

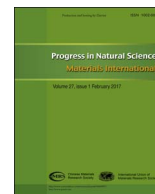
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Review

Dispersion stability of thermal nanofluids[☆]

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ABSTRACT

Thermal nanofluids, the engineered fluids with dispersed functional nanoparticles, have exhibited extraordinary thermophysical properties and added functionalities, and thus have enabled a broad range of important applications. The poor dispersion stability of thermal nanofluids, however, has been considered as a long-existing issue that limits their further development and practical application. This review overviews the recent efforts and progresses in improving the dispersion stability of thermal nanofluids such as mechanistic understanding of dispersion behavior of nanofluids, examples of both water-based and oil-based nanofluids, strategies to stabilize nanofluids, and characterization techniques for dispersion behavior of nanofluids. Finally, on-going research needs, and possible solutions to research challenges and future research directions in exploring stably dispersed thermal nanofluids are discussed.

1. Introduction

As one of the oldest forms of energy, thermal energy is the heart of energy chain linking the primary energy sources such as fuels and optical energy and the secondary energy sources such as mechanical energy and electricity. Currently, ~ 90% of the global energy budget is related to heat generation, transmission, storage or dissipation. In recent years, the rapid development of advanced thermal materials and engineering technologies [1] has spurred intensive investigations on high-performance thermal energy detection [2], thermal transportation [3–5], thermal storage [6,7] and thermal-related applications for different purposes [8–13]. Thermal nanofluids, as one of the newly emerged enabling thermal materials, have been intensively studied in both academic institutes and industrial companies to advance their thermal engineering applications in high thermal conductivity heat transfer [14–18], solar-thermal energy harvesting and storage [7,19], smart cooling [20], and advanced thermal management of electronics [21,22].

Since the establishment of the concept by Choi [23], many experimental and theoretical studies have been carried out to investigate the thermophysical properties of the thermal nanofluids such as thermal conductivity and viscosity [24], and evaluate their effectiveness in improving the performance of thermal devices and systems [25–27]. Commonly, thermal nanofluids use water, ethylene glycol or oil as the

base fluids, and thus the resultant fluids can be classified as either water-based or oil-based fluids. The frequently added NPs include metallic particles, metal oxide particles, ceramic particles, graphite, carbon nanotube, and graphene. To fulfill their potential and realize industrial applications, stable dispersion of thermal nanofluids is a prerequisite. The added NPs, however, generally have poor compatibility with the base fluids and have the strong tendency to form aggregation. Over time, the aggregated NPs would be phase-separated and precipitated out of the fluids. The aggregated nanofluids would not only lose their original advantages, such as enhanced heat transfer and volumetric solar-thermal conversion capability that relies on dynamic Brownian motion of NPs within the base fluids, but also cause clogging and abrasion issues in particular for heat-transfer channels in micro-electronic systems.

To date, dispersion stability has been considered as one of most challenging issues that limit the practical usage and further development of nanofluids [28]. Especially for thermal nanofluids, they are subjected to high temperatures or repeated heating/cooling cycles, which greatly increase the NP collision probability and aggregation tendency. It is thus even more challenging to achieve stable dispersion of thermal nanofluids. To address this problem, great efforts have been devoted to improving the dispersion stability of thermal nanofluids by using various approaches such as mechanical stirring, ultrasonic treatment, introducing surface charges or utilizing chemical surface

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modification with surfactants. Moderate progresses have been made in preparation of homogeneously dispersed nanofluids, but the reported work is discrete, thus calling for a comprehensive overview of the state-of-the-art research in this field. Another fact is that most studies of nanofluids dispersion behavior are carried out by chemists and material scientists, whereas the applications of thermal nanofluids are mostly investigated by researchers in mechanical engineering and thermophysical engineering. A systematic summary of dispersing strategies of thermal nanofluids would provide general guideline on the preparation and characterization of stably dispersed thermal nanofluids, and also help bridge the gap between researches in different disciplines.

In this work, we specifically focus on the dispersion stability of thermal nanofluids, while previous reviews were focused on the fabrication [29–31], thermophysical properties [24–27,32,33] or applications [21,34–37] of thermal nanofluids. We start with discussion of dispersing challenge and dispersing mechanism of thermal nanofluids through analyzing the forces that are exerted on the NPs within the fluids. Then, we overview the specific approaches for preparing both water-based and oil-based thermal nanofluids by using representative nanofluid systems containing metallic NPs, metal oxide NPs, and ceramic NPs as examples. In particular, we summarize the dispersion strategies for carbon-based nanofluids in both water and oil fluids considering their widespread popularity in scientific community and potential technological significance. Typical characterization techniques for the dispersion behavior of thermal nanofluids are also discussed. Finally, we discuss the needs for continued fundamental research effort, point out possible solutions, and identify future research directions in this field.

2. Dispersion of thermal nanofluids

2.1. Dispersing challenge

The dispersion behavior of nanofluids depends on the interplay of various microscopic forces that are exerted on the NPs. For single NP within the base fluid, due to density difference the gravity force tends to cause the sedimentation of NPs. Meanwhile, the NP within fluid is undergoing random thermal motion and thus subjecting to Brownian force, which can counterbalance the gravitational sedimentation and help disperse the NP (Fig. 1). Quantitatively, for a spherical NP with a diameter of d dispersed in a medium with dielectric constant of ϵ , the

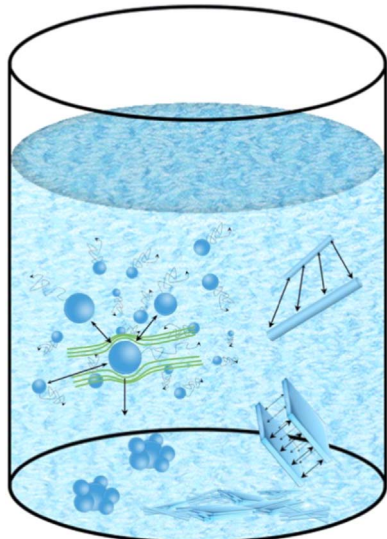


Fig. 1. Schematic of nanofluid dispersion showing various types of forces exerted on single nanoparticle, and interaction between neighboring nanoparticles, nanorods and nanosheets, which leads to aggregation within base fluid.

forces could be estimated [38]. After deducting the buoyancy, the effective gravitational force of the NP is on the order of $O(d^3\Delta\rho g)$, where $\Delta\rho$ is the density difference between the NP and the base fluid and g is the gravitational acceleration ($\sim 9.8 \text{ m/s}^2$). The Brownian force is of the order of $O(k_B T/d)$, where k_B is the Boltzmann's constant, T is the absolute temperature. Based on diffusion-sedimentation equilibrium [39], to keep the NP suspended by virtue of Brownian motion, the sizes of particles need to meet the criterion $d = (\frac{6k_B T}{\pi g \Delta\rho})^{1/4}$. Based on this dependence, for a specific type of NP its theoretical maximum particle size could be roughly estimated. For example, for a low density particle ($\Delta\rho = 1 \text{ g/cm}^3$), the maximum d could be $\sim 1 \text{ }\mu\text{m}$, but for the high density particles such as particles of gold, the maximum d is $\sim 500 \text{ nm}$. For the moving NP, it also subject to viscous force and this force can help mitigate the sedimentation of NPs. According to Stokes law [40], the viscous forces for the particle with a moving speed of v is on the order of $O(\eta dv)$, where η is the viscosity of the fluid. The Stokes sedimentation velocity (V) of NPs within base fluid can be estimated by $V = \frac{d^2}{36\eta} \Delta\rho g$, based upon which the particle size range could be further refined. The typical size for metal, metal oxide or ceramic NP is less than 100 nm , and for low density carbon NPs the dispersible particle size could be sub-micrometer.

Besides these forces that act on single NP, the inter-particle interaction forces have also played dominant role in affecting the dispersion behavior of thermal nanofluids [41,42]. During the interaction between NPs, neighboring NPs tend to aggregate together under the attractive interaction forces, such as van der Waals dispersion force (Fig. 1). The attractive van der Waals dispersion force is on the order of $O(A_{\text{eff}}/d)$, where A_{eff} is the Hamaker constant that depends on the dielectric constant contrast between the NPs and the medium [43]. The electrostatic forces between two neighboring NPs could be estimated by $\epsilon\epsilon_0\zeta^2$, where ϵ is the permittivity of the base fluid, ϵ_0 is the vacuum permittivity and ζ is the electrostatic potential of the NPs. The absolute magnitude of the inter-particle interaction forces is strongly dependent on the distance between neighboring NPs. Within short distances when the attractive force dominates over the repulsive force, NPs favor to form aggregates. In addition to inter-particle distance, the shape of NPs also influences the attractive interaction between neighboring particles. By comparison, the neighboring plated or rod-shaped NPs have larger contact area than the spherical NPs, thus they have stronger attraction between neighbors and stronger tendency to form aggregation [38,41]. For the aggregated particles, the sedimentation or gravitational force, which is much less than Brownian force before the aggregation, starts to dominate the dispersion behavior. Thermodynamically, the nanofluid, as a whole, is subject to entropic force, which homogenizes the distribution of NPs within the base fluid by maximizing the mixing entropy of the dispersion system. For thermal nanofluids, the high service temperature, on one hand, favors the Brownian motion of the NPs within the based fluid. The accelerated movement could increase the collision probability between different NPs, and thus favor the formation of aggregates. On the other hand, the viscosity of the fluid quickly decreases with temperature and thus the reduced dragging force would also favor aggregation. For the thermal nanofluids applied under repeated heating/cooling cycles, the local temperature gradient would cause convective movement of the NPs. Such collective directional movement of the NPs would disturb the homogeneous dispersion of nanofluids and promote aggregation.

2.2. Dispersing mechanism

From the above discussion, it is critical to overcome the attractive inter-particle interaction to obtaining stable dispersion of nanofluids. In general, two types of dispersing mechanisms, namely electrostatic stabilization and steric stabilization, have been developed to increase the repulsive inter-particle interaction, which can counterbalance the attractive van der Waals dispersion force.

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