
editorial

Nanofluids: A New Field of Scientific Research and Innovative Applications

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In the early 1990s, as I began exploring ways to apply nanotechnology to heat transfer engineering, I saw the possibility of breaking down the century-old technical barriers of conventional solid-liquid suspensions by stably suspending nanoparticles. During the past decade, a series of pioneering experiments have discovered that nanofluids exhibit a number of novel thermal transport phenomena. Nanofluids are of great scientific interest because these new thermal transport phenomena surpass the fundamental limits of conventional macroscopic theories of suspensions. Furthermore, nanofluids technology can provide exciting new opportunities to develop nanotechnology-based coolants for a variety of innovative applications. As a result, the study of nanofluids has emerged as a new field of scientific research and innovative applications. The nanofluids review paper in this issue of Heat Transfer Engineering reports on the current status of nanofluids production; shows verified parametric trends and magnitudes in thermal conductivity and heat transfer enhancement in nanofluids; and assesses the current status of nanofluids applications. This paper also points to future research directions to achieve ultrahigh heat transfer enhancement.

Today more than ever, cooling is one of the most pressing needs of many industrial technologies because of ever-increasing heat generation rates at both the micro-level (such as computer chips) and at the macro-level (such as car engines). However, conventional heat transfer fluids such as air, water, ethylene glycol, and oil have inherently low thermal conductivity compared to solids.

Efforts to enhance the inherently poor thermal conductivity of liquids by adding solid particles began more than a century ago, when the great scientist James Clerk Maxwell developed a theoretical model of the electrical conductivity of heterogeneous solid particles [1]. Since then, the classical Maxwell model has been applied to investigations of the thermal conductivity of mixtures of solid particles and liquids. However, all these studies have been confined to millimeter- or micrometer-sized particles. The major problem with the use of microparticles to alter heat transfer is that they settle very rapidly in liquids. They also cause

abrasion, clogging, and additional pressure drop. Furthermore, high particle concentrations are required to obtain appreciable improvements in the thermal conductivities of these suspensions. These problems severely limit the use of conventional solid-liquid suspensions as practical heat transfer fluids. Despite tremendous efforts, the technical barriers mentioned above have remained for more than 100 years.

Modern nanotechnology has enabled the production of nanoparticles with average particle sizes below 100 nm. Nanoparticles generally have mechanical, optical, electrical, magnetic, and thermal properties superior to those of bulk materials of the same composition. In the early 1990s, as I began exploring ways to apply nanotechnology to heat transfer engineering, I saw the possibility of breaking down the century-old technical barriers of conventional solid-liquid suspensions by exploiting the unique properties of nanoparticles. In 1995, I introduced the novel concept of nanofluids and presented the remarkable possibility that with nanofluids, convection heat transfer coefficients could be doubled—the equivalent of increasing pumping power by a factor of ten [2]. Nanofluids are a new class of nanotechnology-based heat transfer fluids

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engineered by dispersing and stably suspending nanoparticles with typical length scales on the order of 10 nm in traditional heat transfer fluids.

During the past decade, a series of pioneering experiments have discovered that nanofluids, when prepared properly, exhibit a number of novel thermal transport phenomena. For example, Eastman et al. [3] found that copper nanofluids show a 40% increase in the thermal conductivity of ethylene glycol at a very low concentration (0.3% by volume) of copper nanoparticles coated with thioglycolic acid. Choi et al. [4], Hong et al. [5], and Murshed et al. [6] discovered that nanofluids containing extremely elongated multiwalled nanotubes or even spherical nanoparticles have a non-linear relationship between thermal conductivity and concentration. Das et al. [7] discovered probably one of the most fantastic features of nanofluids—the thermal conductivity of nanofluids is strongly temperature-dependent, that is, the thermal conductivity enhancement of Al_2O_3 or CuO nanofluids is two to four times that of the base fluid over a small temperature range between 20°C and 50°C . Chon et al. [8] and Chopkar et al. [9] found that nanofluids have strongly size-dependent thermal conductivity. When it was known that nanoparticles decrease the pool boiling heat transfer coefficient, You et al. [10] made the startling discovery that nanofluids containing Al_2O_3 nanoparticles have a three-fold increase in critical heat flux (CHF) over that of pure water at a vanishingly small mass fraction of the order of 10 ppm. Soon Vassallo et al. [11] confirmed this unprecedented enhancement of CHF with SiO_2 nanoparticles in water. Recently, Milanova and Kumar [12] showed that the CHF can be further increased by as much as 350% by increasing fluid pH. Most recently, Kim et al. [13] discovered that the porous nanoparticle layer formed on the heater surface upon boiling of nanofluids significantly improves the surface wettability, which can plausibly explain the CHF enhancement in nanofluids. Ding et al. [14] showed that nanofluids made with carbon nanotubes have a more than two-fold increase in laminar convection heat transfer coefficient, and Xuan and Li [15] showed that water-based nanofluids containing 2 volume % of copper nanoparticles have a nearly 40% increase in turbulent convection heat transfer coefficient compared to base fluids. These discoveries clearly show that traditional macroscopic theories of solid/liquid suspensions have fundamental limits in explaining these new phenomena and that nanofluids technology can provide exciting new opportunities to develop nanotechnology-based coolants for a variety of innovative engineering and medical applications. Hence, the subject of nanofluids is of great interest worldwide for basic and applied research.

There are some indications that basic and applied research in nanofluids is growing and significant. First, the new, young nanofluids community has published more than 250 research articles since 1995. In 2006 alone, the number of publications in this area in Science Citation Index (SCI) journals topped 100. Second, prestigious institutions worldwide have established research groups or interdisciplinary centers with a focus on nanofluids. Several universities have graduated Ph.D.s in this new area. Third, small businesses and large multinational

companies in different industries and markets are working on nanofluids for their specific applications. As a result, the study of nanofluids has emerged as a new field of scientific research and innovative applications.

The nanofluids review paper in this issue of HTE reports on the current status of nanofluids production, including the barriers and challenges to the commercial production of nanofluids; provides a detailed review of experimental results from multiple research groups to show verified parametric trends and magnitudes in thermal conductivity and heat transfer enhancement in nanofluids; and assesses the current status of nanofluids applications, giving examples of actual and potential applications of nanofluids technology in the transportation, microelectronics, defense, nuclear power, space, and biomedical industries. This paper also points to future research directions to achieve heat transfer enhancement of an order of magnitude. This goal challenges the interdisciplinary nanofluids community to intensify their research on nanofluids in close collaboration with thermal scientists and engineers, material scientists, physicists, chemists, chemical engineers, and colloid and interface scientists.

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