lambda_{nf} = \lambda_{base} + \Delta \lambda$

It's critical to keep in mind that each measurement technique has advantages and disadvantages. Since the volume fraction influence on the thermal conductivity of metals and oxide-based nanofluids needs to be examined, it is essential to use the appropriate measuring technique. Sample size, sample preparation, range, and accuracy requirements are all significant factors.

Additionally, measurement sets must be correctly calibrated and validated against well-known reference materials in order to increase the accuracy and dependability of the estimated thermal conductivity values.

Volume fraction effect on thermal conductivity by metal and their oxides

Metal Nanofluids

- **Copper (Cu)**

As the volume fraction rises, the thermal conductivity of copper nanofluids frequently increases drastically. This improvement is owing to the copper nanoparticles' outstanding heat conductivity and the base fluid's aptitude to properly scatter them.

- **Aluminum (Al)**

With increased volume fraction, aluminum nanofluids also exhibit better thermal conductivity. Due to the lesser heat conductivity of aluminum nanoparticles compared to copper, the improvement could not be as great as in copper nanofluids.

- **Silver (Ag)**

Particularly at increasing volume fractions, silver nanofluids display noticeable thermal conductivity increase. High thermal conductivity of silver nanoparticles facilitates effective heat transmission inside the nanofluid.

Oxide-Based Nanofluids

- **Alumina (Al_2O_3)**

When the volume fraction is increased, alumina-based nanofluids often show improved thermal conductivity. Better thermal conductivity is a result of alumina nanoparticles' excellent dispersion and interactions with heat carriers [6].

- **Titanium Dioxide (TiO_2)**

In TiO2 nanofluids, the volume fraction effect on thermal conductivity varies depending on the particle size and surface treatment. In general, though to a lower amount compared to metals, thermal conductivity improvement is seen with increasing volume fraction.

- **Zinc Oxide (ZnO)**

Furthermore, when the volume percentage increases, ZnO nanofluids exhibit enhanced thermal conductivity. ZnO nanoparticles enhance phonon scattering and increase the thermal conductivity of the nanofluid.

It is significant to highlight that a number of variables, including nanoparticle size, shape, surface properties, agglomeration, and interfacial resistance, might affect the volume fraction impact. The experimental setup and particular synthesis techniques used can also have an impact on the volume fraction effect. Therefore, experimental validation and thorough investigation of the nanoparticle-fluid system are essential for a precise evaluation of the volume fraction influence on thermal conductivity of metals including their oxide-based nanofluids.

Influence of Particle Size, Shape, and Surface Modification

Particle Size

- **Nanoparticle Size Distribution:** A narrower size distribution of nanoparticles in a nanofluid promotes better dispersion and enhanced thermal conductivity. Uniformly sized nanoparticles provide efficient pathways for heat transfer and minimize agglomeration or clustering.
- **Size-Dependent Thermal Conductivity:** In some cases, smaller nanoparticles exhibit higher thermal conductivities due to increased phonon scattering at the nanoparticle boundaries. This can contribute to enhanced thermal conductivity even at lower volume fractions.
- **Percolation Threshold:** The particle size distribution can influence the percolation threshold, which is the minimum volume fraction required for a significant enhancement in thermal conductivity. Smaller nanoparticles can lower the percolation threshold, resulting in improved thermal conductivity even at lower volume fractions.

Particle Shape

- **Anisotropic vs. Isotropic Shapes:** The shape of nanoparticles can affect their packing density and interparticle interactions. Anisotropic shapes, such as nanorods or nanowires, may provide enhanced thermal conductivity due to their elongated structure and improved phonon transport along the long axis.
- **Aspect Ratio:** In nanofluids containing elongated nanoparticles, such as nanorods, the aspect ratio (length-to-width ratio) can influence the volume fraction effect. Higher aspect ratios can promote efficient thermal transport and lead to greater thermal conductivity enhancements.

Surface Modification

- **Surface Coating/Functionalization:** Surface modifications of nanoparticles enhance their stability, dispersibility, and interfacial interactions within the nanofluid. Coating or functionalization with surfactants, polymers, or other surface modifiers improves particle dispersion and reduces agglomeration, resulting in enhanced thermal conductivity at higher volume fractions [7].
- **Surface Roughness:** The surface roughness of nanoparticles affects their interfacial interactions with the base fluid and other nanoparticles. Smoother surfaces promote better dispersion and reduce interfacial resistance, leading to increased thermal conductivity enhancement.

It is crucial to remember that the volume fraction effect can be system-specific and dependent on the particular metal- or oxide-based nanofluid under study. This influence can also depend on the particle size, shape, and surface modification. Understanding how these parameters interact and precisely assessing the volume fraction influence on thermal conductivity depends on experimental characterization and validation.

Challenges and Future Directions

Measurement Techniques

There is a lack of standardized measurement techniques for thermal conductivity in nanofluids. Establishing consistent and reliable experimental methods will improve the accuracy and comparability of results across different studies.

Agglomeration and Sedimentation

Nanoparticle agglomeration and sedimentation are common challenges in nanofluid research. Agglomerated nanoparticles can hinder effective heat transfer and reduce the volume fraction effect. Developing strategies to prevent agglomeration and enhance nanoparticle dispersion is crucial.

Interfacial Resistance

The volume fraction impact may be constrained by the base fluid's interfacial resistance between nanoparticles. Understanding and reducing interfacial resistance through surface modifications or interface engineering techniques will enhance thermal conductivity enhancement in nanofluids.

Stability and Long-Term Performance

Nanofluid stability is an ongoing concern, as nanoparticles can agglomerate or settle over time, leading to changes in thermal conductivity. Developing stable nanofluids with long-term performance is essential for practical applications [6].

Cost and Scalability

Cost-effective synthesis methods for producing large quantities of nanofluids with controlled properties are necessary for widespread industrial applications [6]. Scalability and cost considerations need to be addressed for practical implementation.

Optimization of Nanoparticle Properties

Tailoring nanoparticle properties, such as size, shape, and surface characteristics, to maximize the volume fraction effect on thermal conductivity is an area of active research. Understanding the relationship between nanoparticle properties and thermal conductivity enhancement will enable the design of more efficient nanofluids.

Modeling and Simulation

The volume fraction impact can be better understood and nanofluid formulations can be improved with the use of cutting-edge modelling and simulation tools. The volume fraction effect will be better understood as realistic and trustworthy models that take into account the properties of nanoparticles, their dispersion, and interfacial phenomena are developed.

Application-Specific Studies

In particular application contexts, such as heat exchangers or thermal management systems, it is essential to investigate the volume fraction effect. Investigating the volume fraction impact under practical operating settings will facilitate the creation of specialized nanofluids for specific applications.

By addressing those issues and taking new research addresses into consideration, it will be possible to gain a complete understanding of the volume fraction effect on the thermal conductivity of metals and oxide-based nanofluids. This information will aid in the creation of high-performance nanofluids for applications that improve heat transmission.

Conclusion

This in-depth review study will be very helpful for academics and professionals who wish to understand how volume fraction affects the thermal conductivity of metals and their oxide-based nanofluids. By examining the synthesis, characterization, and measurement procedures as well as the influence of particle properties, the review offers insights into how to optimize the thermal conductivity enhancement in nanofluids. Development of sophisticated nanofluid systems with improved thermal characteristics for a range of applications, including heat transfer systems, electronics cooling, and renewable energy technologies, is guided by the difficulties and future opportunities addressed in this article.

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