Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 7, S. 182-205, 6, 2023

Araştırma Makalesi

IJANSER
https://as-proceeding.com/index.php/ijanser
ISSN: 2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 7, pp. 182-205, 6, 2023

Research Article

Physical mechanisms and predictive performance of thermal conductivity models for nanofluids

Nevzat Akkurt*, Tim Shedd [2]

[1]*Department of Mechanical Engineering, Munzur University, 62000 Tunceli/Turkey*

[2]*Engineering Technologist, Office of the CTO, Dell Technologies, Austin, TX United States of America*

(nakkurt@munzur.edu.tr)

(Received: 06 July 2023, Accepted: 24 July 2023)

(5th International Conference on Applied Engineering and Natural Sciences ICAENS 2023, July 10 - 12, 2023)

ATIF/REFERENCE: Akkurt, N. & Shedd, T. (2023). Physical mechanisms and predictive performance of thermal conductivity models for nanofluids. *International Journal of Advanced Natural Sciences and Engineering Researches*, 7(6), 182-205.

Abstract- Nanofluids present a promising group of fluids comprising base fluids like water, ethylene glycol, or oil, mixed with solid particles at the nanoscale. These nanofluids exhibit exceptional physical properties that hold significant potential for revolutionizing heat transfer processes. The objective of this study is to extensively investigate the phenomenon of improved thermal conductivity in nanofluids, focusing on critical factors such as particle volume concentration, size, temperature, and base fluid characteristics. Through a meticulous comparison of experimental data and analytical thermal conductivity models, the primary aim of this research is to uncover the underlying mechanisms responsible for this transformative effect. A comprehensive analysis of existing literature reveals a lack of agreement and conflicting findings regarding the influence of particle size, shape, and surfactants on thermal conductivity in nanofluids. Building upon this knowledge gap, our investigation aims to address and reconcile the observed discrepancies through a comprehensive parametric study. This comprehensive approach not only enhances our current understanding but also holds significant potential for optimizing nanofluids in various heat exchange applications. The importance of this study extends beyond the domain of nanofluid properties. By shedding light on the intricate physical mechanisms driving the enhancement of thermal conductivity, it has the potential to redefine the limits of heat transfer capabilities. The findings of this research hold great promise for engineers, researchers, and industries looking to fully exploit the potential of nanofluids. Through its rigorous methodology and unwavering dedication to unraveling the mysteries surrounding nanofluids, this study paves the way for groundbreaking advancements in the field of heat exchange.

Keywords -Nanofluids,Thermal Conductivity Enhancement, Particle Size, Base Fluid Characteristics, Heat Transfer Process

I. INTRODUCTION

Nanofluids possess remarkable physical properties due to the suspension of nanometer-sized solid particles in base fluids like water, ethylene glycol, or oil. These fluids hold great potential for transforming heat transfer processes. The goal of this study is to gain a comprehensive understanding of how thermal conductivity is enhanced in nanofluids by examining important factors such as particle volume concentration, size, temperature, and base fluids.

The research builds upon the pioneering work of Choi et al. [1], who introduced the concept of nanofluids and highlighted their potential for improving heat transfer efficiency and reducing pumping power in heat exchangers. Lee et al. [2] further confirmed this enhancement, reporting a remarkable 20% increase in thermal conductivity at a particle volume concentration of 4 vol%.

In addition to general thermal conductivity enhancement, the study investigates the specific impact of nanoparticles like Cu and SiC on thermal conductivity. Eastman et al. [3] observed a significant 40% increase in thermal conductivity using Cu nanoparticles, while Timofeeva et al. [4] emphasized the importance of particle size and system temperature for efficient heat transfer. However, there are discrepancies among these findings that need to be addressed to establish a consensus.

The study also explores the effect of particle shape, with Murshed et al. [5] comparing the thermal conductivity enhancement of spherical and cylindrical nanoparticles. Surprisingly, their results showed a higher enhancement with cylindrical nanoparticles, challenging conventional assumptions. Furthermore, Roy et al. [11] examined the impact of particle volume concentration, temperature, and size, highlighting the potential for greater enhancement at higher temperatures and with smaller particles.

The role of particle size is also investigated, with Chopkar et al. [12] demonstrating a nonlinear increase in thermal conductivity enhancement as particle size decreases. Lin et al. [13] expanded the research to non-metal nanoparticles, specifically CuO in ethylene glycol, achieving a notable 22.4% enhancement at a volume concentration of 5 vol%, indicating the viability of non-metal nanoparticles in heat exchange applications.

Despite previous studies, a significant discrepancy remains between experimental and analytical results, necessitating a comprehensive parametric study. This research aims to bridge this gap by elucidating the physical mechanisms underlying thermal conductivity enhancement in nanofluids. The study aims to develop accurate models for predicting nanofluid behavior by providing insights into the relationships between particle properties, system parameters, and thermal conductivity.

The significance of this research lies in its potential to advance the field by providing a better understanding of the factors influencing thermal conductivity enhancement in nanofluids. The outcomes have practical implications, enabling researchers and engineers to optimize the design and performance of nanofluid-based heat transfer systems. Furthermore, addressing the discrepancies between experimental data and analytical models will establish reliable guidelines and standards for the implementation of nanofluids in real-world applications.

Ultimately, this study seeks to unlock the full potential of nanofluids, facilitating the development of more efficient heat transfer systems, reduced energy consumption, and enhanced thermal management across various industries. From electronics cooling to automotive engineering and renewable energy systems, the impact of this research extends to numerous fields, shaping a future where nanofluids revolutionize heat transfer efficiency.

II. MATERIALS AND METHOD

Existing Analytical and Empirical Thermal Conductivity Models

Maxwell [14] presented a theoretical model to estimate the thermal conductivity of solid-liquid mixtures, specifically focusing on highly diluted suspensions of spherical particles. However, it is

essential to recognize the limitations of this model, as it primarily applies to micro or millimeter-sized particles suspended in base fluids. The model specifically considers spherical-shaped nanoparticles with low particle volume concentrations and assumes no interaction between particles. Moreover, it overlooks the impact of particle size and shape, which are critical factors in accurately predicting thermal conductivity enhancement in nanofluids.

$$k_{eff} = \frac{k_p + 2 \cdot k_{bf} + 2 \cdot \left(k_p - k_{bf}\right)\phi}{k_p + 2 \cdot k_{bf} - \left(k_p - k_{bf}\right)\phi} k_{bf} \qquad (1)$$

where, k_{eff} is the thermal conductivities of the solid-liquid mixture.

The realm of nanofluid research, where nanometer-sized solid particles disperse in base fluids, presents a fascinating landscape that defies the predictions of the conventional Maxwell model. Nanofluids exhibit unique physical properties at the nanoscale, characterized by particle-particle interactions, significant interfacial phenomena between particles and the fluid, and a remarkable surface-to-volume ratio. These factors play pivotal roles in governing the thermal conductivity enhancement observed in nanofluids.

To transcend the limitations of the Maxwell model and gain a more accurate understanding of the thermal conductivity enhancement in nanofluids, it is essential to explore alternative models that account for nanoparticle size, shape, and interparticle interactions. Such advancements in modeling hold the promise of improved predictions regarding thermal conductivity behavior, ultimately aiding in the optimization and design of heat transfer systems utilizing nanofluids.

In this context, Bruggeman [15] introduced an integration scheme that incorporates the concentration of dispersed particles surrounding a specific particle. Unlike the Maxwell model, which assumes a highly diluted suspension, the Bruggeman model proves applicable for higher volume concentrations of spherical particles. By considering the gradual increase in particle concentration through infinitesimal additions of the dispersed component, this model provides a more accurate representation of the complex dynamics at play in nanofluids.

$$\phi\left(\frac{k_p - k_{eff}}{k_p + 2k_{eff}}\right) + (1-\phi)\left(\frac{k_{bf} - k_{eff}}{k_{bf} + 2k_{eff}}\right) = 0 \qquad (2)$$

The Bruggeman model offers a valuable approach to estimating the thermal conductivity of solid-liquid mixtures with higher volume fractions of particles. By taking into account the concentration of neighboring particles, this model considers the collective influence of particle interactions on the thermal behavior of nanofluids. It is worth noting that at low volume fractions, the Bruggeman model yields results that are similar to those obtained from the Maxwell model, indicating a convergence between the two models under certain conditions.

To further enhance our understanding of the thermal conductivity enhancement in nanofluids, we will investigate the deviations between the Bruggeman and Maxwell models at different particle concentrations and explore the factors that contribute to these deviations. By gaining insights into the conditions where each model is most applicable, we can refine our comprehension of the underlying mechanisms driving the thermal conductivity enhancement in nanofluids.

In addition to the Bruggeman model, Hamilton and Crosser [16] expanded upon the Maxwell model by considering the influence of particle shape on the thermal conductivity of two-component mixtures. Their modified model incorporated the thermal conductivities of both the solid and liquid phases, the volume concentration of particles, and the specific particle shape. Their focus was on non-spherical particles, and they developed an equation to estimate the thermal conductivity of suspensions containing such particles.

.For a thermal conductivity ratio of two phases larger than 100, $(\frac{k_p}{k_f} > 100)$ the thermal conductivity

of one nanoparticle and one base fluid suspension can be expressed as follow:

$$k_{eff} = \frac{k_p + (n-1)k_{bf} + (n-1)\left(k_p - k_{bf}\right)\phi}{k_p + (n-1)k_{bf} - \left(k_p - k_{bf}\right)\phi} k_{bf} \qquad (3)$$

where n is the empirical shape factor and it is defined as:

$$n = \frac{3}{\psi} \qquad (4)$$

Ψ is the sphericity of the particle. It can be defined as the ratio of the surface area of a sphere with a volume equal to that of the particle, to the surface area of the particle. Thus, n = 3 for spheres, which reduces Eq. (3) to Maxwell's equation for spherical particles (sphericity $\psi = 1$)

The existing thermal conductivity models, such as Maxwell, Hamilton-Crosser, and Bruggeman, were primarily developed for solid-liquid mixtures containing larger-sized particles in the millimeter to micro-meter range. However, when it comes to nanofluids, which involve suspensions of nanometer-sized particles, these models fall short in accurately predicting the thermal conductivity behavior. Recognizing this limitation, extensive research efforts have been dedicated to developing new theoretical models specifically tailored for nanofluids. These models aim to provide more precise estimations by considering the unique characteristics and behaviors exhibited by nanoparticles at the nanoscale.

In the pursuit of better understanding and predicting the thermal conductivity enhancement in nanofluids, numerous theoretical models have emerged in the literature. These models take into account various parameters, including particle size, concentration, shape, interfacial effects, and agglomeration phenomena. By incorporating these factors, the new models strive to capture the complex interactions occurring within nanofluids and their profound influence on thermal conductivity.

One noteworthy contribution in nanofluid thermal conductivity modeling is the work of Xuan et al. [17]. They developed a theoretical framework that integrates the effects of Brownian motion and nanoparticle aggregation. Their model accounts for the random motion of nanoparticles, driven by Brownian motion, as well as the process of diffusion-limited aggregation, which plays a vital role in the behavior of nanofluids. By combining concepts from the theory of Brownian motion and the diffusion-limited aggregation model, Xuan et al. aimed to capture the intricate dynamics of nanoparticle dispersion and clustering within nanofluids. These phenomena are particularly significant in nanofluids due to the small size of nanoparticles and their propensity to form agglomerates or clusters.

$$k_{nf} = \frac{k_p + 2k_{bf} + 2\left(k_p - k_{bf}\right)\phi}{k_p + 2k_{bf} - \left(k_p - k_{bf}\right)\phi} k_{bf} + \frac{\rho_p C_{p,p}\phi}{2k_{bf}} \sqrt{\frac{\kappa T}{3\pi\mu_{eff} r_c}} \qquad (5)$$

In Xuan et al.'s model, they introduced the mean radius of gyration of the cluster, denoted as , r_c and the effective viscosity of the nanofluid, denoted as μ_{eff} . These parameters were used in their equation to describe the behavior of nanofluids. However, it should be noted that their explanation of determining the effective viscosity for nanofluids other than Cu-water nanofluids was not explicitly provided in their work. Upon analyzing Equation (5) in their model, it becomes apparent that the second term in the equation does not possess the units of thermal conductivity, (W/m K). This lack of dimensional consistency is a concern as it affects the overall validity and applicability of the equation. To rectify this issue and ensure dimensional homogeneity, a unit of thermal conductivity, $(\mathrm{m}/\sqrt{s})$, should be assigned to the right-hand side of the second term. This adjustment would render the entire term consistent with the units of thermal conductivity.

Chebbi [18] employed the Einstein-Smolukovski and Stokes-Einstein equations [19] to develop a revised model for the thermal conductivity of

nanofluids. In Equation (6), the revised model was presented, indicating that the Brownian motion of the nanoparticles does not play a significant role in explaining the mechanism behind the thermal conductivity enhancement of nanofluids. Additionally, the model suggests that the clustering effect of nanoparticles has minimal impact on the thermal conductivity of nanofluids. However, it should be noted that the analysis presented in the study may not fully account for the influence of clustering on the observed enhancements of thermal conductivity in nanofluids. While the revised model provides insights into the behavior of nanofluids, it may not capture the complete picture regarding the effect of clustering.

The revised model, expressed as follows [18]:

$$k_{nf} = \frac{k_p + 2k_{bf} + 2\left(k_p - k_{bf}\right)\phi}{k_p + 2k_{bf} - \left(k_p - k_{bf}\right)\phi} k_{bf} + \rho_p C_{p,p} \phi \frac{\kappa T}{6\pi \mu_{eff} r_c} \quad (6)$$

In their study, Vajjha and Das [20] aimed to enhance the existing model proposed by Koo and Kleinstreuer [21] through experimental investigations. The original model by Koo and Kleinstreuer incorporated 133 data points obtained from three specific nanofluids. However, Vajjha and Das focused solely on developing new empirical correlations for a specific type of nanofluid, such as , without modifying the thermal conductivity model derived by Koo and Kleinstreuer. Their objective was to improve the accuracy and applicability of the correlations for this specific nanofluid, rather than modifying the overall thermal conductivity model proposed by Koo and Kleinstreuer.

The efforts of Vajjha and Das were primarily directed towards refining the understanding and predictive capability of the thermal conductivity behavior for this particular nanofluid. They sought to enhance the accuracy of predicting thermal conductivity within the scope of their experimental data by developing empirical correlations specific to the nanofluid they investigated. These correlations could provide improved estimations of thermal conductivity for that particular nanofluid.

However, it is important to note that the contributions of Vajjha and Das's study are limited to the specific nanofluid they examined, and the empirical correlations they developed may not be directly applicable to other nanofluids. Further research and analysis are necessary to explore the generalizability of these correlations to different nanofluids and to assess their compatibility with the broader thermal conductivity models available in the field.

In summary, Vajjha and Das's study focused on enhancing the accuracy of thermal conductivity predictions for a specific nanofluid through the development of empirical correlations. While their work contributes to the understanding of thermal conductivity behavior in that particular nanofluid, additional research is needed to evaluate the broader applicability of their correlations and their compatibility with other thermal conductivity models.

Table 1. Curve-fit relations proposed by Vajjha and Das [18]

Type of Nanoparticles Concentration	β Temperature
Al_2O_3 $1\% \le \phi \le 10\%$	$\beta = 8.4407(100\phi)^{-1.07304}$ 298 K ≤ T ≤ 363 K
ZnO $1\% \le \phi \le 7\%$	$\beta = 8.4407(100\phi)^{-1.07304}$ 298 K ≤ T ≤ 363 K
CuO $1\% \le \phi \le 6\%$	$\beta = 9.881(100\phi)^{-0.9446}$ 298 K ≤ T ≤ 363 K

$$k_{nf} = \left[\frac{k_p + 2k_{bf} - 2(k_{bf} - k_p)\phi}{k_p + 2k_{bf} + (k_{bf} - k_p)\phi}\right] k_{bf} + 5x10^4 \beta\phi\rho_f C_{p,bf} x \sqrt{\frac{\kappa(T+273.15)}{\rho_p d_p}} f(T,\phi) \quad (7)$$

$$f(T,\phi) = (2.8217x10^{-2}\phi + 3.917x10^{-3})\frac{(T+273.15)}{(T_o+273.15)} + (-3.0669x10^{-2}\phi - 3.91123x10^{-3})$$

Khanafer and Vafai [22] presented a more recent study for thermal conductivity of nanofluids, which applies to of Al_2O_3 and CuO nanofluids. They derived a statistical correlation without considering physical enhancement mechanisms for the effective thermal conductivity of Al_2O_3-water and CuO-water nanofluids at ambient temperature using a linear form of the most important variables, volume

concentrations nanoparticle diameters based on the available experimental data in the literature. Their model can be expressed as:

$$\frac{k_{nf}}{k_{bf}} = 1.0 + 1.0112\phi_p + 2.4375\phi_p\left(\frac{47}{d_p(nm)}\right) - 0.0248\phi_p\left(\frac{k_p}{0.613}\right) \quad (8)$$

where k_{bf} is the thermal conductivity of water. One significant drawback of the correlation developed by Khanafer and Vafai [22] is the adverse effect of the thermal conductivity of the nanoparticles on the overall conductivity of the suspension. This is indicated by the negative correlation coefficient (-0.0248), which suggests a decrease in thermal conductivity with increasing nanoparticle thermal conductivity. It raises concerns about the accurate determination of nanoparticle size, especially for non-spherical nanoparticles like Al_2O_3 and CuO. Furthermore, the determination of nanoparticle size for non-spherical nanoparticles is not explicitly addressed in the information provided. This lack of clarity regarding the characterization of nanoparticle size for non-spherical shapes may introduce uncertainties in the applicability and accuracy of the correlation.

In addition, they also developed a general correlation for Al_2O_3-water, which accounts for nanoparticle's diameter, volume concentration, dynamic viscosity of water, effective dynamic viscosity of the nanofluid, and temperature as follows:

$$\frac{k_{nf}}{k_{bf}} = 0.9843 + 0.398\phi_p^{0.7383}\left(\frac{1}{d_p(nm)}\right)^{0.2246}\left(\frac{\mu_{eff}(T)}{\mu_{bf}(T)}\right)^{0.0235} - 3.9517\frac{\phi_p}{T} + 34.034\frac{\phi_p^2}{T^3} + 32.509\frac{\phi_p}{T^2} \quad (9)$$

$$0 \le \phi_p \le 10\%,\ 11\ \text{nm} \le d_p \le 150\ \text{nm},\ 20\ ^oC \le T \le 70\ ^oC$$

where the dynamic viscosity (Pa s) of water (μ_{bf}) and nanofluid (μ_{eff}) at different temperatures can be described as:

$$\mu_{bf}(T) = 2.414\times10^{-5}\times10^{247.8/(T-140)} \quad (10)$$

$$\mu_{eff} = -0.4491 + \frac{28.837}{T} + 0.574\phi_p - 0.1634\phi_p^2 + 23.053\frac{\phi_p^2}{T^2} + 0.0132\phi_p^3 - 2354.735\frac{\phi_p}{T^3} + 23.498\frac{\phi_p^2}{d_p^2} - 3.0185\frac{\phi_p^3}{d_p^2}$$

$$1\% \le \phi_p \le 10\%,\ 13\ \text{nm} \le d_p \le 131\ \text{nm},\ 20\ ^oC \le T \le 70\ ^oC$$

In the research conducted by M. Corcione [23], novel empirical correlations were introduced to estimate the effective thermal conductivity and dynamic viscosity of nanofluids. These correlations were formulated by analyzing numerous experimental datasets gathered from existing literature. By employing regression analysis techniques, a robust average empirical correlation was derived, demonstrating a remarkably low standard deviation of error (1.86%). The resulting correlation can be expressed as follows:

$$\frac{k_{nf}}{k_{bf}} = 1 + 4.4\,\mathrm{Re}^{0.4}\,\mathrm{Pr}^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_{bf}}\right)^{0.03}\phi^{0.66} \quad (11)$$

Where Re is the nanoparticle Reynolds number, Pr is the Prandtl number of the base liquid, T is the nanofluid temperature, T_{fr} is the freezing point of the base fluid. Furthermore, the nanoparticle Reynolds number and the Prandtl number for the base fluid are expressed as:

$$\mathrm{Re} = \frac{\rho_{bf}\kappa T}{3\pi\mu_{bf}^2 l_{bf}} \quad \text{and} \quad \mathrm{Pr} = \frac{c_{p,bf}\mu_{bf}}{k_{bf}} \quad (12)$$

The empirical correlation proposed by M. Corcione [23] was specifically developed for nanofluids composed of alumina, copper oxide, titania, and copper nanoparticles. These nanoparticles have diameters ranging from 10 nm to 150 nm. The nanofluids are suspended in either water or ethylene glycol base fluids. The correlation takes into account a range of nanoparticle volume concentrations, which typically vary from $0.2\% < \phi < 9\%$. The temperature conditions considered in the correlation analysis fall within the range of 294 K and 324 K.

It is important to note that the correlation is applicable to nanofluids consisting of these specific types of nanoparticles and base fluids within the given ranges. For nanofluids comprising different nanoparticles or base fluids, or outside the specified diameter and volume concentration ranges, the correlation may not accurately predict the effective thermal conductivity and dynamic viscosity.

This empirical correlation provides a useful tool for estimating the thermal conductivity and dynamic viscosity of nanofluids containing the mentioned nanoparticles in water or ethylene glycol. It enables researchers and engineers to gain insights into the

thermal behavior of these nanofluids under various temperature and volume concentration conditions, aiding in the design and optimization of nanofluid-based systems and applications.

In their study, Xie et al. [24] put forward the hypothesis that interfacial structures formed by the layering of liquid molecules could significantly influence the effective thermal conductivity of nanofluids. To explore this phenomenon, they developed an analytical model that incorporates the effects of various factors, including nanolayer thickness, nanoparticle size, volume concentration, and the thermal conductivity ratio between the particles and the fluid. The analytical model proposed by Xie et al. successfully captured the observed trends in experimental data and demonstrated good agreement between the predicted and measured thermal conductivities of nanofluids. The model is expressed as follows:

$$\frac{k_{nf}}{k_{bf}} = 1 + 3\theta\phi_T + \frac{3\theta^2\phi_T^2}{1-\theta\phi_T}$$

$$\theta = \frac{\left(\frac{k_{lr}-k_{bf}}{k_{lr}+2k_{bf}}\right)\left[\left(1+\frac{t}{r_p}\right)^3 - \frac{\left(\frac{k_p-k_{lr}}{k_p+2k_{lr}}\right)}{\left(\frac{k_{bf}-k_{lr}}{k_{bf}+2k_{lr}}\right)}\right]}{\left(1+\frac{t}{r_p}\right)^3 + 2\left(\frac{k_{lr}-k_{bf}}{k_{lr}+2k_{bf}}\right)\left(\frac{k_p-k_{lr}}{k_p+2k_{lr}}\right)}$$

$$\phi_T = \phi\left(1+\frac{t}{r_p}\right)^3 \qquad (13)$$

Where ϕ_T is the total volume concentration of nanoparticles and nanolayers.

This equation provides a quantitative description of the effective thermal conductivity of nanofluids, taking into account the interfacial structures formed by liquid molecule layering. By considering the relevant parameters, such as nanolayer thickness, nanoparticle size, volume concentration, and thermal conductivity ratio, the model offers insights into the underlying mechanisms influencing thermal conductivity enhancement in nanofluids.

In more detail, k_{lr} is the thermal conductivity of the nanolayer that is expressed as follow:

$$k_{lr} = \frac{k_{bf}\left[\frac{k_p}{k_{bf}}\left(1+\frac{t}{r_p}\right)-1\right]^2}{\left\{\left[\frac{k_p}{k_{bf}}\left(1+\frac{t}{r_p}\right)-1\right]-\frac{t}{r_p}\right\}\ln\left\{1+\left[\frac{k_p}{k_{bf}}\left(1+\frac{t}{r_p}\right)-1\right]\right\}+\frac{t}{r_p}\left[\frac{k_p}{k_{bf}}\left(1+\frac{t}{r_p}\right)-1\right]} \qquad (14)$$

The calculation of nanolayer thickness in nanofluids currently lacks an established methodology. As a result, researchers have typically relied on assuming a layer thickness that aligns with experimental observations. In light of this, Chao et al. [25] have developed a semi-analytical model to estimate the enhanced thermal conductivity of nanofluids, incorporating the influences of nanoparticle size, interfacial nanolayer thickness, and particle volume concentration.

Chao et al. [25] model offers a significant advancement by considering the effect of interfacial nanolayer thickness, which plays a crucial role in the overall thermal conductivity of nanofluids. By taking into account factors such as nanoparticle size and particle volume concentration, the model allows for the estimation of the nanolayer thickness, which is not considered a constant value but exhibits variations dependent on nanoparticle size.

The proposed semi-analytical model, expressed as Eq.(15), was developed through a combination of the presented model and available experimental data. The model provides a technique to estimate the nanolayer thickness, offering valuable insights into understanding and predicting the thermal conductivity enhancement observed in nanofluids.

It is important to note that the nanolayer thickness is not universally fixed but varies depending on the specific type of nanofluid being considered. This variation can be characterized using the correlation provided in [23].

$$\frac{t}{r_p} = D_1 r_p^{-D_2} \qquad (15)$$

where t is the thickness of the nanolayer and r_p is the radius of the nanoparticle. The parameters of D_1 and D_2 are explained in Table 2.

Chon et al. [26] conducted a study aimed at determining the thermal conductivity of nanofluids by considering the influence of nanoparticle size and temperature. The research covered a wide range of nanoparticle sizes, varying from 11 nm to 150 nm nominal diameters, and temperatures spanning a broad spectrum. (from $21^{o}\mathrm{C}$ to $71^{o}\mathrm{C}$).

To establish the empirical correlation, the Buckingham-Pi theorem was employed in conjunction with a linear regression scheme. Through their analysis, the researchers concluded that the Brownian motion exhibited by the suspended nanoparticles plays a predominant role in influencing the thermal conductivity of nanofluids, surpassing the significance of other mechanisms. The correlation is given as:

$$\frac{k_{nf}}{k_{bf}} = 1 + 64.7\phi^{0.7460}\left(\frac{d_{bf}}{d_p}\right)^{0.3690}\left(\frac{k_p}{k_{bf}}\right)^{0.7476} \mathrm{Pr}^{0.9955}\,\mathrm{Re}^{1.2321} \quad (16)$$

Where d_{bf} is the molecular diameter of the base fluid; $\mathrm{Pr}=\frac{c_{p,bf}\,\mu_{bf}}{k_{bf}}$ is the Prandtl number of the base fluid and $\mathrm{Re}=\frac{\rho_{bf}\,\kappa T}{3\pi\mu_{bf}^2 l_{bf}}$ is the Reynolds number; l_{bf} is the mean-free path for the base fluid.

In their study, Chon et al. [26] employed a constant value of 0.17 nm for the mean free path of water throughout the range of temperatures investigated. It is important to note that this choice of constant value is specific to their analysis and may not necessarily account for variations in the mean free path at different temperatures.

The empirical correlation proposed by Chon et al. is primarily based on a statistical analysis approach. While this approach provides a useful tool for predicting the thermal conductivity of nanofluids, it is important to acknowledge that it does not explicitly incorporate or address other potential enhancement mechanisms influencing the thermal conductivity behavior of nanofluids. The thermal conductivity enhancement observed in nanofluids is a complex phenomenon, influenced by multiple factors such as nanoparticle size, concentration, and interfacial effects. While the Brownian motion of nanoparticles is identified as a significant mechanism in the studied correlation, it is essential to consider that other mechanisms, such as particle clustering, interfacial layering, and nanoparticle-fluid interactions, may also contribute to the overall enhancement.

Therefore, while the empirical correlation proposed by Chon et al. provides valuable insights into the thermal conductivity of nanofluids, it is important to recognize that further research and analysis are required to fully understand and account for all the underlying mechanisms responsible for the thermal conductivity enhancement observed in nanofluids.

In this study, the thermophysical properties of water and the Ethylene glycol: Water (EG: W) mixture were obtained from the ASHRAE handbook [27]. The data obtained from the handbook was further analyzed and fitted to mathematical equations to describe their temperature dependence. The following equations [28] were used for curve fitting:

-Thermophysical properties of water

$$\rho_{bf} = -0.0036T^2 + 1.9159T + 748.19 \quad (17)$$

$$c_{p,bf} = -0.00\times01T^3 + 0.1155T^2 - 41.296T + 9017.8 \quad (18)$$

$$k_{bf} = -8\times10^{-6}T^2 + 0.0062T - 0.5388 \quad (19)$$

$$\mu_{bf} = 0.00002414\times10^{(247.8/T-140)} \quad (20)$$

Thermophysical properties of EG: W

$$\rho_{bf} = -0.002475T^2 + 0.9998T + 1002.5 \quad (21)$$

$$c_{p,bf} = 4.248T + 1882.4 \quad (22)$$

$$k_{bf} = -3.196\times10^{-6}T^2 + 0.0025T - 0.1054 \quad (23)$$

$$\mu_{bf} = 0.001\times\exp\left(3135.6\times\frac{1}{T} - 8.9367\right) \quad (24)$$

To determine the viscosity of Al_2O_3-Water and Al_2O_3-60:40 EG/W nanofluids, Vajjha et al.'s [29] model has been implemented with two parameters A and B, which are determined based on the experimental data of Kim et al. [28].

$$\mu_{eff} = \mu_{bf}(T) A \exp(B\phi) \quad (25)$$

This correlation can be applied for $20\ ^{\circ}\mathrm{C} \le \mathrm{T} \le 90\ ^{\circ}\mathrm{C}$ and $1\% \le \phi \le 10\%$ with A = 0.9 and B = 10.0359.

For the viscosity of the CuO-water and CuO-60:40 EG/W nanofluids, Eq. (25) is also employed, while constants $A = 0.9197$ and $B = 22.8536$ are obtained following Vajjha et al. [29]

To determine the effective viscosity of TiO_2-water and ZnO-60:40 EG/Water nanofluids, Corcione [23] empirical correlation with a 1.84 % standard deviation error was employed as expressed follow:

$$\frac{\mu_{eff}}{\mu_{bf}} = \frac{1}{1 - 34.87\left(\frac{d_p}{d_{bf}}\right)^{-0.3} \phi^{1.03}} \quad (26)$$

where d_{bf} is the equivalent diameter of a base fluid molecule that is given by

$$d_{bf} = 0.1\left(\frac{6M}{N\pi\rho_{bf0}}\right) \quad (27)$$

Where M is the molecular weight of the base fluid is, N is the Avogadro number, and ρ_{bf0} is the mass density of the base fluid calculated at temperature $T_o = 293$ K.

III. RESULTS

This study explores the effects of key parameters, namely particle volume concentration, temperature, and base fluid, on the effective thermal conductivity of nanofluids. The significant impact of these parameters on nanofluid behavior has motivated the development of numerous thermal conductivity models. However, to date, no single model has adequately captured the experimental thermal conductivity enhancement observed in nanofluids. Hence, this study focuses on comparing existing thermal conductivity models with available experimental data to identify the most suitable correlations, which are crucial for industrial heat transfer applications.

To bridge the gap between analytical predictions and experimental findings, a comprehensive parametric study is conducted to elucidate the individual contributions of each parameter to the thermal conductivity of nanofluids. By employing state-of-the-art thermal conductivity models, the effects of particle volume concentration, temperature, and base fluid are thoroughly examined to provide insights into the underlying physical mechanisms responsible for the observed thermal conductivity improvements in nanofluids.

This investigation not only advances our fundamental understanding of nanofluid behavior but also offers practical implications for various heat transfer systems. The findings contribute to the development of more accurate and reliable thermal conductivity models, enabling improved design and optimization of nanofluid-based heat transfer applications in industrial settings.

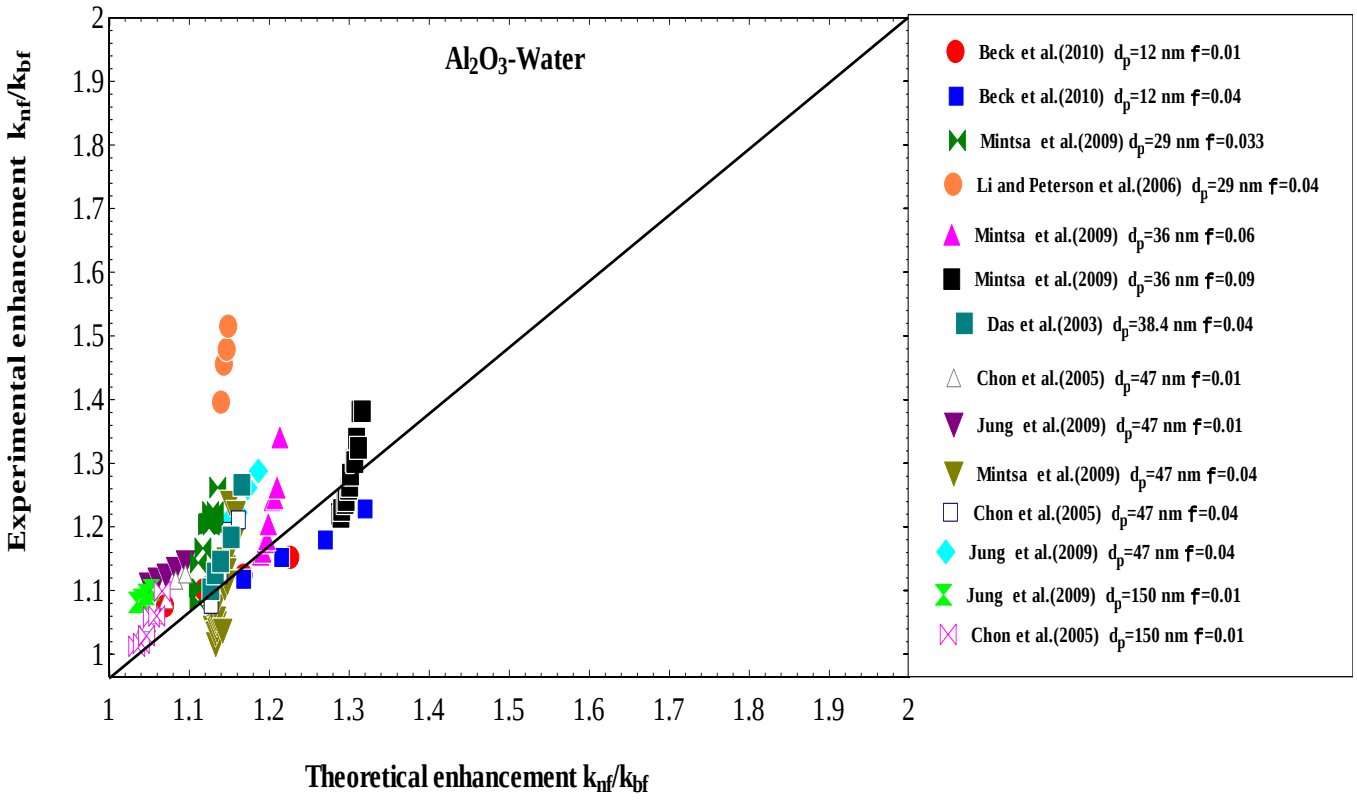

Fig. 1 Comparison of the thermal conductivity ratio calculated from the (Eq. (7)) with the values obtained from the available experimental data on Al_2O_3-Water nanofluid as a function of particle volume concentration.

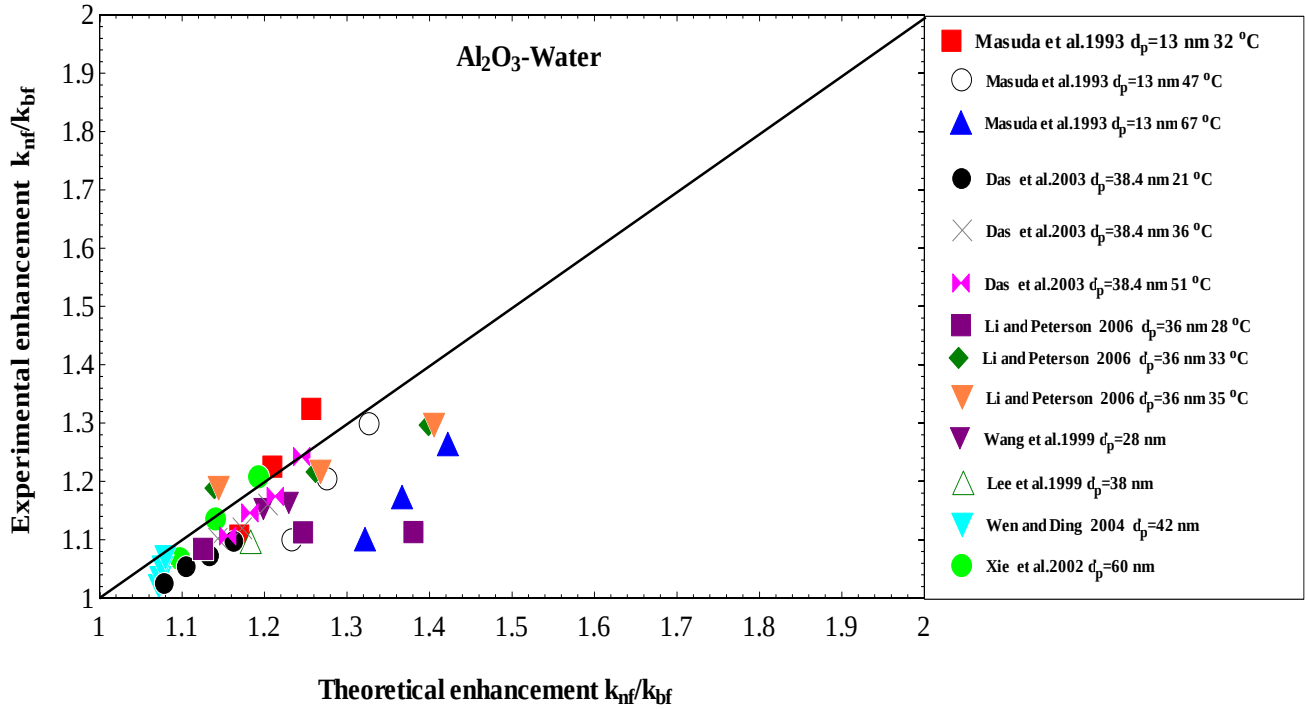

Fig. 2 Comparison of the thermal conductivity ratio calculated from the (Eq. (7)) with the values obtained from the available experimental data on Al_2O_3-Water nanofluid as a function of temperature.

The thermal conductivity models for nanofluids have been a subject of extensive research to accurately predict the thermal conductivity enhancement in these complex systems. However, despite the numerous models proposed, none have been able to fully capture the experimental thermal conductivity data of nanofluids. This discrepancy between theory and experiment necessitates a critical evaluation of existing models and the development of improved correlations that are crucial for industrial heat transfer applications.

Among the existing models, the Koo and Kleinstreuer model stands out as it considers the significance of Brownian motion at higher temperatures, which has been experimentally observed. Nevertheless, its applicability is limited by the empirical function that relates temperature and particle volume concentration. As temperature and volume concentration increase, the deviation between experimental data and the Koo and Kleinstreuer model becomes more pronounced. This can be attributed to intensified interparticle interactions and accelerated agglomeration phenomena, resulting in a rapid decline in the thermal conductivity ratio at elevated temperatures.

To address these limitations and shed light on the precise effects of key parameters, Vajjha and Das conducted a comprehensive series of experiments to thoroughly investigate the thermal conductivity enhancement in nanofluids. Their refined correlation, based on an improved understanding of the underlying mechanisms, exhibits a remarkable agreement with experimental data (refer to Fig. 1 and 2).

The work of Vajjha and Das emphasizes the critical role played by interparticle interactions and provides a more accurate prediction of the thermal conductivity enhancement in nanofluids. By incorporating these factors into their correlation, they have achieved a significant improvement over previous models, particularly at higher particle volume concentrations and elevated temperatures. These findings contribute to a better understanding of the complex nature of nanofluids and provide valuable insights for designing efficient heat transfer systems in various industrial applications.

The results underscore the necessity of continued research in this field to develop more robust models that account for the intricate interplay between nanoparticle properties, volume concentration, temperature, and other relevant factors. The pursuit of accurate thermal conductivity predictions is paramount for optimizing heat transfer processes and maximizing the potential benefits offered by nanofluids in practical engineering applications.

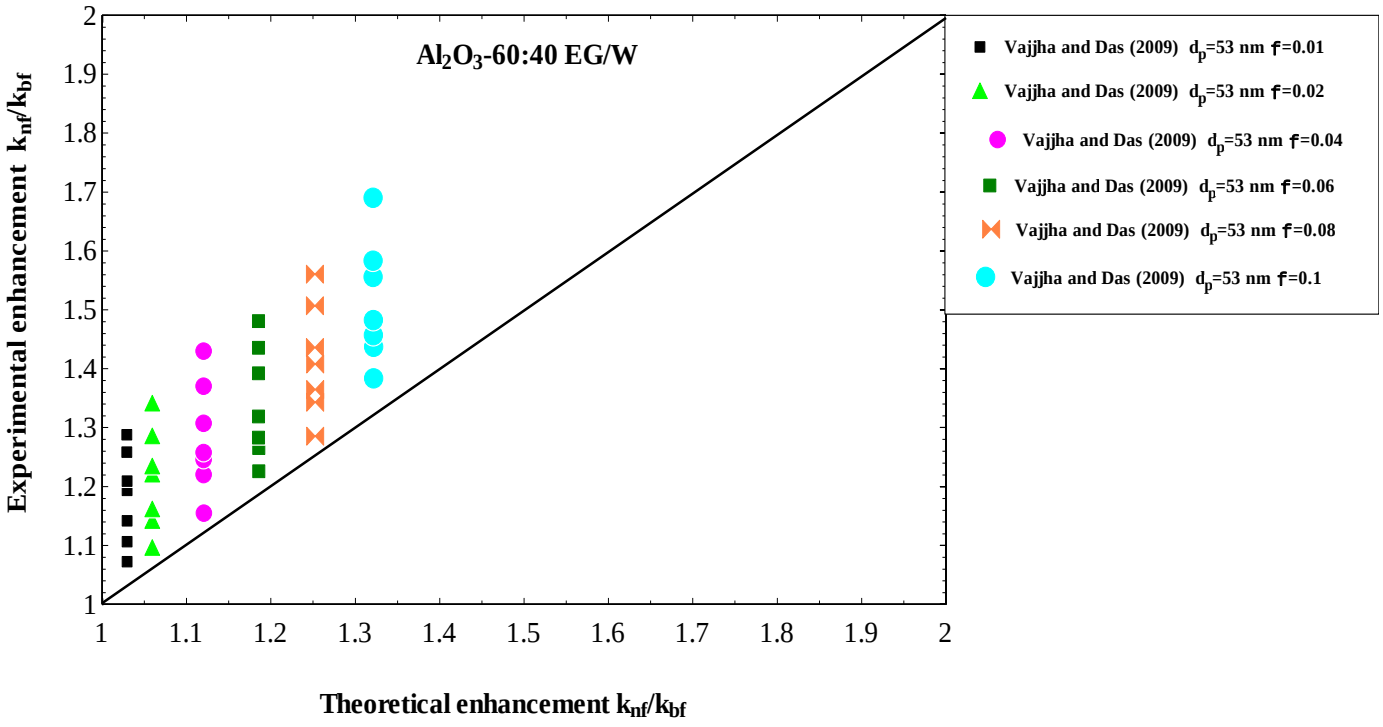

Fig. 3 Comparison of the thermal conductivity ratio calculated from the (Eq. (6)) with the values obtained from the available experimental data on Al_2O_3-60:40 EG/Water nanofluid as a function of temperature.

The influence of base fluids on the thermophysical properties of nanofluids remains an area that requires deeper investigation and comprehensive understanding. Although some publications have addressed the effects of base fluids on the viscosity and thermal conductivity of nanofluid suspensions, the underlying mechanisms are not well-explored. Different base fluids form distinct fluid layers around the nanoparticles, and the thickness and structure of these diffuse fluid layers significantly impact the effective volume concentration of nanofluids, thereby affecting viscosity enhancement [31].

To elucidate the impact of base fluids on thermal conductivity enhancement, available experimental data was compared with existing thermal conductivity models. Notably, the revisited Xuan et al. [17] analytical thermal conductivity model proposed by Chebbi [18] did not demonstrate a reasonable agreement with the experimental data (Figure 3). Additionally, Eq. (25) was employed to determine the effective viscosity of Al_2O_3-60:40 EG/W the nanofluid since the viscosity term was not provided for other types of nanofluids in Eq. (6). As the temperature and particle volume concentration increased, a significant discrepancy between the revisited analytical model (Eq. 6) and experimental results emerged. It was observed that the amended model consistently underestimated the experimental data (Figure 3). This analysis challenges the notion that the thermal conductivity of nanofluids is significantly influenced by the Brownian motion of nanoparticles. Furthermore, the impact of nanoparticle clustering on the thermal conductivity enhancement of nanofluids was found to be insignificant.

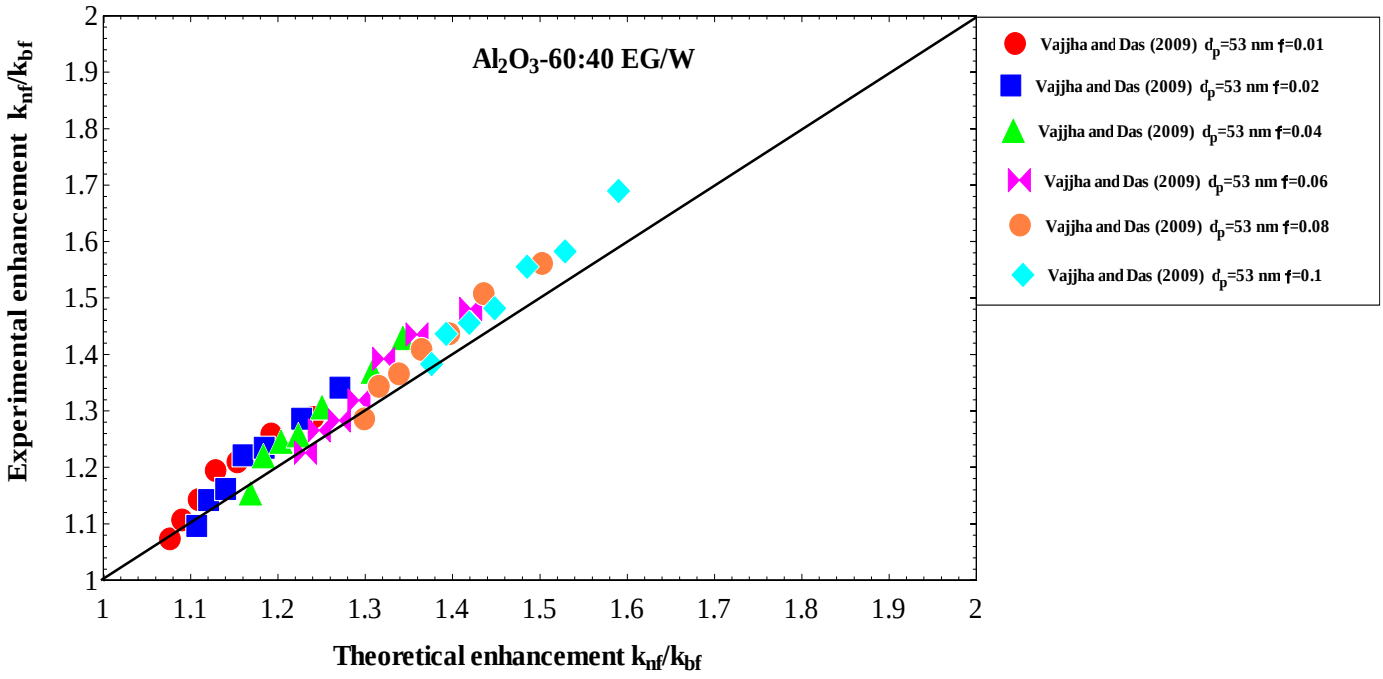

Fig. 4 Comparison of the thermal conductivity ratio calculated from the (Eq. (7)) with the values obtained from the available experimental data on Al_2O_3-60:40 EG/Water nanofluid as a function of temperature.

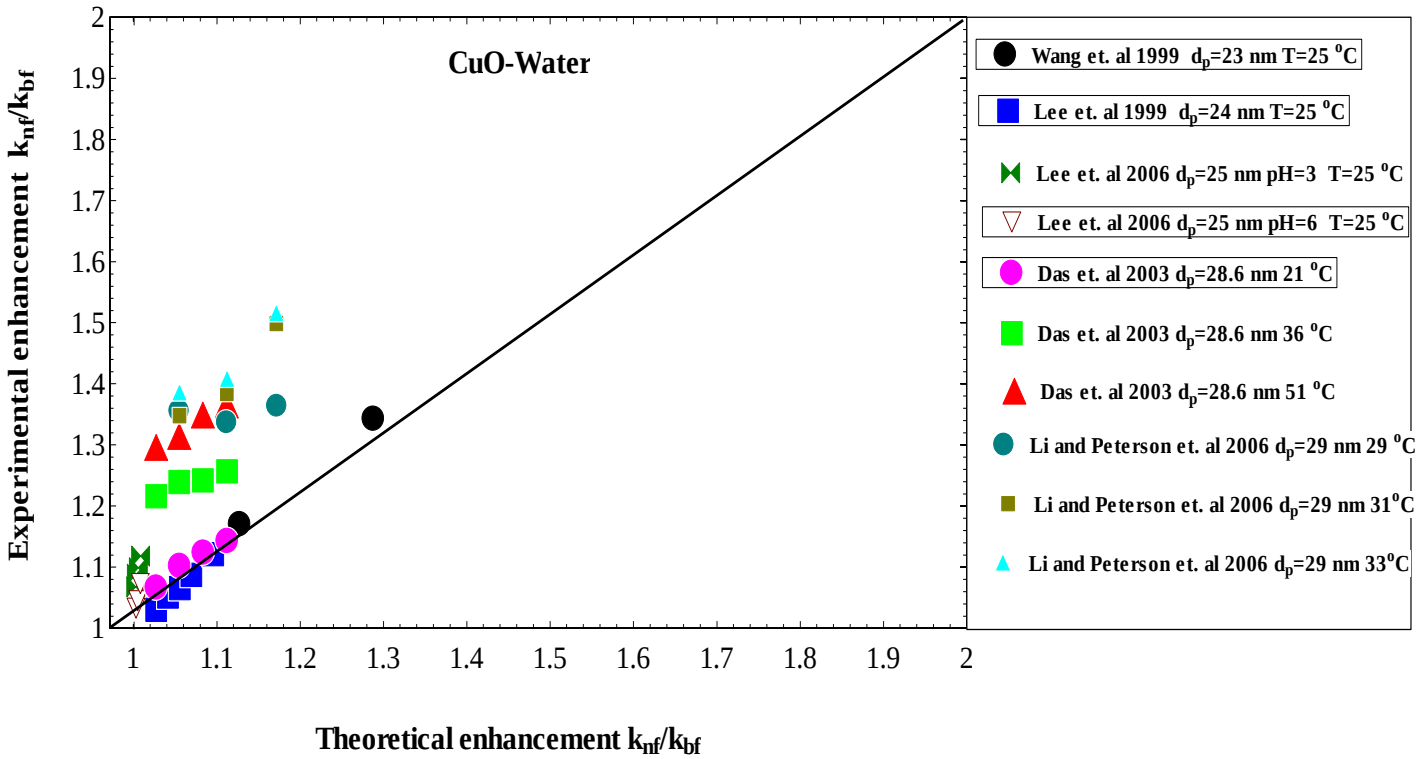

Fig. 5 Comparison of the thermal conductivity ratio calculated from the (Eq. (6)) with the values obtained from the available experimental data on CuO-Water nanofluid as a function of particle volume concentration.

In contrast, the correlation proposed by Vajjha and Das exhibited excellent agreement with their experimental data, demonstrating that their developed correlations effectively capture the effects of base fluids on thermal conductivity enhancement in nanofluids (Figure 4). These findings indicate that temperature plays a crucial role in the thermal conductivity enhancement of nanofluids, highlighting the potential benefits of utilizing nanofluids in high-temperature applications.

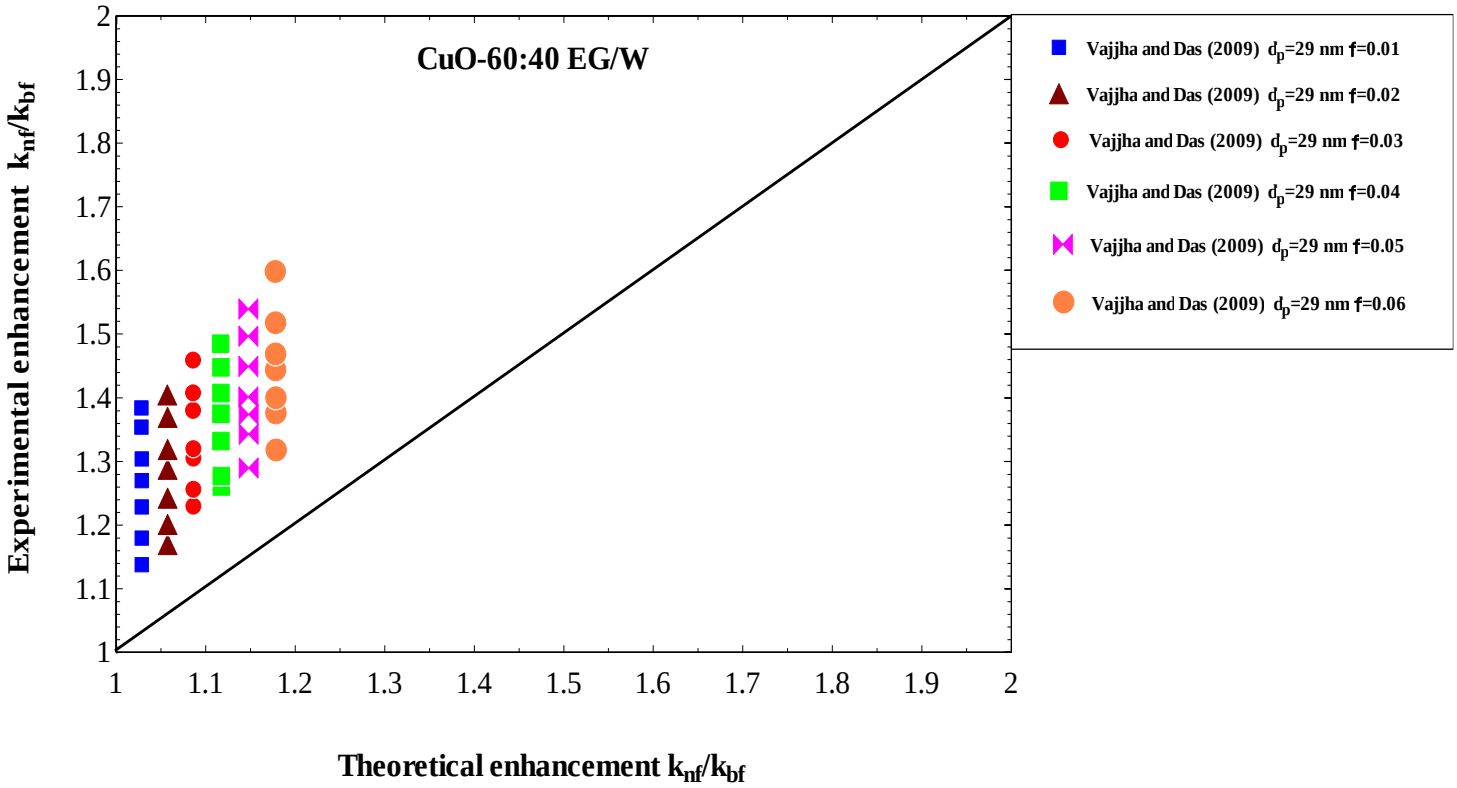

Fig.6 Comparison of the thermal conductivity ratio calculated from the (Eq. (6)) with the values obtained from the available experimental data on CuO-60:40 EG/Water nanofluid as a function of particle volume concentration.

The outcomes of this study underscore the importance of considering base fluid effects and temperature variations when predicting the thermal conductivity enhancement in nanofluids. The correlations developed by Vajjha and Das provide valuable insights into the influence of base fluids on nanofluid behavior and can facilitate the design and optimization of nanofluid applications in optimization of nanofluid applications in various industries.

The revisited analytical model, Eq. (6), demonstrated reasonable predictive capabilities for the experimental thermal conductivity data at room temperature as a function of particle volume concentration. However, as the temperature increased while maintaining the same particle size, a growing deviation between the analytical model and experimental findings was observed. The viscosity term in Eq. (6) was derived from previous work (Li and Xuan, 2000) on Cu-water nanofluids, which relied on limited experimental data. To further investigate the effect of viscosity on the thermal conductivity enhancement of nanofluids, a new viscosity model developed by Vajjha et al., Eq. (25), was utilized.

Surprisingly, it was observed that altering the viscosity of the nanofluid did not significantly affect the thermal conductivity of the suspension. This finding suggests that drawing definitive conclusions regarding the base fluid effect on the thermal conductivity of nanofluids solely based on

viscosity changes may not be appropriate. Additional investigations and analyses are required to comprehensively understand the complex interplay between viscosity, thermal conductivity, and other influencing factors in nanofluids.

These results in the Fig. 5 and Fig. 6 highlight the need for further research and the development of more accurate models to capture the intricate relationships between various parameters affecting the thermal conductivity enhancement of nanofluids. The influence of base fluids and their interactions with nanoparticle characteristics and temperature variations should be thoroughly explored to obtain a comprehensive understanding of nanofluid behavior and facilitate their effective utilization in practical applications.

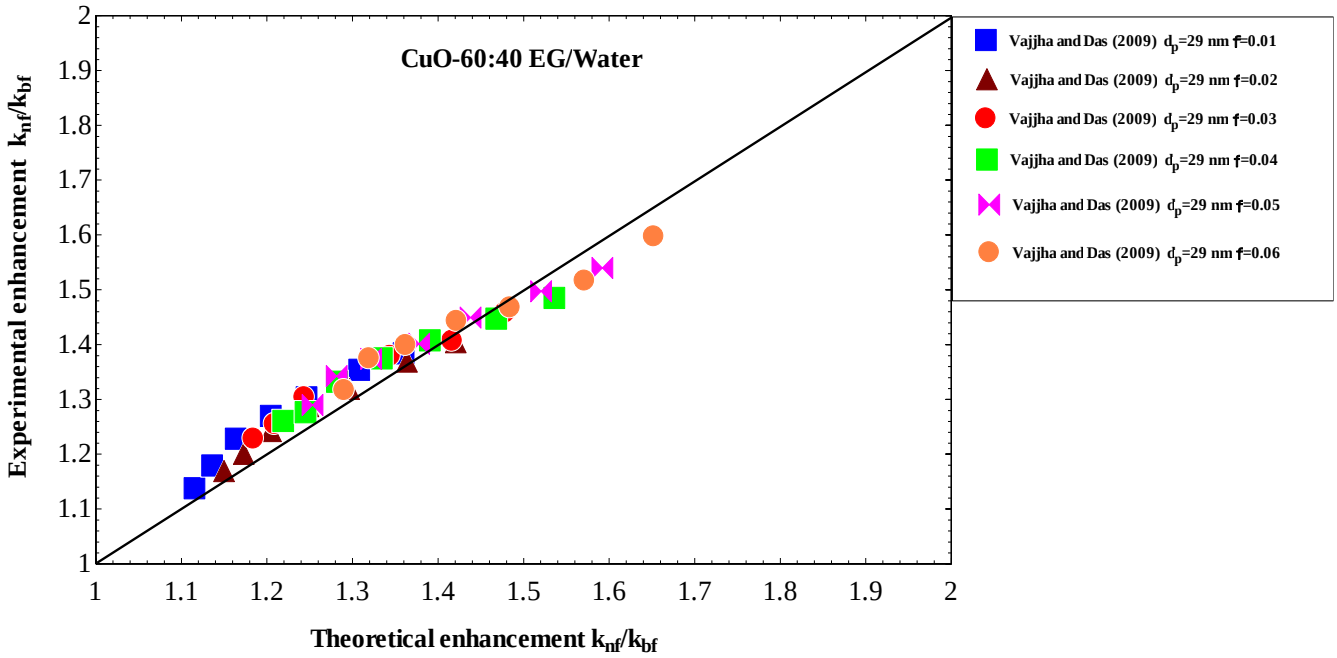

Fig. 7 Comparison of the thermal conductivity ratio calculated from the (Eq. (7)) with the values obtained from the available experimental data on CuO-60:40 EG/Water nanofluid as a function of temperature.

The base fluid effect on the thermal conductivity ratio of CuO-60:40 EG/Water nanofluid has been thoroughly investigated. It was observed that the revisited analytical model, Eq. (6), fails to accurately predict the experimental thermal conductivity when both the particle volume concentration and temperature are increased simultaneously. This discrepancy can be attributed to the significant increase in the agglomeration structure of nanoparticles as the particle volume concentration rises. However, despite the reduction in the apparent cluster radius r_c, this particle clustering phenomenon does not significantly impact the enhancement of thermal conductivity. Therefore, it contradicts the notion that clustering plays a significant role in the thermal conductivity of nanofluids.

In contrast, Eq. (7) demonstrates excellent agreement in explaining the base fluid effect on the thermal conductivity improvement of nanofluids. This equation accounts for the temperature and volume concentration effects for a specific nanoparticle size. The results, as depicted in Figure 7, confirm the strong agreement between the predicted values based on Eq. (7) and the experimental data, indicating the model's ability to capture the intricate relationship between base fluid properties, temperature, and particle volume concentration in enhancing thermal conductivity.

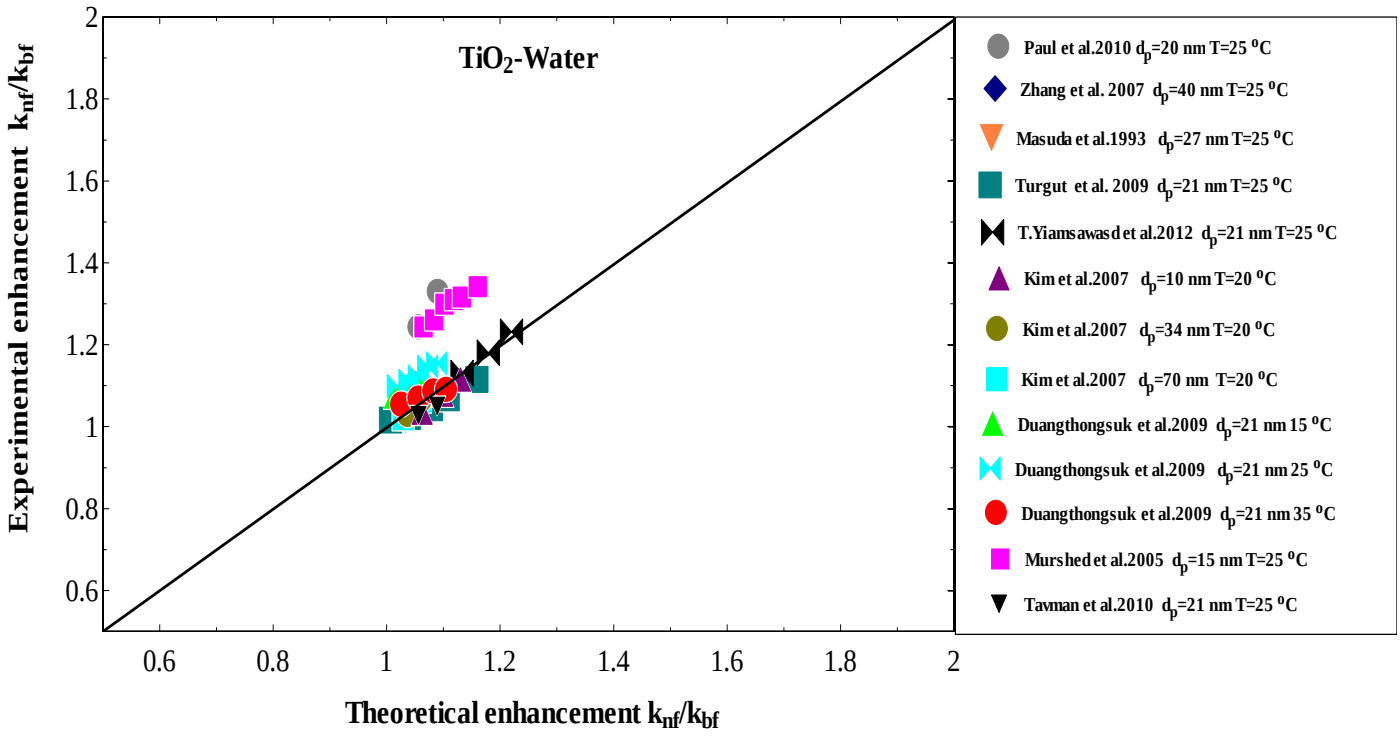

Fig. 8 Comparison of the thermal conductivity ratio calculated from the (Eq. (11) and Eq. (12)) with the values obtained from the available experimental data on TiO_2-Water nanofluid as a function of particle volume concentration.

The Corcione correlation [23] successfully captures the experimental thermal conductivity enhancement of nanofluids, as demonstrated in Fig. 8. This model was developed through regression analysis, resulting in a mean empirical correlation with a low standard deviation of error (1.86%). It proves to be particularly applicable for determining the thermal conductivity of nanofluids at room temperature.

Table 2. The parameters expressed in Eq. (14) for determining the nanolayer thickness (t) of different type of nanofluids [25].

	CuO-ethylene glycol		
Al_2O_3-water	TiO_2-water	Al_2O_3- ethylene glycol	
Parameter value (D_1)	3.042	761.43	1.8082
0.5253			
Parameter value (D_2)	1.059	3.555	0.912
0.355			

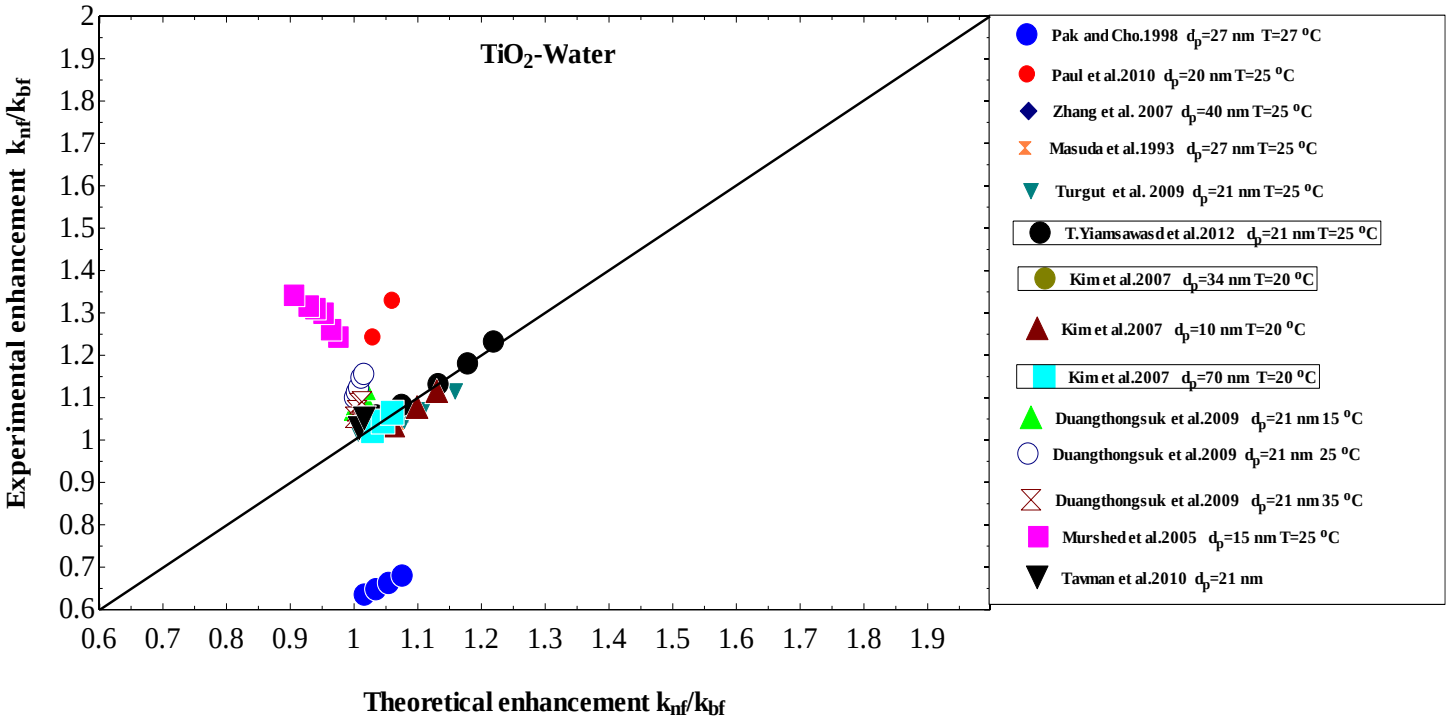

Fig. 9 Comparison of the thermal conductivity ratio calculated from the (Eq. (13), Eq. (14) and Eq. (15)) with the values obtained from the available experimental data on TiO_2-Water nanofluid as a function of particle volume concentration.

To delve deeper into the influence of the interfacial layer on the thermal conductivity enhancement mechanism of nanofluids, the thermal conductivity model proposed by Xie et al. [24] was employed in the study. This model combines Equation (15) to consider the effect of the nanolayer, and the thickness and thermal conductivity of the nanolayer were calculated using data from Table 2. Notably, the combined model (Equations 13-15) demonstrates a close agreement between experimental and theoretical thermal conductivity results, particularly for a specific particle size and at room temperature, as shown in Fig.9.

The reason for this agreement lies in the fact that the nanolayer thickness and its thermal conductivity are influenced by the affinity of intermolecular forces between the nanoparticles and base fluid molecules. These intermolecular forces play a crucial role in enhancing thermal conductivity. However, it is essential to acknowledge that the interfacial layer theory alone does not fully explain the observed experimental thermal conductivity enhancement of nanofluids. This is supported by molecular dynamics simulations that consider the properties of this nanolayer [53].

These findings underscore the intricate nature of the thermal conductivity enhancement mechanism in nanofluids and suggest that multiple factors, including interfacial effects and intermolecular forces, contribute to the observed experimental results. Further research integrating advanced computational methods and comprehensive experimental investigations is necessary to deepen our understanding of these mechanisms and refine existing models for accurately predicting thermal conductivity enhancement in nanofluids.

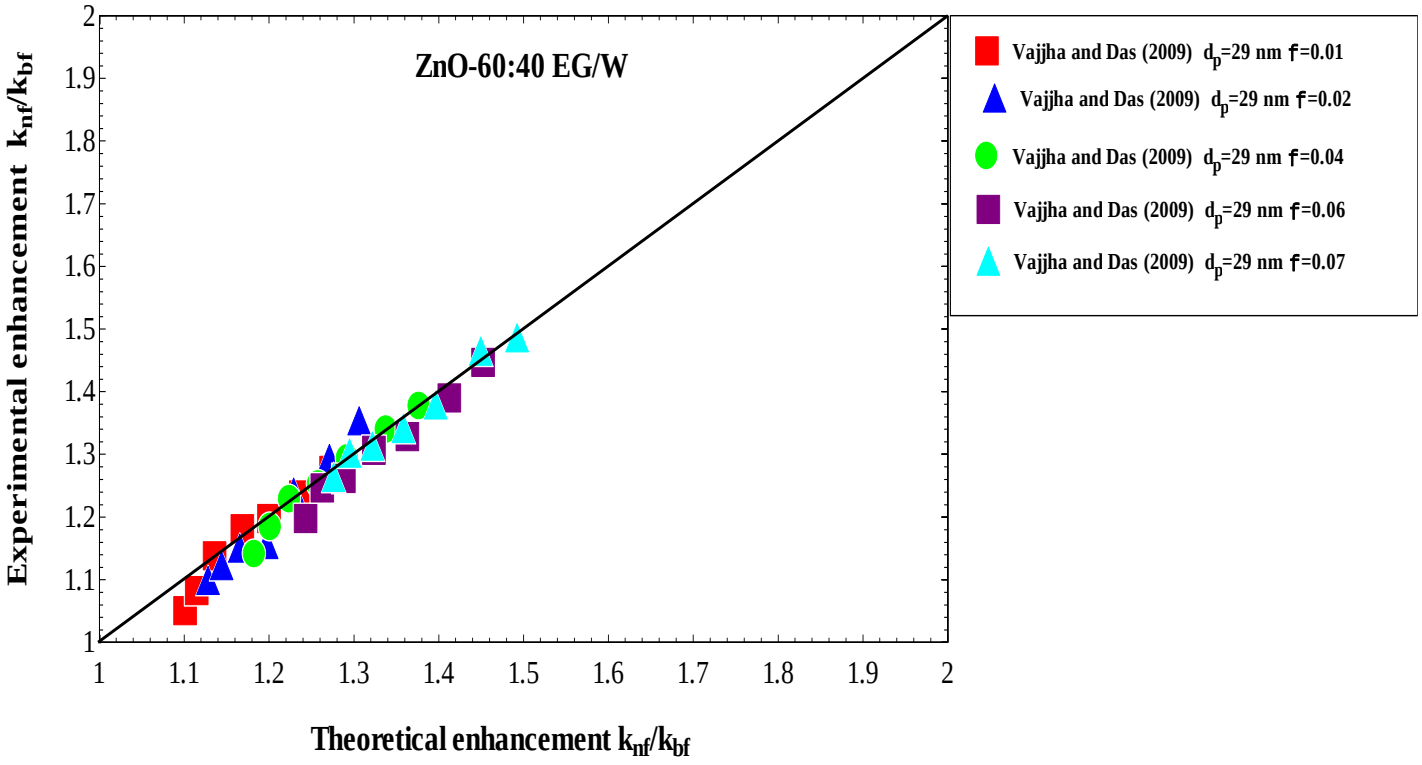

Fig.10 Comparison of the thermal conductivity ratio calculated from the (Eq. (7)) with the values obtained from the available experimental data on ZnO-60:40 EG/Water nanofluid as a function of temperature.

The thermal conductivity correlations proposed by Vajjha and Das [18] demonstrate remarkable accuracy in predicting the thermal conductivity of ZnO-60:40 EG/Water nanofluid across a wide range of particle volume concentrations and temperatures. Specifically, for the given nanoparticle size, d_p =29 nm the developed correlation Eq. (7) exhibits excellent agreement with the experimental thermal conductivity data of nanofluids, as illustrated in Fig.10.

This finding highlights the reliability and applicability of the Vajjha and Das correlations in capturing the thermal conductivity enhancement of ZnO-60:40 EG/Water nanofluid. By considering the effects of both particle volume concentration and temperature, the correlation accurately predicts the observed thermal conductivity behavior of the nanofluid system. These results provide valuable insights into the underlying mechanisms governing the thermal conductivity enhancement and demonstrate the potential of the Vajjha and Das correlations for practical applications in various industries involving heat transfer processes.

IV. DISCUSSION

The results of this study demonstrate the significant impact of key parameters, including particle volume concentration, temperature, and base fluid, on the effective thermal conductivity of nanofluids. The comparison of existing thermal conductivity models with experimental data revealed that no single model adequately captured the observed enhancements in nanofluids. This discrepancy emphasized the need for improved correlations that can accurately predict the thermal conductivity behavior of nanofluids in industrial heat transfer applications.

To bridge the gap between analytical predictions and experimental findings, a comprehensive parametric study was conducted. State-of-the-art thermal conductivity models were employed to thoroughly examine the individual contributions of

each parameter to the thermal conductivity of nanofluids. This in-depth investigation shed light on the underlying physical mechanisms responsible for the observed enhancements in thermal conductivity.

The findings of this study have both fundamental and practical implications. On a fundamental level, they advance our understanding of nanofluid behavior and challenge the conventional understanding of thermal conductivity enhancement mechanisms. The empirical analysis revealed that factors beyond Brownian motion and nanoparticle clustering play a crucial role in determining thermal conductivity, particularly the interplay of interatomic forces and molecular interactions in the base fluid. This discovery opens up new avenues for exploring the complex dynamics at the interfaces within nanofluids and highlights the importance of deeper investigations into these intricate mechanisms.

From a practical standpoint, this study has significant implications for the design and optimization of nanofluid-based heat transfer applications in industrial settings. The newly developed correlation (Eq. 7) exhibited exceptional predictive capabilities for a range of nanofluids, enabling more accurate and reliable thermal conductivity predictions. Engineers and researchers involved in industrial heat transfer can leverage this correlation to improve the design and efficiency of heat exchange systems utilizing nanofluids.

Moreover, the study introduced novel correlations specifically tailored for TiO_2-water nanofluids (Eq. 11, Eq. 13-15). These correlations demonstrated excellent agreement with experimental data, highlighting the importance of considering interatomic forces and nanolayer effects when predicting the thermal conductivity enhancements observed in TiO_2-water nanofluids.

This study not only evaluated existing thermal conductivity models but also uncovered new findings and insights into the complex nature of thermal conductivity enhancements in nanofluids. The development of accurate correlations and the identification of the influence of interatomic forces and molecular interactions provide a solid foundation for future research and advancements in the design and application of nanofluids in industrial heat transfer processes. By refining our understanding of nanofluid behavior and the mechanisms driving thermal conductivity improvements, this study paves the way for groundbreaking advancements in the field of heat exchange.

V. CONCLUSION

In the study, various models for predicting the thermal conductivity of nanofluids were evaluated and compared to experimental data. The goal was to identify the most accurate and reliable models and gain a deeper understanding of the underlying mechanisms.

One of the existing analytical models, represented by Eq. (6), was found to be inadequate in accurately predicting the thermal conductivity of several nanofluids, including Al_2O_3-60:40 EG/Water, CuO-Water, and CuO-60:40 EG/Water. This limitation highlighted the need for improved correlations that can capture the complex behavior of nanofluids.

However, a significant breakthrough was achieved with the introduction of a newly developed correlation, represented by Eq. (7). This correlation demonstrated exceptional predictive capabilities for nanofluids such as Al_2O_3-Water, Al_2O_3-60:40 EG/Water, CuO-60:40 EG/Water, and ZnO-60:40 EG/Water, across a wide range of particle volume concentrations and temperatures. The accuracy and reliability of this correlation make it a valuable tool for engineers and researchers involved in industrial heat transfer applications using these nanofluids.

Moreover, the study challenged the conventional understanding of thermal conductivity enhancement mechanisms in nanofluids. Contrary to previous assumptions, the empirical analysis revealed that thermal conductivity improvements cannot be solely attributed to Brownian motion and nanoparticle clustering. Instead, the interplay of interatomic forces and molecular interactions was identified as crucial factors influencing the effect of the base fluid (60:40 EG/Water) on thermal conductivity. This finding opens up new avenues

for investigating the complex dynamics at the interfaces within nanofluids and emphasizes the need for a deeper understanding of these intricate mechanisms.

Additionally, the study introduced novel correlations, such as Eq. (11) and Eq. (13-15), specifically tailored for TiO_2-water nanofluids. These correlations exhibited excellent agreement with experimental thermal conductivity data, emphasizing the significance of considering interatomic forces and nanolayer effects in accurately predicting the observed enhancements in TiO_2-water nanofluids.

This study not only evaluated existing thermal conductivity models for nanofluids but also uncovered new findings and insights into the complex nature of thermal conductivity enhancements. The development of the accurate correlation Eq. (7) and the discovery of the influence of interatomic forces and molecular interactions highlight the importance of advancing our understanding of nanofluid behavior. These findings provide a solid foundation for future research and advancements in the design and application of nanofluids in industrial heat transfer processes.

REFERENCES

[1] Chol, S. U. S. "Enhancing thermal conductivity of fluids with nanoparticles."*ASME-Publications-Fed* 231 (1995): 99-106.

[2] Lee, S., SU-S. Choi, S, and Li, and J. A. Eastman."Measuring thermal conductivity of fluids containing oxide nanoparticles." Journal of Heat Transfer121, no. 2 (1999): 280-289.

[3] Eastman, J. A., Choi, S. U. S., Li, S., Yu, W., and Thompson, L. J., 2001, "Anomalously Increased Effective Thermal Conductivities of Ethylene Glycol-Based Nanofluids Containing Copper Nanoparticles," Appl. Phys. Lett., **78**(6), pp. 718-720.

[4] Elena V. Timofeeva, Wenhua Yu, David M. France, Dileep Singh, and Jules L. Routbort, "Base fluid and temperature effects on the heat transfer characteristics of SiC in ethylene glycol/H2O and H2O nanofluids" Journal of Applied Physics, vol. 109, 2011.

[5] Murshed, S., Leong, K., and Yang, C., 2005, "Enhanced Thermal Conductivity of TiO_2-Water Based Nanofluids," Int. J. Therm. Sci., **44**(4), pp. 367-373.

[6] Hamilton, R. L. and Crosser, O. K., "Thermal conductivity of heterogeneous two-component system," Industrial & Engineering Chemistry Fundamentals, vol. 1, no. 3, pp. 187–191, 1962.

[7] Y. Xuan, Q. Li, "Heat transfer enhancement of nanofluids", International Journal of Heat and Fluid Flow 21 (2000) 58-64.

[8] X.Q. Wang, A.S. Mujumdar, "A review on nanofluids-part I: theoretical and numerical investigations", Brazilian Journal of Chemical Engineering 25 (2008) 613-630.

[9] E.V. Timofeeva, J.L. Routbort, D. Singh, "Particle shape effects on thermophysical properties of alumina nanofluids", J. Appl. Phys. 106 (2009) 014304.

[10] Khedkar, Rohit S., Shriram S. Sonawane, and Kailas L. Wasewar. "Influence of CuO nanoparticles in enhancing the thermal conductivity of water and monoethylene glycol based nanofluids." *International Communications in Heat and Mass Transfer* 39, no. 5 (2012): 665-669.

[11] Mintsa, Honorine Angue, Gilles Roy, Cong Tam Nguyen, and Dominique Doucet. "New temperature dependent thermal conductivity data for water-based nanofluids." *International Journal of Thermal Sciences* 48, no. 2 (2009): 363-371.

[12] Chopkar, M., S. Sudarshan, P. K. Das, and I. Manna. "Effect of particle size on thermal conductivity of nanofluid." *Metallurgical and Materials Transactions A*39, no. 7 (2008): 1535-1542.

[13] Liu, Min-Sheng, Mark Ching-Cheng Lin, C. Y. Tsai, and Chi-Chuan Wang. "Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method." *International Journal of Heat and Mass Transfer* 49, no. 17 (2006): 3028-3033.

[14] J.C.A. Maxwell, Treatise on Electricity and Magnetism, second ed., Clarendon Press, Oxford, UK, 1881.

[15] D.A.G. Bruggeman, Berechnung verschiedener physikalischer konstanten von heterogenen substanzen, I. Dielektrizitatskonstanten und leitfahigkeiten der mischkorper aus isotropen substanzen, Ann. Phys., Leipzig, 24 (1935) 636– 679.

[16] R.L. Hamilton, O.K. Crosser, "Thermal conductivity of heterogeneous two- component systems", I&EC Fundam. 1 (1962) 182–191.

[17] Xuan, Y., Q.Li, and W.Hu (2003) "Aggregation structure and thermal conductivity of nanofluids, AIChe J., 49(4): 1038-1043.

[18] Chebbi, Rachid. "Thermal conductivity of nanofluids: Effect of brownian motion of nanoparticles." *AIChE Journal* (2015).

[19] Berg JC. "An Introduction to interfaces & colloids, the bridge to nanoscience". Singapore: World Scientific, 2010.

[20] R.S. Vajjha, D.K. Das, Experimental determination of thermal conductivity of three nanofluids and development of new correlations, Int. J. Heat Mass Transfer 52 (21–22) (2009) 4675–4682.

[21] Koo, Junemoo, and Clement Kleinstreuer. "A new thermal conductivity model for nanofluids." *Journal of Nanoparticle Research* 6, no. 6 (2004): 577-588.
[22] K. Khanafer, K. Vafai "A critical synthesis of thermophysical characteristics of nanofluid," International Journal of Heat and Mass Transfer 54 (2011) 4410–4428.
[23] Corcione, Massimo. "Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids." *Energy Conversion and Management* 52, no. 1 (2011): 789-793.
[24] Xie, Huaqing, Motoo Fujii, and Xing Zhang. "Effect of interfacial nanolayer on the effective thermal conductivity of nanoparticle-fluid mixture." *International Journal of Heat and Mass Transfer* 48, no. 14 (2005): 2926-2932.
[25] Tso, C. Y., S. C. Fu, and Christopher YH Chao. "A semi-analytical model for the thermal conductivity of nanofluids and determination of the nanolayer thickness." *International Journal of Heat and Mass Transfer* 70 (2014): 202-214.
[26] Chon, Chan Hee, Kenneth D. Kihm, Shin Pyo Lee, and Stephen US Choi. "Empirical correlation finding the role of temperature and particle size for nanofluid (Al 2 O 3) thermal conductivity enhancement." *Applied Physics Letters* 87, no. 15 (2005): 153107-153107.
[27] ASHRAE Handbook: Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA, 2005.
[28] Etminan-Farooji, Vahid, Ehsan Ebrahimnia-Bajestan, Hamid Niazmand, and Somchai Wongwises. "Unconfined laminar nanofluid flow and heat transfer around a square cylinder." *International Journal of Heat and Mass Transfer* 55, no. 5 (2012): 1475-1485.
[29] Vajjha, Ravikanth S., Debendra K. Das, and Praveen K. Namburu. "Numerical study of fluid dynamic and heat transfer performance of Al2O3 and CuO nanofluids in the flat tubes of a radiator." *International Journal of Heat and fluid flow* 31, no. 4 (2010): 613-621.
[30] D. Kim, Y. Kwon, Y. Cho, C. Li, S. Cheong, Y. Hwang, J. Lee, D. Hong, S. Moon, Convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions, Curr. Appl Phys. 9 (2) (2009) e119–e123.
[31] Timofeeva, Elena V., Wenhua Yu, David M. France, Dileep Singh, and Jules L. Routbort. "Base fluid and temperature effects on the heat transfer characteristics of SiC in ethylene glycol/H 2 O and H 2 O nanofluids." *Journal of Applied Physics* 109, no. 1 (2011): 014914-014914.
[32] Das, Sarit Kumar, Nandy Putra, Peter Thiesen, and Wilfried Roetzel. "Temperature dependence of thermal conductivity enhancement for nanofluids."*Journal of Heat Transfer* 125, no. 4 (2003): 567-574.
[33] Li, Calvin H., and G. P. Peterson. "Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids)." *Journal of Applied Physics* 99, no. 8 (2006): 084314.
[34] Wang XW, Xu XF, Choi SUS: "Thermal conductivity of nanoparticle-fluid mixture." Journal of Thermal physics and Heat Transfer 1999, 13:474-480.
[35] Lee S, Choi SUS: "Measuring thermal conductivity of fluids containing oxide nanoparticles." Journal of Heat Transfer 1999, 121:280-289.
[36] Wen D, Ding Y: "Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions." International Journal of Heat and Mass Transfer 2004, 47:5181-5188.
[37] Xie H, Wang J, Xi T, Liu Y: "Thermal conductivity of suspensions containing nanosized SiC particles." International Journal of Thermophysics 2002, 23(2):571-580.
[38] Beck, Michael P., Yanhui Yuan, Pramod Warrier, and Amyn S. Teja. "The thermal conductivity of alumina nanofluids in water, ethylene glycol, and ethylene glycol+ water mixtures." *Journal of Nanoparticle research* 12, no. 4 (2010): 1469-1477.
[39] Mintsa, Honorine Angue, Gilles Roy, Cong Tam Nguyen, and Dominique Doucet. "New temperature dependent thermal conductivity data for water-based nanofluids." *International Journal of Thermal Sciences* 48, no. 2 (2009): 363-371
[40] Chon, Chan Hee, Kenneth D. Kihm, Shin Pyo Lee, and Stephen US Choi. "Empirical correlation finding the role of temperature and particle size for nanofluid (Al 2 O 3) thermal conductivity enhancement." *Applied Physics Letters* 87, no. 15 (2005): 153107-153107.
[41] Jung, Jung-Yeul, and Jung Yul Yoo. "Thermal conductivity enhancement of nanofluids in conjunction with electrical double layer (EDL)." *International Journal of Heat and Mass Transfer* 52, no. 1 (2009): 525-528.
[42] Vajjha, Ravikanth S., and Debendra K. Das. "Experimental determination of thermal conductivity of three nanofluids and development of new correlations."*International Journal of Heat and Mass Transfer* 52, no. 21 (2009): 4675-4682.
[43] Venerus, David C., Madhu S. Kabadi, Sunmook Lee, and Victor Perez-Luna. "Study of thermal transport in nanoparticle suspensions using forced Rayleigh scattering." *Journal of Applied Physics* 100, no. 9 (2006): 094310.
[44] Lee, Donggeun, Jae-Won Kim, and Bog G. Kim. "A new parameter to control heat transport in nanofluids: surface charge state of the particle in suspension."*The Journal of Physical Chemistry B* 110, no. 9 (2006): 4323-4328.
[45] Pak, Bock Choon, and Young I. Cho. "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles." *Experimental Heat Transfer an International Journal* 11, no. 2 (1998): 151-170.
[46] Paul G, Chopkar M, Manna I, Das PK. "Techniques for measuring the thermal conductivity of nanofluids." a review. Renewable and Sustainable Energy Reviews 2010, 14:1913-1924

[47] Zhang, Xing, Hua Gu, and Motoo Fujii. "Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles." *Experimental Thermal and Fluid Science* 31, no. 6 (2007): 593-599.
[48] Turgut, A., I. Tavman, M. Chirtoc, H. P. Schuchmann, C. Sauter, and S. Tavman. "Thermal conductivity and viscosity measurements of water-based TiO2 nanofluids." *International Journal of Thermophysics* 30, no. 4 (2009): 1213-1226.
[49] Kim, Sang Hyun, Sun Rock Choi, and Dongsik Kim. "Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation."*Journal of Heat Transfer* 129, no. 3 (2007): 298-307.
[50] Yiamsawasd, Thakleaw, Ahmet Selim Dalkilic, and Somchai Wongwises. "Measurement of the thermal conductivity of titania and alumina nanofluids."*Thermochimica Acta* 545 (2012): 48-56.
[51] Duangthongsuk, Weerapun, and Somchai Wongwises. "Measurement of temperature-dependent thermal conductivity and viscosity of TiO_2-water nanofluids." *Experimental thermal and fluid science* 33, no. 4 (2009): 706-714.
[52] Murshed, S. M. S., K. C. Leong, and C. Yang. "Enhanced thermal conductivity of TiO_2—water based nanofluids." *International Journal of Thermal Sciences*44, no. 4 (2005): 367-373.
[53] Tavman, I., and A. Turgut. "An investigation on thermal conductivity and viscosity of water based nanofluids." In *Microfluidics Based Microsystems*, pp. 139-162. Springer Netherlands, 2010.
[54] Masuda H, Ebata A, Teramea K, Hishinuma N: "Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles" Netsu Bussei 1993, 4:227-233.
[55] Michaelides, Efstathios E.(Stathis), Nanofluidics: Thermodynamic and transport properties textbook Cham, Switzerland : Springer, 2014
[56] http://www.fchart.com/ees/