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Particle migration in nanofluids: A critical review

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ABSTRACT

Particle migration in nanofluids has received less than due attention in the literature, and is generally an open research topic requiring more investigation. Particle migration can have great influences on the characteristics of nanofluids through disturbing the distributions of nanoparticle concentration and thermophysical properties. This paper attempts to review and summarize the studies conducted on nanofluids, considering particle migration, including those conducted via methods such as Eulerian-Lagrangian, Buongiorno model, molecular dynamics simulation, and different theoretical approaches. Several important issues are highlighted that deserve greater attention. It is shown that there are still several hot debates for flow and thermal mechanisms in nanofluids, particularly regarding the behavior of nanoparticles. Besides, this survey identifies the challenges and opportunities for future research.

1. Introduction

Nanofluids have emerged as an interesting and novel class of nanotechnology-based heat transfer fluids and have grown significantly in the past few years. Compared to conventional fluids, the superior thermal conductivity and better convective heat transfer as well as little pressure drop have made nanofluids one of the most promising emerging technologies in heat transfer applications. Therefore, there is much excitement about applying nanofluids to meet new challenges in cooling techniques and thermal management of high heat flux equipment. There is, however, only limited knowledge of the mechanisms by which these improvements are evaluated, and how several features (such as particle clustering, interactions with the walls, particle migration, and so forth) affect the behavior of nanofluids. In spite of the substantial amount of effort invested in this area, a satisfactory theoretical explanation has not yet been fully provided for possible heat transfer enhancement mechanism related to nanofluids. Researchers are being challenged to discover the many unexpected hydrothermal characteristics of these fluids, to suggest new mechanisms and unconventional models to explain their behavior. The broad differences in the results presented by different researchers for the same type of, and similar, nanofluids increase the complexity of the problem further.

The number of publications on this subject in the recent years has increased so incrementally such that the number of publications has increased from a few ones before the year 2000 to several hundred in recent years. In spite of fifteen years of serious research effort, the vision of the widespread applicability of nanofluids is still a promise rather than a reality. Despite the ever increasing nanofluid research projects, the state of nanofluid research has not yet clearly been determined, and even has proved to be confusing in several cases. Many inconsistent experimental results existing alongside unproven hypothetical theories in the relevant literature is indicative of the above statement. There are many challenges that need to be pursued in the future. Some of the studies conducted on nanofluids have yielded incomplete results, some have delivered conflicting results, and some have produced doubtful results.

The state of the art in the research of nanofluids is still in its initial phases. A review carried out by Ozerinc et al. [1] shows significant inconsistencies among the available experimental data, and between the experimental results and the predictions of theoretical models. Many reasons may account for this situation. The complex nature of nanoparticles, even the more complex nanoparticle-based fluid interactions as well as different preparation methods employed in experimental investigations, that are often coupled with diverse surfactants, are among reasons resulting in such inconsistencies in research projects on nanofluids. Another significant reason can be the fact that nanofluids are commonly considered by many researchers as a homogenous (single-phase) medium with a uniform distribution of

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nanoparticles. Such an approach can lead to great errors in nanofluid simulation results. In fact, one of the main factors accounting for inconsistencies prevalent in nanofluid research projects is ignoring the effects of particle migration on flow and heat transfer characteristics.

Flow-induced particle migration has been attributed by some researchers as a probable important mechanism for enhanced heat transfer in nanofluids. Particle migration modifies profiles of velocity and thermophysical properties by disturbing the particle concentration distribution; this, as a result, can change the heat transfer rate. Physically, the particle migration idea is to consider that nanofluids are a heterogeneous two-phase mixture. Its success in predicting laminar flow and heat transfer reveals that particle-fluid interaction missing in the widely applied homogeneous models of nanofluids should be explored further to show the essential mechanisms of thermal transport in nanofluids. In order to improve our understanding of convection heat transfer of nanofluids, it is critical to understand the dynamics of nanoparticles.

Particle migration in conventional suspensions (i.e., suspensions containing millimeter and micrometer particles) has been subject to many studies. The studies show that suspensions with spherical particles have a non-uniform concentration distribution in a nonhomogeneous shear flow [2]. In suspensions with rather larger particles, factors such as non-uniform shear rate and viscosity gradient affect particle migration. However, as particles get smaller, factors such as Brownian motion and thermophoresis, in addition to above mentioned parameters, gain some significance.

Unlike suspensions containing micron-sized particles, a few studies have evaluated the particle migration in nanofluids. There are very few studies conducted on suspensions of particles for which Brownian motion is important. For Brownian suspensions, Brownian motion can have a significant effect on the cross-stream migration, as concluded by Frank et al. [3]. Wen and Ding [4] examined the movement of nanoparticles in laminar pressure-driven pipe flows considering Brownian motion for dilute suspensions. They demonstrated that the particle concentration near the wall is noticeably smaller than that at the tube center.

With changes in particle size, even the dependency of particle migration on flow rate undergoes some changes. For instance, Semwogerere et al. [5] presented the concentration profile of suspensions of Brownian particles. They demonstrated that, in contrast with non-Brownian suspensions, flow rate has a significant effect on the concentration profile in a Brownian suspension. Regarding the important effect of particle size, the results of previous studies (i.e., the studies performed on suspensions containing particles larger than nano-scale) cannot be applied to suspensions containing nanoparticles (i.e. nanofluids).

It is very important to understand the flow behavior and particle migration in nanofluids in order to make application of nanofluids feasible in the near future. Particle migration can affect overall heat transfer performance. When concentration shows non-uniform distribution, the effective properties will incorporate non-uniform distributions. The convective heat transfer coefficient and pressure drop are significantly affected by the values of near-wall thermal conductivity and viscosity. Therefore, it is crucially important to consider particle migration in the analysis of nanofluid problems, which has thus far been overlooked in most of the studies carried out on nanofluids.

Most of the studies have considered a uniform particle distribution for nanofluids [6,7]. However, particles can migrate under conditions of shear and viscosity gradient [8], such that using uniform concentration will introduce errors to the results. Nanoparticle motion (believed to have a key contribution to enhanced heat transfer) is governed by superposition of several effects (thermophoresis, Saffman lift force, Brownian motion, Soret and Dufour effects, and so forth), some of which are not yet fully understood since they only become important at very small length scales. Studying particle migration in nanofluids can help better understand the physics concepts behind nanofluids, and also decrease some of the inconsistencies existing in the current literature.

It is not the objective of this survey to generally review the related literature of nanofluids, since it has been done in a number of recent publications [9–12]. In fact, this paper aims to review the conducted studies in which particle migration in nanofluids has been taken into consideration. Particle migration is a subject which is less studied in related investigations conducted on nanofluids. This review paper also identifies the existing challenges and opportunities in this area and attempts to present directions for future studies. The author of this paper hopes that the current contribution can provide a brighter path for further research on nanofluids.

2. Particle migration in conventional suspensions

Suspensions have motivated a great number of researchers to study this subject due to their widespread applications in industry. These studies are focused on suspensions containing particles of micron and millimeter sizes, in which Brownian motion does not usually play a key role. Before evaluating the subject of particle migration in nanofluids, the most significant studies conducted on conventional suspensions considering particle migration are introduced.

Particle migration is an important issue in suspensions in a vast range of engineering applications such as composite materials, transport of sediments, heat transfer, oil recovery, chromatography, sequestration processes in porous media, and even flow of blood. Research studies on the cross-stream migration of particles have occupied a significant position in suspension rheology since the study performed by Segre and Silberberg [13] in 1962 on the inertial migration of particles in a tube flow, and the study conducted by Leighton and Acrivos [8] in 1987 on the particle–particle interaction in a concentrated suspension.

Several studies have been conducted on the mechanisms of particle migration in suspensions containing micron-sized particles both by experiment [14,15] and combined simulation and modeling [16,17]. Many models have been suggested for the study of suspension flows. The continuum models that are applied to explain the particle migration fall basically into two categories: the diffusive flux model by Phillips et al. [18], and the suspension balance model by Nott and Brady [19]. These models have attained some level of success in predicting qualitative features of migration process and concentration distribution.

Phillips et al. [18] applied the scaling arguments of Leighton and Acrivos [8] to develop the so-called diffusive flux model. In this model, particle migration results from gradients in viscosity, shear rate, and concentration. This model was modified by Fang et al. [20] to account for the various rates of migration in the shear plane. In an alternative modeling method based on the conservation laws, designated as the balance model of suspension, the stress in particle phase is expressed via a constitutive equation, and particle transport is evaluated by rheological models. The suspension balance model was refined by Morris and Boulay [21] and Shapley et al. [22] to explain non-isotropic migration rates and to progress the modeling of particle velocity fluctuations. Applying this model and the finite volume method, Miller and Morris [23] simulated the pressure driven flow of a non-colloidal suspension in a two-dimensional geometry and axisymmetric circular channels. Furthermore, Miller et al. [24] modified the established shear-based rheological model of Morris and Boulay [21] and introduced a