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Recent advancements in Computational Fluid Dynamics (CFD) modelling of nanofluids: A Review

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ABSTRACT

The present study focuses on providing a comprehensive review of modelling nanofluids containing both metallic and non-metallic nanoparticles using Computational Fluid Dynamics within last ten years. CFD is a prominent branch of fluid mechanics employed by scientists and engineers to numerically solve complex fluid flow equations using discretisation methods. In this study, different approaches in CFD were reviewed including Eulerian-Lagrangian, Eulerian-Eulerian, and single-phase approaches for modelling nanofluid problems. This literature review includes the topics such as forced and natural convection heat transfer, thermal conductivity enhancement, and CFD simulations of nanofluids. Based on the findings, it is concluded that while the Eulerian-Lagrangian method is considered the best CFD technique compared to other methods in CFD, Eulerian-Eulerian is the most effective and computationally efficient method in modelling nanofluid-based fluid flow problems. Apart from the advancements in CFD techniques, the study highlights a current gap in the literature: the absence of a dedicated numerical solution for precisely forecasting the hydrodynamic of two-phase flow in nanofluids.

KEYWORDS: *Numerical Modelling, Nanofluid, CFD, Flow Simulation, Multiflows*

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1 INTRODUCTION

Because of its great heat removal capacity, nanofluid has been more and more popular in recent years (Ali et al. 2021; Chamsa-ard et al. 2017; Siriwardana, Bandara & Ranasinghe 2022; Yu & Xie 2012). Fluids that contain both metallic and non-metallic nanoscale particles, such as copper, aluminium, gold, alumina, carbon nanotubes (CNT), cupric oxide, amorphous carbon, diamond, and graphite, are referred to as nanofluids. Usually, ethyl glycol, oil, or water are used as base fluids for dispersing these nanoparticles (Nuim Labib et al. 2013). The base fluid's density, viscosity, thermal conductivity, and specific heat capacity are all changed when nanoparticles are present (Chen, Phuoc & Martello 2010; Liu, Yang & Guo 2007). The method used to mix the base fluid with nanoparticles varies based on the intended use. While oil-based nanofluids offer a broad range of uses, water-based nanofluids have been demonstrated to be more stable than other types of nanofluids. Synthetic oil-based nanofluids, for instance, are employed in high-temperature applications. Conversely, silicone oil-based nanofluids are utilised in non-corrosive and non-toxic situations. On the other hand, mineral-based oils are employed in applications that demand high stability since they are resistant to oxidation and heat deterioration (Chavez Panduro et al. 2022).

Since nanofluids have such strong thermal transfer capabilities, they have a widespread use in applications needing high heat removal. The gadgets used in these applications range in size from large to tiny. For instance, internal combustion engines can use nanofluids as an engine coolant to remove heat (Said, Sohail & Tiwari 2022). Moreover, nanofluids can be employed in micro heat exchangers as the working fluid (Kamsuwan et al. 2023). Their superior heat transmission capacity over their basis fluid, even in high-pressure and high-heat-flush environments, accounts for all of these applications (Bellos & Tzivanidis 2019; Peña-Parás et al. 2014).

1.1 Advantage of using CFD in nanofluid research

The main disadvantages of conducting nanofluid-based research is that it is experimentally expensive and time consuming. Therefore, researchers have preferred the numerical investigation. The primary advantage of utilising a numerical simulation instead of an experimental test is the significant reduction in the overall cost of the former option. This is especially the case when dealing with nanofluid flows on a microscale. As a consequence of this, the development of a dependable numerical solver for the examination of these types of flows would be of great assistance to the research community.

Multiphase numerical modelling is a very useful technique to modelling fluid flow with two or more phases within the system. This includes liquid-liquid flows, liquid-gas flows, liquid-solid flow, and gas-solid flows. Computational fluid dynamics (CFD) allows users to predict the fluid flow behaviours in multi-flow and multiphase applications particularly in droplet formation studies with a low cost and affordable manner. This allows the

researchers to quantify different properties such as velocity distribution, local pressure, and temperature distribution. Dispersed fluid flow systems and immiscible fluid flow systems are commonly modelled using multiphase fluid modelling, apart from its many uses (Abidi et al. 2021; Chen, Xu & Wang 2019). Specifically, CFD allows scientists and engineers to model and solve the complex fluid flows by numerically solving the governing equations. Due to its affordability, this approach can be very useful for optimisation and research fluid behaviour in systems (Abbas & Kumar 2017; Al-Baghdadi 2021; Wang, Jasim & Chen 2018).

1.2 Use of CFD approaches

As mentioned earlier, one of the important areas of research in CFD is the analysis of multiphase flows, which helps model and understand systems which have two or more coexisting and interacting fluid phases. An example of multiphase flow is the movement of water and air in open channels such as rivers, lakes and canals (Tezdogan, Incecik & Turan 2016). In addition, multiphase flows include nanofluids, granular flows, and phase-changing flows such as boiling and condensation (Çobanoğlu et al. 2019; Dey & Sahu 2021; Wang, Liu & Yuan 2022). Multiphase flows can also be observed when studying the behaviour of droplets or bubbles in a liquid, as well as in pipelines that experience multiphase flow. In order to accurately investigate such complicated systems, a more advanced or refined computational approach is required, one that takes into account the complex physics and interactions related to multiphase flows.

CFD mainly uses the volume of fluid method (VOF), the Eulerian-Eulerian approach (EE), and the Eulerian-Lagrangian approach (EL) to analyse the dynamics of multiphase fluids. Furthermore, several methodologies depend on the interface tracking of the two phases. These include the level set method and the phase field method (Ariyaratne et al. 2018).

The EE framework is the most commonly used multiphase approach for dispersed phases. Especially when the two phases have different physical properties. Both phases will be considered interpenetrating continuous phases when using this method. As a result, each phase has a unique set of governing equations. Each phase's volume fraction will be tracked over time and space. Figure 01 shows the fluid-solid coupling uses in EE method. Also, this figure depicts couplings between the phases, including volume fraction coupling, momentum coupling, and heat and mass transfer coupling. The diagram also details specific aspects of each coupling type, such as drag on the solid phase and convection.

When discrete particle analysis is required, the most common approach is the EL approach, because the fluid is treated as an Eulerian phase, while the other phase is considered as the Lagrangian phase, where it is treated as discrete particles or droplets. This method is commonly used for particle-driven flows, bubble-containing flows, and dispersed substance combustion. The effect of the dispersed particles can be formulated using this method. Figure 02 illustrates the physics coupling

between the solid phase and the fluid phase when using EL method.

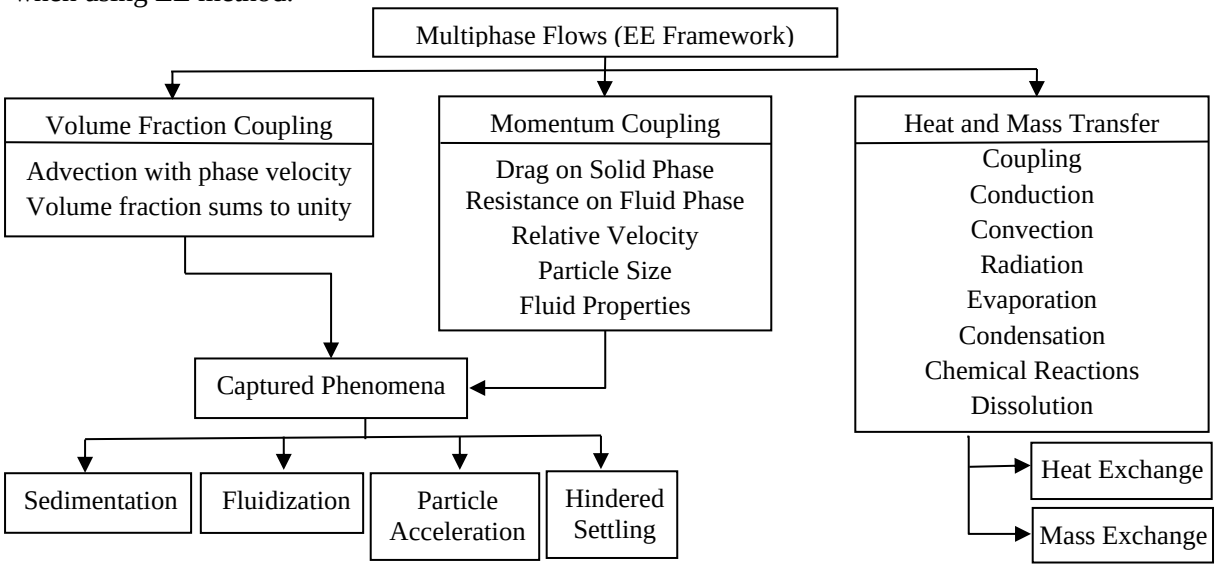

Figure 1. Fluid-solid coupling uses in EE method

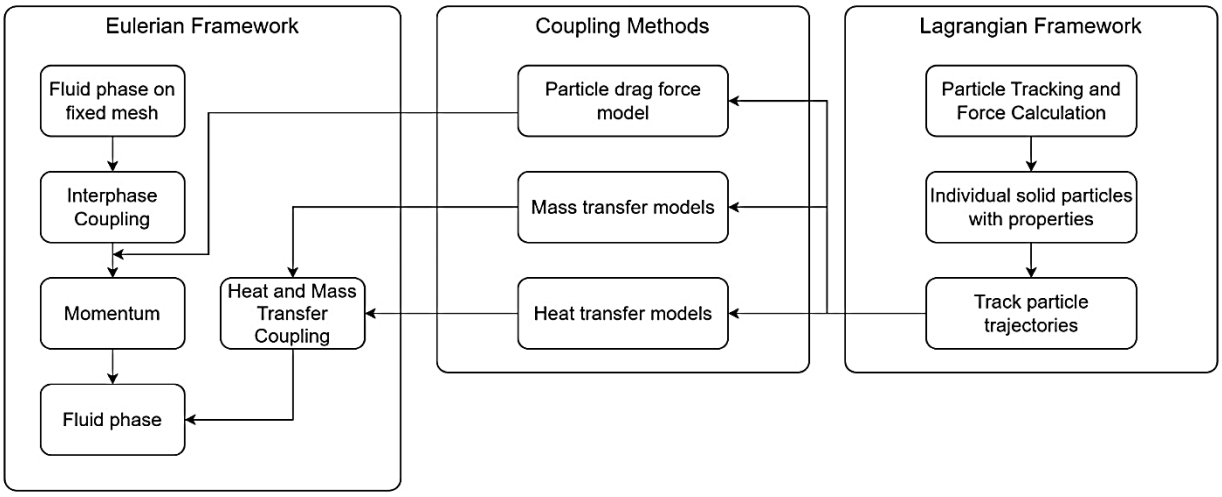

Figure 2. Fluid-solid coupling uses in EL method

The volume of fluid method is a popular numerical method for solving flows with free surfaces and phase interfaces. By solving the governing equations, this method tracks either the free surface or the interface of the two fluids. The curvature of the interface between the two fluids will be defined by interfacial surface tension in this method. When two or more immiscible fluids interact, the volume of fluid method is more commonly used.

CFD multiphase techniques offer many benefits, of which the most significant one is the ability to include various physics in the system. For example, the energy equation can be used in conjunction with the aforementioned multiphase techniques to look into heat transfer between the phases of a particular system. Because of this, users of CFD can model a wide range of engineering systems, including heat exchangers, gas or steam turbines, and any other system that involves heat transfer (Samarasinghe, Abeykoon & Turan 2018). Ultimately, CFD and its numerical methods have created new paths for low-cost research

and study by enabling the investigation of fluid flows in complicated systems without the requirement for initial experimental systems. On the other hand, there are more chances to create novel numerical techniques to solve intricate systems, including heat transfer flows based on nanofluids.

2 CFD MODELLING OF NANOFLUIDS

Nanofluids are challenging to numerically model due to their nature such as being a two-phase fluid. The numerous strategies found in the literature to numerically model the nanofluids are the main focus of this section.

2.1 Type of different approaches in CFD

As mentioned in the introduction, researchers often use CFD as a technique to solve fluid flow problems numerically. Because of its capabilities, multiphase numerical modelling was applied, especially in situations requiring nanofluid flows. Studying the various methods used by scientists to forecast the flow and heat transfer capabilities of nanofluids is critical for gaining a thorough understanding of the subject. The literature's available fluid modelling techniques are displayed in Figure 3. As illustrated in the figure, fluids can represent continuum models like Euler, Navier-Stokes, or Burnett models, or molecular models like molecular dynamics (MD), statical models like Direct Simulation Monte Carlo (DSMC) or Boltzmann models. In this review, the discussed models are limited to continuum models.

Because of the properties of nanofluids, molecular dynamics and lattice-Boltzmann numerical methods would be the best choices. These methods will yield results that meet or exceed the researchers' expectations (Cui, Wang & Liu 2019; Radhakrishnan 2021; Rostami et al. 2020; Vaka et al. 2020). Despite this, traditional CFD approaches still remain as the most popular methods when addressing nanofluid flow problems.

There are several ways for numerically modelling nanofluids. They include the EL approach, the volume of fluid method, the mixed approach, the EE approach, and the single-phase approach. Each of these strategies has advantages and disadvantages of its own. Consider the modelling approach for single-phase nanofluids, which is computationally efficient but requires treating the nanofluid as a stable, homogeneous fluid with constant properties like density, viscosity, and thermal conductivity (Amoo & Layi Fagbenle 2020; Dey & Sahu 2021; Gonçalves et al. 2021).

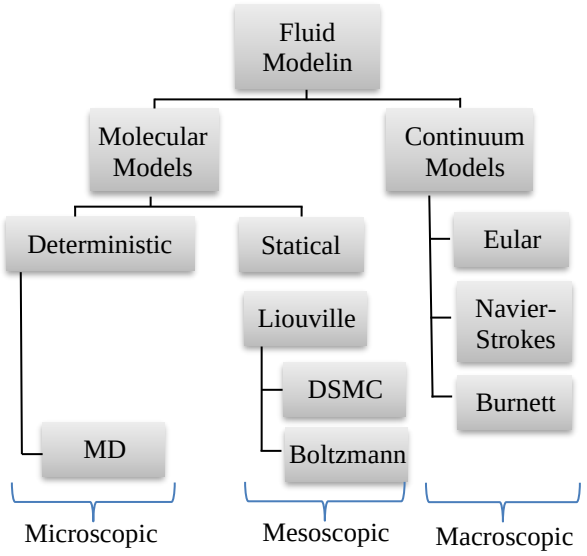

Figure 3. General relationships of models in fluid dynamics (adapted from Rosa, Karayiannis & Collins 2009)

Moreover, applying a multiphase model such as the EE approach would regard the nanofluid as a two-phase system since nanofluid is inherently a two-phase solid-liquid system. As a result, the findings have greater computing capacity and are more accurate.

As previously stated, modelling nanofluids with multiphase models has been shown to produce more accurate results. This is due to its ability to model the impact of nanoparticle migration on the performance of its heat transfer capabilities (Li et al. 2021; Liang & Mudawar 2019).

It is possible to conclude that each of these models requires further investigation in order to create a modified custom solver capable of predicting nanofluid in microscale devices. In the following section, the earlier models, specifically single phase, EE and EL models will be broken down into parts in more detail.

2.1.1 Single-phase modelling

Single-phase system modelling assumes that the nanofluid under consideration is a stable and homogeneous fluid separate from its base fluid. To run numerical simulations, the physical properties of the nanofluid, such as bulk fluid thermal conductivity, viscosity, and density, must be calculated. Temperature, nanoparticle size, and volume concentration all have an effect on these properties (Çobanoğlu et al. 2019; Ying et al. 2020). Following the determination of these physical properties, they can be entered into the material solver, allowing the completing of a numerical simulation similar to that of a conventional single-phase fluid simulation.

Sadeghi et al. (2022) have conducted a comprehensive review of natural convection of nanofluids in various enclosure shapes, covering geometries like square, circular, triangular, trapezoidal, and unconventional shapes. Furthermore, they have found that with rising Rayleigh number (Ra) numbers and decreased heat transfer with higher Hatta number (Ha) numbers has increased the heat transfer. According to the literature, the single phase modelling is capable of predicting the other flow properties like contact angle and droplet shape (Çobanoğlu et al. 2019). Ho et al. (2023) mentioned, the phenomenon of natural heat transfer enhancement within two-dimensional rectangular enclosures of varying aspect ratios is increasing with the nanoparticle concentration. Another study accomplished this by using nanofluids made of Al_2O_3/water and TiO_2/water with nanoparticle volume fractions (ϕ) ranging from 0% to 20%. In their study, the researchers found that the low aspect ratio condition improved more than the increased aspect ratio condition (Rasheed, Alias & Salman 2021). Ahmadi et al. (2019) and Ho et al. (2023) have mentioned an interesting fact that incorporating nanoparticles such as Cu, Ag, Al_2O_3, and TiO_2 (with concentration up to 20%) improved the cooling efficiency of pure water within a two-dimensional enclosure heated from the bottom. This improvement was especially noticeable at lower Ra numbers. Furthermore, when the volume concentration of Al_2O_3, Cu, and TiO_2 nanoparticles is less than

0.05, naturally induced convective heat transfer within a two-dimensional cavity increases (Ahmadi et al. 2019; Scott, Ewim & Eloka-Eboka 2022). Also, a positive correlation between the mean Nusselt number and the volume concentration of the nanofluid was discovered (Ying et al. 2020). The researchers studied the heat transfer increment of nanofluids containing TiO_2, Au, Cu and Al_2O_3 nanoparticles in a cavity modelled in two-dimensional space with volume fractions (ϕ) ranging up to 10%.

The Nusselt number (Nu) is commonly used as a metric in the aforementioned studies to evaluate the heat transfer effectiveness of nanofluids along the heating boundary condition. Considering the above-mentioned single-phase CFD simulations, it is possible to conclude that adding nanoparticles to pure liquids has improved the fluid's natural ability to transfer heat via convection. Furthermore, this growth is associated with an increase in Ra numbers and volume fractions (ϕ) in the nanoparticle phase. In contrast to previous experimental studies, which frequently reported deteriorations of natural convection, heat transfer in nanofluid keep the debate continue regarding heat transfer. The disputed conclusions are attributed, in part, to the potential relative velocity between the nanoparticles and the base fluid.

The thermal conductivity and dynamic viscosity of Al_2O_3 nanoparticles dispersed in ethylene glycol (EG) and water (W) mixtures of varying volume ratios were investigated by Chiam et al. (2017) In order to produce the Al_2O_3 nanofluids, three distinct mixtures with volume ratios of 40:60, 50:50, and 60:40 (W:EG) are utilised in two distinct phases. The thermal properties analyser and rheometer were employed to determine the thermal conductivity and viscosity, respectively, over a temperature range of 30 to 70°C and at volume concentrations of 0.2% to 1.0%. The study findings indicate that the average increase in thermal conductivity of Al_2O_3 nanofluids across the three base ratios varied from 2.6% to 12.8%. An increase in the concentration of ethylene glycol results in enhanced nanofluids. In contrast, at 60:40 (W:EG), the average dynamic viscosity increased by as much as 50%. The proportion of ethylene glycol utilised in nanofluids resulted in a reduction in viscosity. The concentration, temperature, and base ratio all have a major effect on the characteristics of Al_2O_3 nanofluids. The coefficient of heat transfer and the stress caused by shear stress on the wall were both raised by the inclusion of nanoparticles, according to the experimental data. Comparatively, it has been found that wall shear stress is more affected by nanoparticles than is the coefficient of heat transport. Bekhti & Saim (2022) examined the flow field and heat transfer of various nanofluids (Al_2O_3, CuO, SiO_2, and ZnO) using turbulent forced convection in a channel. The channel's surface is heated, with a temperature of 310 K. Simulations are performed using a constant water Prandtl number (Pr) of 6.99, Re numbers of 20,000, 30,000, 40,000, 50,000 to 60,000, nanoparticle volume fractions of 0, 0.01, 0.02, 0.03, and 0.04, and nanoparticle diameters of 30 nm. The governing equations

are numerically solved using the finite volume approach, the SIMPLE algorithm, and the k-ε function. The numerical results indicated that as Re numbers and volume fractions increased, so did the average Nu number. A numerical study of the heat transfer properties of nanofluids and converging flow passages in microchannel heat sinks effectively enhance convection heat transfer coefficients, resulting in a 2.35 times greater heat transfer coefficient than pure water flowing through a straight channel (Dehghan, Daneshipour & Valipour 2018). The presented results suggest using nanofluids in conjunction with converging flow passages to achieve an effective enhancement in the convection heat transfer coefficient and to boost the improvement obtained by each individual enhancement technique, particularly in thermally developed regions where the convection heat transfer coefficient cannot be increased by increasing the inlet velocity/pressure in the laminar flow regime. Another study revealed that, Nanofluids can flow over permeable sheets in the presence of suction, thermal radiation, and a heat source/sink, resulting in reduced skin friction and stable velocity and temperature profiles (Jamaludin, Nazar & Pop 2019). The study concentrated on the flow of these nanofluids within an open cavity that was uniformly heated from below. The study considered Re number ranging from 100 to 500. Both the Re number and volumetric fraction of the nanoparticles were found to be related to heat transfer by the researchers. The significance of selecting these constraints was mentioned to achieve the greatest possible heat transfer enhancement.

The local heat transfer coefficient and Nu number are consistently used as metrics to assess the performance of nanofluid forced convection along the heated surface in the aforementioned studies on forced convection of nanofluids. Based on the previously single-phase CFD simulations, it can be deduced that the volume fraction of nanoparticles and the Re number have a direct influence on the enhancement of forced convection heat transfer in nanofluids. This is consistent with previous empirical investigations. Nonetheless, the addition of nanoparticles to the base fluid increases viscosity, which impedes the flow of nanofluids. The primary factor contributing to the disparity between numerical and experimental findings in previous studies was frequently attributed to the relative motion of nanoparticles and the base fluid. However, the inherent limitations of single-phase CFD simulations make accounting for interactions between nanoparticles and the base fluid impractical.

2.1.2 Eulerian-Lagrangian Framework

When considering nanofluid as a true two-phase flow, it can be thought of as having two distinct components: the base fluid and the nanoparticles. One method is to first resolve the governing equations intended for the base fluid, afterward use the obtained fluid movement information to make predictions about the motion of nanoparticles using the principles outlined in Newton's second law. To account for the interactions among the solid phase and fluid phase, additional terms for energy and momentum are incorporated into the governing equations. Previous publications, on the other

hand, have presented a variety of explanations for the forces that act on nanoparticles.

A novel EL hybrid approach was utilized to model nanofluid-based direct absorption solar collectors, revealing the importance of considering the discrete nature of nanoparticles. This approach highlighted the impact of Re number on nanoparticle distribution and, consequently, on the optical and thermal properties of the nanofluid. The study identified a critical Re number beyond which the assumption of homogeneous particle distribution becomes invalid, leading to inaccuracies in conventional modelling approaches (Ambreen, Saleem & Park 2021). However, the authors did not specify how many particles were used in their study to represent nanoparticles. It is impossible to effectively monitor the entire population of real nanoparticles using the Lagrangian approach. This limitation is due to the large number of particles involved—approximately 5.7 x 10^{20} nanoparticles with a diameter of 100 nm in a volume of 1 cm^3.

The addition of Al_2O_3 nanoparticles to deionised (DI) water in a condenser tank enhances both conduction heat transfer in the pipe and convection in the fluid, resulting in a lower thermal resistance compared to DI water alone. Higher Nu numbers and lower Ra numbers were observed for the nanofluids. Another study based on the Buongiorno two-phase model numerically simulated the effects of fin shape and nanoparticle diameter on natural convective heat transfer of Al_2O_3-water nanofluid within a square cavity (Singh & Singh 2020). The study concluded that at high Ra number, a low volume fraction of the nanofluid works best and the trapezoidal fin shape is the most effective. Furthermore, decreasing the nanoparticle diameter was found to significantly increase heat transfer, while increasing the diameter can reduce convective heat transfer to a level below that of the base fluid.

Furthermore, the heat transmission characteristics of Al_2O_3-water base nanofluids were investigated utilising a dissipative particle dynamics (DPD) method (Azimikivi, Purmahmud & Mirzaee 2020). A variety of nanoparticle concentrations were simulated using different Ra numbers in the study. This demonstrated that heat transfer was enhanced by the addition of nanoparticles, specifically at low Ra numbers. The regions surrounding the hot wall of the cavity underwent the most significant enhancement in heat transfer, whereas the region adjacent to the cold wall encountered a decline in heat transmission as a result of the nanoparticle addition. The study also highlighted that the role of Brownian motion is negligible near the hot and cold walls but plays a significant role at the middle and lower walls of the cavity at low Ra numbers and high volume fractions of nanoparticles.

Zhang et al. (2021) stated in their study, the hybrid Al_2O_3-CuO/water nanofluid significantly enhances heat transfer performance in circular tubes, with pressure drop enlargement up to 12%, and different thermophysical property models show similar trends but different magnitudes. Unlike earlier

studies, this one includes a thorough examination of Brownian force, Saffman lift force and thermophoretic force in relation to nanofluid CFD research. Particle force balance was used to calculate the motions of individual nanoparticles tracked within the Lagrangian frame. Using this methodology, they were able to achieve a favourable correspondence between their computational findings and the empirical results documented in existing literature. The authors, however, did not provide any information regarding the number of Lagrangian particles used in their study.

Kumar & Puranik (2017) carried out a numerical investigation to compare the single-phase homogenous model with multiphase models, including the EL model, under constant and temperature dependent properties of the nanofluid. The findings indicated that the EL model managed to overestimate heat transfer coefficients, while the mixture model showed an unrealistic increase in heat transfer at high particle volume fractions. In contrast to the alternative models, the single-phase approach demonstrated a notable adherence to experimental data, specifically in regard to temperature-dependent properties. The average heat transfer coefficient exhibited the least amount of variation, reaching 5.9%. Additionally, it was observed that the heat transfer coefficient exhibited an upward trend as the Re number and particulate volume fraction increased. However, it is important to note that this research was carried out under conditions of elevated pressure drop and wall shear stress.

The investigation conducted by Albojamal & Vafai (2017) concerned the conveyance of Al_2O_3 and CuO/water nanofluids via undulating channels and horizontal tubes. The EL model was among the single-phase and two-phase models utilised in this study. In horizontal tubes, it was critical to assume variable fluid properties in order to predict heat transfer enhancement. However, in wavy channels, where blending and recirculation within the channel were significant, the distinction between constant and variable properties was inconsequential. The study also found that the dispersion model agreed well with experimental data, but the lack of reference values for the adjustable factor used in the study, raised questions about its reliability. The study concluded that the homogenous single-phase model with appropriate thermal conductivity and viscosity correlations was dependable and efficient in terms of computational resources.

Finally, the EL framework can be used as a viable model to simulate nanofluids. This is mainly due to the fact that, within the underlying fluid medium, nanoparticles can be thought of as physically suspended particles. However, when accounting for the behaviour of nanoparticles in previous CFD studies conducted within the EL framework, the consideration of drag force has been the sole focus. One could make a valid argument that this viewpoint overlooks numerous complexities associated with particle motion characteristics. Moreover, the main goal of a conventional EL approach is to study the interplay between discrete particles and

continuous flow. However, the interactions between discrete particles are not considered. As a result, this omission may result in a lack of relevant information for nanofluid research.

2.1.3 Eulerian-Eulerian Framework

The Eulerian frame has been used to investigate the behaviour of nanofluids in the context of fluid dynamics simulations. For CFD simulations and modelling of nanofluids, several approaches have been used, including the Mixture method, VOF Method and EE method. It is generally accepted that the phase of nanoparticles can be characterised as a pseudo-fluid, irrespective of the method that is utilised. Within each numerical cell in the computational region, both the base fluid and the fluid containing nanoparticles can coexist. Given this, all three approaches within the Eulerian framework must satisfy the criterion stated as $\phi_f + \phi_n = 1$, indicating that the combined volume fraction of the primary fluid also known as the based fluid (ϕ_f) and the nanoparticle (ϕ_n) is equal to 100%. The VOF method is used to solve a unique set of momentum and energy equations for the two phases while also tracking the volume fractions of the phases throughout the fluid domain or the computational domain (Akbari et al. 2012). The volume concentration of the nanoparticle phase in each mesh cell is used to compute the properties of the nanofluid. In the current methodology, the variables of velocity, pressure, and temperature are shared by both the base fluid and nanoparticle phases. The VOF method, on the other hand, is primarily built on the assumption that there is not any penetration between the domain phases. Each elementary computational cell's volume fraction must be $\phi_n = 0$ or $\phi_n = 1$. Hirt and Nichols (1981) state that the interface information between the two phases must be monitored when the condition $0 < \phi_n < 1$ meet. Using a mixture approach, multi-phase flow and heat transfer phenomena can be represented by solving a single set of equations encompassing continuity, momentum, energy, and volume fraction. This methodology necessitates the use of various algebraic expressions to calculate the relative velocities between distinct phases. With the use of the Mixture approach, particular factors that have been found to be particularly relevant to the sedimentation of nanoparticles can be identified based on experimental research. The Mixture model does not necessitate explicit tracking of the interface between the two phases, in contrast to the VOF model. When the numerical mesh is fine, using a mixture model can greatly lower the amount of computational resources needed.

Hazeri-Mahmel, Shekari & Tayebi (2021), investigated a hybrid Al_2O_3-CuO/water nanofluid, and CFD simulations were performed using different models, including the mixture model. The mixture model, along with the Eulerian model, showed desirable prediction accuracies for the experimental heat transfer coefficient, with the mixture model having a deviation of 10.2% from the experimental data. Zhang et al. (2021) did not directly compare single-phase and mixture models but focused on the thermophysical

properties of Al_2O_3-CuO hybrid nanofluid at different nanoparticle mixture ratios. The thermal conductivity and viscosity of the nanofluid were measured, and a new correlation was proposed to predict the thermal conductivity with high accuracy.

Wanatasanappan, Abdullah & Gunnasegaran (2020) performed a 3D analysis of forced convection of Al_2O_3/water nanofluid in a horizontal pipe using both single-phase and two-phase mixture models. At a particle volume fraction of 0.01, mixed models outperformed single-phase models in terms of heat transfer coefficients. The mixture model was more accurate, particularly the non-Newtonian mixture model, which produced more superior results than the other models. To make the simulation more practical, the researchers considered the base fluid's temperature-dependent density and viscosity. According to their findings, all three multiphase models outperformed the single-phase model in terms of prediction of the properties of the nanofluid. However, there were no noticeable variations in the results predicted by the three multiphase models proposed in the study. The Al_2O_3-CuO hybrid nanofluid (nanoparticle ratio of 60:40) has the maximum thermal conductivity, and a proposed correlation in the study predicts the results with 95% accuracy.

Three two-phase models were compared to a single-phase model by Moraveji and Ardehali (2013). Laminar forced convection of nanofluids containing 0.5, 1, and 6 wt% Al_2O_3/water in a mini-channel heat sink was the objective of this investigation. According to the findings of this investigation, the outcomes generated by the three multi-phase models were remarkably comparable. Based on their comparative analysis, it was determined that multi-phase approaches outperformed single-phase approaches. To strike a balance between increased result accuracy and decreased CPU utilisation, they suggested employing a mixture model. A study conducted by Garoosi et al. (2014) examined the heat transmission properties of water nanofluids containing Al_2O_3 at different concentrations (maximum: 5%) using both natural and mixed convection mechanisms. The tests were carried out in a square cavity that was heated laterally. To simulate the behaviour of a nanofluid mixture, the researchers solved the standard Navier-Stokes equations. They did, however, include a new term in the energy equation to account for the potential energy flux caused by Brownian motion and the thermophoretic effects of nanoparticles. The researchers discovered an optimum volume fraction of nanoparticles for achieving the highest heat transfer rate at specific Ra and Richardson numbers. Furthermore, it was discovered that when the Rayleigh numbers were low and the Richardson numbers (Ri) were high, the particle distribution exhibited a relatively non-uniform pattern.

Based on the preceding investigations and comparisons, it is widely accepted in the academic community that considering nanofluid as a multi-phase system within the Eulerian framework is a more practical approach in terms of computational efficiency than the EL approach. This is so that a single set

of governing equations may be used, since it is assumed that the scattered particles are in a pseudo continuous phase. In terms of increased computational efficiency, the Mixture technique is generally considered to be superior to both the EE approach and the VOF approach.

2.2 Comparing strengths and weaknesses in considered modelling methods

As previously mentioned, there are three main methods of modelling nanofluids using CFD. The strengths and weaknesses of each method has been identified for selecting best possible method for nanofluid modelling. After extensive research about these methods, the strengths and weaknesses of each method for modelling nanofluid based flow are presented in table 1. In order to understand their strengths and weaknesses, the analysis of these methods is based on eight criteria: fluid phase representation, volume fraction variation, interphase interaction modelling, multiphase flow dynamics, particle tracking and distribution, scalability and computational cost, validation and experimental correlation, and application areas. Thus, the findings of the literature survey regarding the modelling of nanofluid on a microscale are summarised in table 1.

Table 1. Comparing strengths and weaknesses in considered modelling methods

Criteria	Eulerian-Eulerian Method	Lagrangian-Eulerian Method	Single Phase Method
Fluid-Phase Representation	Nanofluids often involve a base fluid and dispersed nanoparticles. The EE framework allows for the independent tracking of each phase, crucial for capturing nanofluid behaviour.	Lagrangian approach focuses on tracking individual particles, while the Eulerian component handles the fluid phase.	Single-phase models consider nanofluids as homogeneous, neglecting particle-phase details.
Volume Fraction Variation	The framework handles varying volume fractions of nanoparticles efficiently, providing a realistic representation of nanofluid concentrations across the computational domain.	EL methods allow for adaptive refinement and coarsening to capture local variations in particle concentration.	Single-phase models assume a uniform particle distribution, limiting the ability to account for concentration variations.
Interphase Interaction Modelling	Nanoparticle-fluid and nanoparticle-nanoparticle interactions are important. EE framework enables the incorporation of detailed interphase models, accounting for forces, collisions, and agglomeration.	EL method excels at capturing detailed particle interactions, including Brownian motion and interparticle forces.	Single-phase models lack the capability to stand for interphase interactions, simplifying the simulation.
Multiphase Flow Dynamics	Nanofluids exhibit multiphase flow characteristics. EE CFD is	EL method offers flexibility in handling multiphase flows,	Single-phase models do not consider the multiphase nature of

Criteria	Eulerian-Eulerian Method	Lagrangian-Eulerian Method	Single Phase Method
	well-suited for simulating complex multiphase flows, capturing interactions between phases accurately.	especially when distinct phases have disparate behaviours.	nanofluids, supplying a simplified representation.
Particle Tracking and Distribution	The framework helps particle tracking but not induvial particle tracking, essential for understanding nanoparticle distribution, sedimentation, and dispersion patterns within the nanofluid.	EL method excels in tracking individual particles, supplying detailed information on particle trajectories and dispersion.	Single-phase models do not involve particle tracking, making it challenging to analyse particle behaviour within the fluid.
Scalability and Computational Cost	EE methods often supply computational efficiency, making it feasible to simulate large-scale nanofluid systems or complex geometries within reasonable timeframes.	EL methods can be computationally expensive due to particle tracking but offer scalability through parallel computing.	Single-phase models are computationally efficient but may struggle with scalability for large-scale simulations.
Validation and Experimental Correlation	This framework allows for easier validation against experimental data, as it explicitly models the fluid and particle phases separately, helping comparison with real-world observations.	EL methods enable validation against particle tracking experiments, providing a comprehensive comparison with real-world data.	Single-phase models may struggle with validation, as they oversimplify nanofluid behaviour compared to experimental observations.
Application Areas	EE framework finds applications in various nanofluid-related scenarios, such as heat transfer enhancement, nanofluidic devices, and biomedical applications.	EL methods are suitable for detailed studies on particle behaviour and dispersion, applicable in areas like drug delivery and aerosol science.	Single-phase models may be suitable for preliminary studies but lack the detail needed for applications requiring correct representation of nanofluid behaviour.

3 CONCLUSION AND RECOMMENDATIONS

A comprehensive overview of the literature was presented in this study, covering a wide range of subjects such as forced and natural convection heat transfer, thermal conductivity enhancement, and CFD simulations of nanofluids. Based on the analyses carried out in this review, the following conclusion may be made:

- Most researchers agree that the EL method is the easiest of the several CFD techniques to understand.
- It is proven that simulations carried out in the EE framework are more effective and demand less computer power.
- It is generally accepted that the best way to obtain extra computational efficiency benefits is to use the Mixture technique within the EE framework.

- A dedicated numerical solution for precisely forecasting the dynamics of two-phase flow in nanofluids is lacking in the literature currently available.

According to the conclusion, several recommendations can be made to improve the modeling of nanofluids:

- The current Eulerian-Eulerian (EE) and Eulerian-Lagrangian (EL) models have some potential for simulating nanofluid behaviour. Furthermore, advanced multiphase models require further refinement and development to reach their beginning. These models will need to be built on detailed analytical representations of complex interparticle phenomena like nanoparticle aggregation, breakup, and combination, all of which have a significant impact on nanofluid flow and heat transfer performance.
- Simulation of nanofluids using modelling techniques necessitates thorough research into nanoparticle behaviour mechanisms such as diffusion, phoretic effect, and particle-particle interactions. To that end, more research is needed to understand the role of these phenomena in computational models in order to improve the existing capabilities of predicting nanofluid behaviour under varying flow and geometry conditions.
- The incorporation of multidimensional experimental validation and verification serves as the foundation for imparting reliability and precision to nanofluidic simulations. Prospective research should focus on developing well-structured experimental series with the precision required to satisfy requests for model verification and prediction performance across a wide range of nanofluid challenges.
- Particularity modelling of nanofluids is an excellent approach, but scalability and computational efficiency are critical. As a result, a practical implementation is unlikely unless this issue is fully resolved, including for microscale devices. In addition, new directions should consider developing numerical methods, parallel computing strategies, or optimised algorithms to achieve high-performance computing without sacrificing accuracy.

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