1 Introduction

Ultrahigh-performance cooling is one of the most vital needs of many industrial technologies. However, inherently low thermal conductivity is a primary limitation in developing energy-efficient heat transfer fluids that are required for ultrahigh-performance cooling. Modern nanotechnology can produce metallic or nonmetallic particles of nanometer dimensions. Nanomaterials have unique mechanical, optical, electrical, magnetic, and thermal properties. Nanofluids are engineered by suspending nanoparticles with average sizes below 100 nm in traditional heat transfer fluids such as water, oil, and ethylene glycol. A very small amount of guest nanoparticles, when dispersed uniformly and suspended stably in host fluids, can provide dramatic improvements in the thermal properties of host fluids. Nanofluids (nanoparticle fluid suspensions) is the term coined by Choi (1995) to describe this new class of nanotechnology-based heat transfer fluids that exhibit thermal properties superior to those of their host fluids or conventional particle fluid suspensions. Nanofluid technology, a new interdisciplinary field of great importance where nanoscience, nanotechnology, and thermal engineering meet, has developed largely over the past decade. The goal of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentrations (preferably < 1% by volume) by uniform dispersion and stable suspension of nanoparticles (preferably < 10 nm) in host fluids. To achieve this goal it is vital to understand how nanoparticles enhance energy transport in liquids.

Since Choi conceived the novel concept of nanofluids in the spring of 1993, talented and studious thermal scientists and engineers in the rapidly growing nanofluids community have made scientific breakthrough not only in discovering unexpected thermal properties of nanofluids, but also in proposing new mechanisms behind enhanced thermal properties of nanofluids, developing unconventional models of nanofluids, and identifying unusual opportunities to develop next-generation coolants such as smart coolants for computers and safe coolants for nuclear reactors. As a result, the research topic of nanofluids has been receiving increased attention worldwide. The recent growth of work in this rapidly emerging area of nanofluids is most evident from the exponentially increasing number of publications. Figure 1.1 shows clear evidence of the significance of nanofluids research.

Since 1999 the nanofluids community has published more than 150 nanofluid-related research articles. In 2005 alone, 71 research articles were published in
Fig. 1.1 Annual SCI publications on nanofluids.

*Science Citation Index* (SCI) journals such as *Nature Materials Physical Review Letters*, and *Applied Physics Letters*. In addition to the increasing number of articles published per year, there are two more indicators that give weight to the argument that nanofluid research is getting more and more active and important. First, prestigious institutions worldwide, including the Massachusetts Institute of Technology (MIT), the University of Leeds, and the Royal Institute of Technology, Sweden have established nanofluid research groups or interdisciplinary centers that focus on nanofluids. Several universities have graduated Ph.D.s in this new area of nanofluids. Second, small businesses and large multinational companies in different industries and markets are working on these promising coolants for their specific applications. Escalating interest in nanofluids is based on the realization that it is possible to develop ultrahigh-performance coolants whose thermal properties are drastically different from those of conventional heat transfer fluids, because in the nanoscale range, fundamental properties of nanomaterials such as nanofluids depend strongly on particle size, shape, and the surface/interface area.

The main objective of this introductory chapter is to sketch out a big picture of the small world of nanofluids through a brief review of some historically major milestones such as the concept of nanofluids, the production and performance of nanofluids, the mechanisms and models of nanofluids, and potential applications and benefits of nanofluids. Finally, future research on the fundamentals and applications of nanofluids is addressed. The future research directions described in this chapter are not inclusive but illustrate how to undertake the challenges inherent in developing theory of nanofluids and in scaling up production of nanofluids. Nanofluids are being developed to achieve ultrahigh-performance cooling.
and have the potential to be next-generation coolants, thus representing a very significant and far-reaching cooling technology for cross-cutting applications.

1.1. FUNDAMENTALS OF COOLING

1.1.1. Cooling Challenge

Cooling is indispensable for maintaining the desired performance and reliability of a wide variety of products, such as computers, power electronics, car engines, and high-powered lasers or x-rays. With the unprecedented increase in heat loads (in some cases exceeding 25 kW) and heat fluxes (in some cases exceeding 2000 W/cm²) caused by more power and/or smaller feature sizes for these products, cooling is one of the top technical challenges facing high-tech industries such as microelectronics, transportation, manufacturing, metrology, and defense. For example, the electronics industry has provided computers with faster speeds, smaller sizes, and expanded features, leading to ever-increasing heat loads, heat fluxes, and localized hot spots at the chip and package levels. These thermal problems are also found in power electronics or optoelectronic devices. Air cooling is the most basic method for cooling electronic systems. However, heat fluxes over 100 W/cm² in electronic devices and systems will necessitate the use of liquid cooling. Recently, single-phase liquid cooling technologies such as the microchannel heat sink, and two-phase liquid-cooling technologies such as heat pipes, thermosyphons, direct immersion cooling, and spray cooling for chip- or package-level cooling have emerged. Nanofluid technology offers a great potential for further development of high-performance, compact, cost-effective liquid cooling systems.

In the transportation industry, cooling is a crucial issue because the trend toward higher engine power and exhaust-gas regulation or hybrid vehicles inevitably leads to larger radiators and increased frontal areas, resulting in additional aerodynamic drag and increased fuel consumption. A pressing need for cooling also exists in ultrahigh-heat-flux optical devices with brighter beams, such as high-powered x-rays.

1.1.2. Conventional Methods to Enhance Heat Transfer

The conventional way to enhance heat transfer in thermal systems is to increase the heat transfer surface area of cooling devices and the flow velocity or to disperse solid particles in heat transfer fluids. However a new approach to enhancing heat transfer to meet the cooling challenge is necessary because of the increasing need for more efficient heat transfer fluids in many industries, such as the electronics, photonics, transportation, and energy supply industries.

Conventional Solid–Liquid Suspensions and Their Limitations The century-old technique used to increase cooling rates is to disperse millimeter- or micrometer-sized particles in heat transfer fluids. The major problem with suspensions containing millimeter- or micrometer-sized particles is the rapid settling
of these particles. If the fluid is kept circulating to prevent particle settling, millimeter- or micrometer-sized particles would wear out pipes, pumps, and bearings. Furthermore, such particles are not applicable to microsystems because they can clog microchannels. These conventional solid fluid suspensions are not practical because they require the addition of a large number of particles (usually, \( >10 \text{ vol}\% \)), resulting in significantly greater pressure drop and pumping power.

**Microchannel Cooling and Its Limitations** Another way to increase heat rejection rates is to use extended surfaces, such as fins and microchannels, for air or liquid cooling. The present-day manufacture of microchannel structures with characteristic dimensions of less than 100 \(\mu\text{m} \) and the application of these microchannel structures to heat exchangers (Tuckerman and Peace, 1981) represents an engineering breakthrough in heat transfer technology because microscale heat-exchangers have the potential to reduce the size and effectiveness of various heat-exchange devices.

Microscale heat exchangers have numerous attributes, including high thermal effectiveness, high heat transfer surface/volume ratio, small size, low weight, low fluid inventory, and design flexibility. Because their microchannel systems are extremely compact and lightweight compared to conventional systems, materials and manufacturing costs could be lowered, an attractive advantage that would draw the interest of many manufacturing firms. For example, the electronics industry has applications in cooling advanced electronic packages; for the automotive industry, the weight difference between conventional and microchannel systems (such as in air conditioners) could lead to significant gains in fuel economy; in the heating, ventilation, and air-conditioning (HVAC) industry, refrigeration and air-conditioning equipment volumes could be reduced, and this would save space in buildings; and in chemical and petroleum plants, plant size could be reduced through process intensification. Minimizing the size and weight of cooling systems based on microchannel cooling technology is also crucial in the military–avionics industry. Unfortunately, current designs of thermal management systems have already adopted this extended surface technology to its limits. Therefore, with continued miniaturization and increasing heat dissipation in new generations of products, the cooling issue will intensify in many industries: from electronics and photonics to transportation, energy supply, defense, and medical. Nanofluids are being developed in response to these pressing needs for more efficient heat transfer fluids in many industries.

### 1.2. FUNDAMENTALS OF NANOFLOUIDS

Heat transfer is one of the most important processes in many industrial and consumer products. The inherently poor thermal conductivity of conventional fluids puts a fundamental limit on heat transfer. Therefore, for more than a century since Maxwell (1873), scientists and engineers have made great efforts to break this fundamental limit by dispersing millimeter- or micrometer-sized particles in
liquids. However, the major problem with the use of such large particles is the rapid settling of these particles in fluids. Because extended surface technology has already been adapted to its limits in the designs of thermal management systems, technologies with the potential to improve a fluid’s thermal properties are of great interest once again. The concept and emergence of nanofluids is related directly to trends in miniaturization and nanotechnology. Maxwell’s concept is old, but what is new and innovative in the concept of nanofluids is the idea that particle size is of primary importance in developing stable and highly conductive nanofluids.

1.2.1. Miniaturization and Nanotechnology

Since Nobel prize winner Richard P. Feynman presented the concept of micromachines in his seminal talk, “There’s Plenty of Room at the Bottom—An Invitation to Enter a New Field of Physics,” in December 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (available on the Web at http://nano.xerox.com/nanotech/feynman.html), miniaturization has been a major trend in modern science and technology. Almost 40 years later, another Nobel prize winner, H. Rohrer, presented the chances and challenges of the nano-age and declared that nanoscience and nanotechnology had entered the limelight in the 1990s from virtual obscurity in the 1980s (Rohrer, 1996). Nano is a prefix meaning one-billionth, so a nanometer is one-billionth of a meter. Nanotechnology is the creation of functional materials, devices, and systems by controlling matter at the nanoscale level, and the exploitation of their novel properties and phenomena that emerge at that scale.

Early reviews of research programs on nanotechnology in the United States, China, Europe, and Japan show that nanotechnology will be an emerging and exciting technology of the twenty-first century and that universities, national laboratories, small businesses, and large multinational companies have established nanotechnology research groups or interdisciplinary centers that focus on nanotechnology (Fissan and Schoonman, 1998; Hayashi and Oda, 1998; Li, 1998; Roco, 1998).

Just as downsizing is a fashion in the world of business, downscaling such as microelectromechanical system (MEMS) technology and nanotechnology is a clear fashion in the world of science and technology. One feature of these rapidly emerging technologies is that they are strongly interdisciplinary. In the coming nano-age, nanotechnology with unforeseen applications is expected to revolutionize many industries. Nanotechnology is expected to affect society in the twenty-first century as much as the silicon transistor, plastics, and antibiotics did in the twentieth century. It is estimated that nanotechnology is at a level of development similar to that of computer/information technology in the 1950s (Roco, 1998).

Engineers now fabricate microscale devices such as microchannel heat exchangers and micropumps that are the size of dust specks. Further major advances would be obtained if the coolant flowing in the microchannels were
to contain nanoscale particles to enhance heat transfer. Nanofluid technology will thus be an emerging and exciting technology of the twenty-first century. With the continued miniaturization of technologies in many fields, nanofluids with a capability of cooling high heat fluxes exceeding 1000 W/cm² would be paramount in the advancement of all high technology.

1.2.2. Emergence of Nanofluids

The emergence of nanofluids as a new field of nanoscale heat transfer in liquids is related directly to miniaturization trends and nanotechnology. Here a brief history of the Advanced Fluids Program at Argonne National Laboratory (ANL) is described to show that the program has encompassed a wide range (meters to nanometers) of size regimes and how a wide research road has become narrow, starting with large scale and descending through microscale to nanoscale in this program, culminating in the invention of nanofluids.

**Large-Scale Heat Transfer Experiments** In 1985, ANL started a long-term research program to develop advanced energy transmission fluids. Sufficient funding for this program was provided through the Buildings and Community Systems staff of the U.S. Department of Energy (DOE). Early efforts focused on the development of advanced energy transmission fluids for use in district heating and cooling (DHC) systems. These systems are characterized by long distribution pipes of large diameter that convey pumped energy transmission fluids between the source and sink heat exchangers. These systems operate with small temperature differences, and therefore large volumes of fluids must be pumped to satisfy load demands. The Advanced Fluids Program for DHC applications included friction-reducing additives and phase-change materials. Friction-reducing additives have been tested in a large-scale DHC system simulator with a pipe diameter of 0.15 m and a length of 21.34 m.

Realizing that large-scale experiments are very costly, the advanced fluids team had to find an exit from large-scale tests. Choi learned that mirror cooling was an important issue at ANL’s new advanced photon source (APS). His proposal was funded by the APS Laboratory Directed Research and Development (LDRD) Program. This project represented a dramatic downscaling, from 0.15-m pipe to 50-µm channels. However, he did not stop in this microworld but continued his downscaling journey until his research culminated in the invention of nanofluids.

**Microscale Heat Transfer Project** The APS is a user facility for synchrotron radiation research. The first optical elements of the APS beamlines absorb a tremendous amount of energy that is rapidly transformed to heat as the elements reflect the beam. Cooling these high-heat-load x-ray optical elements proved to be a formidable task that could not be handled by conventional cooling technologies, and thus a new and innovative cooling method was needed. In 1991, Choi developed a new project to design and analyze a microchannel heat exchanger that uses liquid-nitrogen as the cooling fluid. The work by Choi et al. (1992) on
microchannel liquid-nitrogen cooling of high-heat-load silicon mirrors represents a milestone in the area of microscale forced-convection heat transfer (Duncan and Peterson, 1994). For Choi, this project had another significance: It was crucial in positioning him for bridging microtechnology with nanotechnology, as described in the next section.

**Nanoscale Heat Transfer as a New Heat Transfer Enhancement Approach**

When Choi worked on microchannel liquid-nitrogen cooling, he noted its limit: that the pressure drop in the microchannel heat exchanger increases significantly as the diameter of the flow passage decreases and that a cryogenic system is needed for liquid-nitrogen cooling. In a microchannel liquid-nitrogen heat exchanger, the heat transfer would be excellent, but at the cost of high pumping power and an expensive cryogenic system. Furthermore, continuing cooling demands from future x-ray source intensities at the APS have driven him to think of a new heat transfer enhancement approach. He wanted to develop a new heat transfer fluid concept that enables heat transfer enhancement without a large pumping power increase and without cryogenic coolants. So he focused on the thermal conductivity of the fluid itself rather than on channel size.

Although Maxwell’s idea of using metallic particles to enhance the electrical or thermal conductivity of matrix materials is well known (Maxwell, 1873), Choi realized through his research project experience with suspensions of micrometer-sized particles and fibers in the 1980s that such conventional particles cannot be used in microchannel flow passages. However, modern nanotechnology provides great opportunities to process and produce materials with average crystallite sizes below 50 nm. Recognizing an opportunity to apply this emerging nanotechnology to established thermal engineering, Choi focused on a smaller world and while reading several articles on nanophase materials, wondered, what would happen if nanoparticles could be dispersed into a heat transfer fluid and visualized the concept of nanofluids: stable suspensions of dancing nanoparticles in liquids. Choi first thought of validating the idea when he read an article in the ANL publication *Logos* on nanocrystalline materials (Siegel and Eastman, 1993) and realized that ANL’s Materials Science Division (MSD) has a unique capability to produce nanophase materials. DOE’s Basic Energy Sciences office has funded MSD to work on the synthesis, microstructural characterization, and properties of nanophase materials, although all of that work was focused on producing nanoparticles and consolidating them to make solids and then characterizing the novel properties of these solid bulk nanophase materials.

When Choi received an ANL director’s call for proposals in May 1993, he wrote a proposal in which he proposed that nanometer-sized metallic particles could be stably suspended in industrial heat transfer fluids to produce a new class of engineered fluids with high thermal conductivity. He submitted his first nanofluids proposal to an annual competition within the lab for startup funding. This proposal was not funded, however, nor was a second proposal developed with MSD’s J. A. Eastman. A third proposal, in 1994, was successful. This first nanofluids project was funded for three years and ended in 1997. Since then,
Argonne’s nanofluids research has received external funding from DOE to work on issues related to both fundamentals and applications of nanofluids. In addition to the work at Argonne, investigators in Japan and Germany have published articles that describe fluids resembling those developed at ANL. However, it should be noted that ANL developed the concept of nanofluids independent of the work in Japan and Germany. Masuda et al. worked on the thermal conductivity and viscosity of suspensions of Al$_2$O$_3$, SiO$_2$, and TiO$_2$ ultrafine particles and published a paper written in Japanese (Masuda et al., 1993). Although there are similarities between the Japanese work and our own, there are also several important distinctions. For example, the Japanese investigators added an acid (HCl) or base (NaOH) to produce suspensions of oxide particles because their oxide particles did not form stable suspensions in fluids. However, we were able to make stable nanofluids with no dispersants at all. We discovered that our oxide nanoparticles have excellent dispersion properties and form suspensions that are stable for weeks or months. Furthermore, the unique thermal features of ANL’s nanofluids are the principal distinction between the Japanese and ANL work.

In 1993, Arnold Grimm, an employee of R.-S. Automatis in Mannheim, Germany obtained a patent related to improved thermal conductivity of a fluid containing dispersed solid particles (Grimm, 1993). He dispersed Al particles measuring 80 nm to 1µm into a fluid. He claimed a 100% increase in the thermal conductivity of the fluid for loadings of 0.5 to 10 vol%. The serious problem with these suspensions was rapid settling of the Al particles, presumably because in his study the particle size was much larger than in Argonne’s nanofluids work.

1.2.3. Development of the Concept of Nanofluids

In the development of energy-efficient heat transfer fluids, the thermal conductivity of the heat transfer fluids plays a vital role. Despite considerable previous research and development efforts on heat transfer enhancement, major improvements in cooling capabilities have been constrained because traditional heat transfer fluids used in today’s thermal management systems, such as water, oils, and ethylene glycol, have inherently poor thermal conductivities, orders-of-magnitude smaller than those of most solids. Due to increasing global competition, a number of industries have a strong need to develop advanced heat transfer fluids with significantly higher thermal conductivities than are presently available.

It is well known that at room temperature, metals in solid form have orders-of-magnitude higher thermal conductivities than those of fluids (Touloukian et al., 1970). For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil, as shown in Table 1.1. The thermal conductivity of metallic liquids is much greater than that of nonmetallic liquids. Therefore, the thermal conductivities of fluids that contain suspended solid metallic particles could be expected to be significantly higher than those of conventional heat transfer fluids.
Table 1.1 Thermal Conductivity of Various Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m · K)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic solids</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>429</td>
</tr>
<tr>
<td>Copper</td>
<td>401</td>
</tr>
<tr>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Nonmetallic solids</td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>3300</td>
</tr>
<tr>
<td>Carbon nanotubes</td>
<td>3000</td>
</tr>
<tr>
<td>Silicon</td>
<td>148</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td>40</td>
</tr>
<tr>
<td>Metallic liquids</td>
<td></td>
</tr>
<tr>
<td>Sodium at 644 K</td>
<td>72.3</td>
</tr>
<tr>
<td>Nonmetallic liquids</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0.613</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>0.253</td>
</tr>
<tr>
<td>Engine oil</td>
<td>0.145</td>
</tr>
</tbody>
</table>

$^a$At 300 K unless otherwise noted.

For more than 100 years, scientists and engineers have made great efforts to enhance the inherently poor thermal conductivity of liquids by adding solid particles in liquids. Numerous theoretical and experimental studies of the effective thermal conductivity of suspensions that contain solid particles have been conducted since Maxwell presented a theoretical basis for predicting the effective conductivity of suspensions more than 100 years ago (Maxwell, 1873). However, all of the studies on the thermal conductivity of suspensions have been confined to millimeter- or micrometer-sized particles. This conventional approach has two major technical problems: (1) conventional millimeter- or micrometer-sized particles settle rapidly in fluids, and (2) the conductivities of these suspensions are low at low particle concentrations. Furthermore, these conventional suspensions do not work with the emerging “miniaturized” devices because they can clog the tiny channels of such devices.

Modern nanotechnology has enabled the production of metallic or nonmetallic nanoparticles with average crystallite sizes below 100 nm. The mechanical, optical, electrical, magnetic, and thermal properties of nanoparticles are superior to those of conventional bulk materials with coarse grain structures. Recognizing an excellent opportunity to apply nanotechnology to thermal engineering, Choi conceived the novel concept of nanofluids by hypothesizing that it is possible to break down these century-old technical barriers by exploiting the unique properties of nanoparticles. Nanofluids are a new class of nanotechnology-based heat transfer fluids engineered by dispersing nanometer-sized particles with typical length scales on the order of 1 to 100 nm (preferably, smaller than 10 nm in diameter) in traditional heat transfer fluids. At the 1995 annual winter meeting of the American Society of Mechanical Engineers (Choi, 1995) Choi presented the remarkable possibility of doubling the convection heat transfer coefficients using ultrahigh-conductivity nanofluids instead of increasing pumping power by a factor of 10.
1.2.4. Importance of Nanosize

As noted above the basic concept of dispersing solids in fluids to enhance thermal conductivity is not new; it can be traced back to Maxwell. Solid particles are added because they conduct heat much better than do liquids. The major problem with the use of large particles is the rapid settling of these particles in fluids. Other problems are abrasion and clogging. These problems are highly undesirable for many practical cooling applications. Nanofluids have pioneered in overcoming these problems by stably suspending in fluids nanometer-sized particles instead of millimeter- or micrometer-sized particles. Compared with microparticles, nanoparticles stay suspended much longer and possess a much higher surface area. The surface/volume ratio of nanoparticles is 1000 times larger than that of microparticles. The high surface area of nanoparticles enhances the heat conduction of nanofluids since heat transfer occurs on the surface of the particle. The number of atoms present on the surface of nanoparticles, as opposed to the interior, is very large. Therefore, these unique properties of nanoparticles can be exploited to develop nanofluids with an unprecedented combination of the two features most highly desired for heat transfer systems: extreme stability and ultrahigh thermal conductivity. Furthermore, because nanoparticles are so small, they may reduce erosion and clogging dramatically. Other benefits envisioned for nanofluids include decreased demand for pumping power, reduced inventory of heat transfer fluid, and significant energy savings.

Because the key building block of nanofluids is nanoparticles (1000 times smaller than microparticles), the development of nanofluids became possible simply because of the advent of nanotechnology in general and the availability of nanoparticles in particular. Researchers in nanofluids exploit the unique properties of these tiny nanoparticles to develop stable and high-thermal-conductivity heat transfer fluids. Stable suspension of small quantities of tiny particles makes conventional heat transfer fluids cool faster and thermal management systems smaller and lighter.

It should be noted that in today’s science and technology, size matters. Size is also an important physical variable in nanofluids because it can be used to tailor nanofluid thermal properties as well as the suspension stability of nanoparticles. Maxwell’s concept is old, but what is new and innovative with the concept of nanofluids is the idea of using nanometer-sized particles (which have become available to investigators only recently) to create stable and highly conductive suspensions, primarily for suspension stability (gravity is negligible) and for dynamic thermal interactions. Nanotechnology offers excellent prospects for producing a new type of heat transfer fluid that has excellent thermal properties and cooling capacity, due primarily to novel nanoscale phenomena—phenomena that overturn our sense of familiarity. Therefore, the pioneers of nanofluids have taken the solid–fluid suspension concept to an entirely new level. Table 1.2 contrasts suspensions of microparticles and nanoparticles and shows the benefits of nanofluids containing nanoparticles.
### Table 1.2 Comparison of the Old and the New

<table>
<thead>
<tr>
<th></th>
<th>Microparticles</th>
<th>Nanoparticles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>Settle</td>
<td>Stable (remain in suspension almost indefinitely)</td>
</tr>
<tr>
<td>Surface/volume ratio</td>
<td>1</td>
<td>1,000 times larger than that of microparticles</td>
</tr>
<tr>
<td>Conductivity\textsuperscript{a}</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Clog in microchannel?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Erosion?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Pumping power</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Nanoscale phenomena?</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\textsuperscript{a}At the same volume fraction.

### 1.3. MAKING NANOFLUIDS

Materials for base fluids and nanoparticles are diverse. Stable and highly conductive nanofluids are produced by one- and two-step production methods. Both approaches to creating nanoparticle suspensions suffer from agglomeration of nanoparticles, which is a key issue in all technology involving nanopowders. Therefore, synthesis and suspension of nearly nonagglomerated or monodispersed nanoparticles in liquids is the key to significant enhancement in the thermal properties of nanofluids.

#### 1.3.1. Materials for Nanoparticles and Fluids

Modern fabrication technology provides great opportunities to process materials actively at nanometer scales.Nanostructured or nanophase materials are made of nanometer-sized substances engineered on the atomic or molecular scale to produce either new or enhanced physical properties not exhibited by conventional bulk solids. All physical mechanisms have a critical length scale below which the physical properties of materials are changed. Therefore, particles smaller than 100 nm exhibit properties different from those of conventional solids. The noble properties of nanophase materials come from the relatively high surface area/volume ratio, which is due to the high proportion of constituent atoms residing at the grain boundaries. The thermal, mechanical, optical, magnetic, and electrical properties of nanophase materials are superior to those of conventional materials with coarse grain structures. Consequently, research and development investigation of nanophase materials has drawn considerable attention from both material scientists and engineers (Duncan and Rouvray, 1989).

1. **Nanoparticle material types.** Nanoparticles used in nanofluids have been made of various materials, such as oxide ceramics (Al$_2$O$_3$, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors
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(TiO₂, SiC), carbon nanotubes, and composite materials such as alloyed nanoparticles Al₇₀Cu₃₀ or nanoparticle core–polymer shell composites. In addition to nonmetallic, metallic, and other materials for nanoparticles, completely new materials and structures, such as materials “doped” with molecules in their solid–liquid interface structure, may also have desirable characteristics.

2. Host liquid types. Many types of liquids, such as water, ethylene glycol, and oil, have been used as host liquids in nano fluids.

1.3.2. Methods of Nanoparticle Manufacture

Fabrication of nanoparticles can be classified into two broad categories: physical processes and chemical processes (Kimoto et al., 1963; Granqvist and Buhrman, 1976; Gleiter, 1989). Currently, a number of methods exist for the manufacture of nanoparticles. Typical physical methods include inert-gas condensation (IGC), developed by Granqvist and Buhrman (1976), and mechanical grinding. Chemical methods include chemical vapor deposition (CVD), chemical precipitation, micro emulsions, thermal spray, and spray pyrolysis. A sonochemical method has been developed to make suspensions of iron nanoparticles stabilized by oleic acid (Suslick et al., 1996).

The current processes for making metal nanoparticles include IGC, mechanical milling, chemical precipitation, thermal spray, and spray pyrolysis. Most recently, Chopkar et al. (2006) produced alloyed nanoparticles Al₇₀Cu₃₀ using ball milling. In ball milling, balls impart a lot of energy to a slurry of powder, and in most cases some chemicals are used to cause physical and chemical changes. These nanosized materials are most commonly produced in the form of powders. In powder form, nanoparticles are dispersed in aqueous or organic host liquids for specific applications.

1.3.3. Dispersion of Nanoparticles in Liquids

Stable suspensions of nanoparticles in conventional heat transfer fluids are produced by two methods: the two-step technique and the single-step technique. The two-step method first makes nanoparticles using one of the above-described nanoparticle processing techniques and then disperses them into base fluids. The single-step method simultaneously makes and disperses nanoparticles directly into base fluids. In either case, a well-mixed and uniformly dispersed nanofluid is needed for successful production or reproduction of enhanced properties and interpretation of experimental data. For nanofluids prepared by the two-step method, dispersion techniques such as high shear and ultrasound can be used to create various particle–fluid combinations.

Most nanofluids containing oxide nanoparticles and carbon nanotubes reported in the open literature are produced by the two-step process. If nanoparticles are produced in dry powder form, some agglomeration of individual nanoparticles may occur due to strong attractive van der Waals forces between nanoparticles. This undesirable agglomeration is a key issue in all technology involving
MAKING NANOFLUIDS

Making nanofluids using the two-step processes has remained a challenge because individual particles quickly agglomerate before dispersion, and nanoparticle agglomerates settle out in the liquids. Well-dispersed stable nanoparticle suspensions are produced by fully separating nanoparticle agglomerates into individual nanoparticles in a host liquid. In most nano fluids prepared by the two-step process, the agglomerates are not fully separated, so nanoparticles are dispersed only partially. Although nanoparticles are dispersed ultrasonically in liquid using a bath or tip sonicator with intermittent sonication time to control overheating of nano fluids, this two-step preparation process produces significantly poor dispersion quality. Because the dispersion quality is poor, the conductivity of the nano fluids is low. Therefore, the key to success in achieving significant enhancement in the thermal properties of nano fluids is to produce and suspend nearly monodispersed or nonagglomerated nanoparticles in liquids.

A promising technique for producing nonagglomerating nanoparticles involves condensing nanophase powders from the vapor phase directly into a flowing low-vapor-pressure fluid. This approach, developed in Japan 20 years ago by Akoh et al. (1978), is called the VEROS (vacuum evaporation onto a running oil substrate) technique. VEROS has been essentially ignored by the nanocrystalline-materials community because of subsequent difficulties in separating the particles from the fluids to make dry powders or bulk materials. Based on a modification of the VEROS process developed in Germany (Wagener et al., 1997), Eastman et al. (1997) developed a direct evaporation system that overcomes the difficulties of making stable and well-dispersed nano fluids. The direct evaporation–condensation process yielded a uniform distribution of nanoparticles in a host liquid. In this much-longed-for way to making nonagglomerating nanoparticles, they obtained copper nano fluids with excellent dispersion characteristics and intriguing properties. The thermal conductivity of ethylene glycol, the base liquid, increases by 40% at a Cu nanoparticle concentration of only 0.3 vol%. This is the highest enhancement observed for nano fluids except for those containing carbon nanotubes. However, the technology used by Eastman et al. has two main disadvantages. First, it has not been scaled up for large-scale industrial applications. Second, it is applicable only to low-vapor-pressure base liquids. Clearly, the next step is to see whether they can compete with the chemical one-step method described below.

Zhu et al. (2004) developed a one-step chemical method for producing stable Cu-in-ethylene glycol nano fluids by reducing copper sulfate pentahydrate (CuSO₄·5H₂O) with sodium hypophosphite (NaH₂PO₂·H₂O) in ethylene glycol under microwave irradiation. They claim that this one-step chemical method is faster and cheaper than the one-step physical method. The thermal conductivity enhancement approaches that of Cu nano fluids prepared by a one-step physical method developed by Eastman et al. (2001). Although the two-step method works well for oxide nanoparticles, it is not as effective for metal nanoparticles such as copper. For nano fluids containing high-conductivity metals, it is clear that the single-step technique is preferable to the two-step method.
The first-ever nanofluids with carbon nanotubes, nanotubes-in-synthetic oil (PAOs), were produced by a two-step method (Choi et al., 2001). Multiwalled carbon nanotubes (MWNTs) were produced in a CVD reactor, with xylene as the primary carbon source and ferrocene to provide the iron catalyst. MWNTs having a mean diameter of \( \sim 25 \text{ nm} \) and a length of \( \sim 50 \mu\text{m} \) contained an average of 30 annular layers. Chopkar et al. (2006) used ball milling to produce Al\(_{70}\)Cu\(_{30}\) nanoparticles and dispersed their alloyed nanoparticles in ethylene glycol.

1.4. EXPERIMENTAL DISCOVERIES

Experimental work in a growing number of nanofluids research groups worldwide has discovered that nanofluids exhibit thermal properties superior to those of base fluids or conventional solid–liquid suspensions. For example, thermal conductivity measurements have shown that copper and carbon nanotube (CNT) nanofluids possess extremely high thermal conductivities compared to those of their base liquids without dispersed nanoparticles (Choi et al., 2001; Eastman et al., 2001) and that CNT nanofluids have a nonlinear relationship between thermal conductivity and concentration at low volume fractions of CNTs (Choi et al., 2001). Soon, other distinctive features, such as strong temperature-dependent thermal conductivity (Das et al., 2003b) and strong size-dependent thermal conductivity (Chon et al., 2005) were discovered during the thermal conductivity measurement of nanofluids.

Although experimental work on convection and boiling heat transfer in nanofluids is very limited compared to experimental studies on conduction in nanofluids, revolutionary discoveries such as a twofold increase in the laminar convection heat transfer coefficient (Faulkner et al., 2004) and a threefold increase in the critical heat flux in pool boiling (You et al., 2003) are as unexpected as the discoveries related to conduction. The potential impact of these discoveries on heat transfer applications is large. Therefore, nanofluids promise to bring about a revolution in cooling technologies. As a consequence of these discoveries, research and development on nanofluids has drawn considerable attention from industry and academia over the past several years.

1.4.1. Milestones in Thermal Conductivity Measurements

Initial experimental work has focused on thermal conductivity measurements as a function of concentration, temperature, and size. Later experimental work on boiling and convection heat transfer of nanofluids has added another dimension to the superb heat transfer properties of nanofluids. The effective thermal conductivities of nanofluids were typically measured using a transient hot-wire (THW) method, as this is one of the most accurate ways to determine the thermal conductivities of materials (Lee et al., 1999). Other methods are the oscillating temperature method and the steady-state method.
Metallic Nanofluids with High Thermal Conductivity at Low Concentrations

Although measurements of the thermal conductivity of nanofluids started with oxide nanoparticles (Masuda et al., 1993; Lee et al., 1999), nanofluids did not attract much attention until Eastman et al. (2001) showed for the first time that copper nanofluids, produced using the single-step direct evaporation method, have more dramatic conductivity increases than those of oxide nanofluids produced by the two-step method. For some nanofluids, a small amount of thioglycolic acid (< 1 vol%) was added to further improve the dispersion. Interestingly, Cu nanoparticles coated with thioglycolic acid gave a 40% increase in the thermal conductivity of ethylene glycol at a particle loading of only 0.3 vol%. This work has demonstrated that metallic nanoparticles whose surface is modified with surfactant molecules produce stable and highly conductive nanofluids at concentrations one order of magnitude lower than those of oxides. Furthermore, this work has shown that the measured thermal conductivities of the copper nanofluids greatly exceed the values predicted by currently available macroscopic theories. Thus, it can be concluded that studies on metallic nanofluids have opened a new horizon with highly enhanced thermal conductivity with low-particle-volume fractions.

Nonlinear Relationship between Thermal Conductivity and Concentration

The high thermal conductivity multiwalled of carbon nanotubes (see Table 1.1), combined with their low densities compared with metals, makes them attractive candidate nanomaterials for use in nanofluids. Choi et al. (2001) were the first to disperse MWNTs into a host material, synthetic poly(α-olefin) oil by the two-step method and measured the effective thermal conductivity of nanotube-in-oil suspensions. They discovered that nanotubes yield an anomalously large increase in thermal conductivity (up to a 150% increase in the conductivity of oil at approximately 1 vol% nanotubes), which is by far the highest thermal conductivity enhancement ever achieved in a liquid. This measured increase in thermal conductivity of nanotube nanofluids is an order of magnitude higher than that predicted using existing theories (Maxwell, 1873; Hamilton and Crosser, 1962; Bonnecaze and Brady, 1990). In fact, all values calculated from these models are almost identical at low volume fractions. The results of Choi et al. show another anomaly. The measured thermal conductivity is nonlinear with nanotube loadings, while all theoretical predictions clearly show a linear relationship. This nonlinear behavior is not expected in conventional fluid suspensions of micrometer-sized particles at such low concentrations. Interestingly, similar results have been reported for polymer–nanotube composites (Devpura et al., 2001; Biercuk et al. 2002). Thus, there could be some common enhancement mechanism (such as percolation) between these two dispersions of carbon nanotubes, one in liquids and the other in polymers.

Xie et al. (2003) dispersed MWNTs in water and ethylene glycol without any surfactant for the first time. The as-received nanotubes were treated with concentrated nitric acid, and their surface was made hydrophilic using a oxygen-containing functional group. Yang et al. (2006) studied the dispersing
energy effect on the thermal conductivity of CNT nanofluids and showed that the aspect ratio of the nanotubes decreased significantly with increased sonication time or dispersing energy, confirming the proposition of Assael et al. (2005). Ding et al. (2006) were the first to study temperature-dependent conductivity of CNT–water nanofluids.

It should be noted that nonlinear relationship between thermal conductivity and concentration has been found with Fe–ethylene glycol nanofluids (Hong et al., 2005). It is interesting to note that the enhancement they got was higher than that obtained by Eastman et al. (2001) with Cu nanoparticles. Murshed et al. (2005) also discovered the nonlinear behavior of water-based nanofluids containing spherical and rod-shaped TiO$_2$ nanoparticles. The Al$_{70}$Cu$_{30}$ nanofluids produced by Chopkar et al. (2006) also show strong nonlinear behavior and thus more than 200% enhancement in thermal conductivity with less than 2.0 vol% of the nanoparticles, which is probably due to uniformly dispersed Al$_{70}$Cu$_{30}$ nanoparticles in ethylene glycol.

**Strongly Temperature-Dependent Thermal Conductivity** Das et al. (2003b) discovered that nanofluids have strongly temperature-dependent conductivity compared to base fluids. Their data for water-based nanofluids containing Al$_2$O$_3$ or CuO nanoparticles show a two- to fourfold increase in thermal conductivity enhancement over a small temperature range between 20 and 50°C. This work opens up the possibility that nanofluids could be employed as “smart fluids,” “sensing” local hot spots, spontaneously increasing their thermal conductivity, and providing more rapid cooling in those regions. This unique feature would make nanofluids very attractive coolants for high–heat-flux devices or applications at elevated temperatures. Das et al. suggested that the strong temperature dependence of thermal conductivity is due to the motion of nanoparticles.

**Strongly Size-Dependent Thermal Conductivity** The size of suspended nanoparticles is critical to the thermal properties of nanofluids. Chon et al. (2005) measured the temperature and nanoparticle size dependency of nanofluid thermal conductivity. Recently, Chopkar et al. (2006) studied the effect of particle size on the thermal conductivity of ethylene glycol–based nanofluids containing Al$_{70}$Cu$_{30}$ nanoparticles and showed a strongly size-dependent thermal conductivity.

**1.4.2. Milestones in Convection Heat Transfer**

Although increases in effective thermal conductivity are important in improving the heat transfer behavior of fluids, a number of other variables also play key roles. For example, the heat transfer coefficient for forced convection in tubes depends on many physical quantities related to the fluid or the geometry of the system through which the fluid is flowing. These quantities include intrinsic properties of the fluid such as its thermal conductivity, specific heat, density, and viscosity, along with extrinsic system parameters such as tube diameter and length and average fluid velocity. Therefore, it is essential to measure the heat transfer performance of nanofluids directly under flow conditions.
Experimentalists have shown that nanofluids have not only better heat conductivity but also greater convective heat transfer capability than that of base fluids. Experiments show unexpectedly that the heat transfer coefficients of nanofluids are much better than expected from enhanced thermal conductivity alone in both laminar and turbulent flow. However, for natural convection, nanofluids have lower heat transfer than that of base fluids.

**Two- to 3.5-fold Increase in the Laminar Heat Transfer Coefficient** Faulkner et al. (2004) conducted fully developed laminar convection heat transfer tests and made the startling discovery that water-based nanofluids containing CNTs provide significant enhancements to the overall heat transfer. First, the heat transfer coefficients of the nanofluids increase with Reynolds number. The heat transfer coefficients of the nanofluid were roughly twice those of plain water at the upper end of the Reynolds number range tested, and it appears that this enhancement will continue to increase with larger Reynolds numbers. Second, nanofluids outperform water, but nanofluids with low particle concentrations (1.1 vol%) perform better than those with higher concentrations (2.2 and 4.4 vol%). This is an unexpected and, indeed, counterintuitive result. This negative concentration dependence of the heat transfer enhancement could be due partially to the interaction between particles. Faulkner et al. proposed that the pseudoturbulence induced by rolling and tumbling CNT agglomerates in a microchannel results in microscale mixing, which enhances the laminar heat transfer coefficient. Since heat transfer applications operate over a wide range of Reynolds numbers and heat fluxes, additional work is needed to develop nanofluids that can provide the most significant benefit to specific heat transfer applications.

In contrast to the work of Faulkner et al., Yang et al. (2005) measured the convective heat transfer coefficients of several nanofluids under laminar flow in a horizontal tube heat exchanger. The average diameter of the disk-shaped graphite nanoparticles used in this research is about 1 to 2 µm, with a thickness of around 20 to 40 nm. Their results indicate that the increase in the heat transfer coefficient of the nanofluids is much less than that predicted from a conventional correlation. Near-wall particle depletion in laminar shear flow is one possible reason for the phenomenon. However, there is a doubt whether this work falls in the category of nanofluids at all because the particle diameter is too large for the particles to be called nanoparticles.

Wen and Ding (2004) were first to study the laminar entry flow of nanofluids and showed a substantial increase in the heat transfer coefficient of water-based nanofluids containing γ-Al₂O₃ nanoparticles in the entrance region and a longer entry length for the nanofluids than for water. Ding et al. (2006) were first to study the laminar entry flow of water-based nanofluids containing multiwalled carbon nanotubes (CNT nanofluids). For nanofluids containing only 0.5 wt% CNTs, the maximum enhancement in the convection heat transfer coefficient reaches over 350% at Re = 800. Such a high level of enhancement could not be attributed purely to enhanced thermal conductivity. They proposed possible mechanisms such as particle rearrangement, reduction of thermal boundary layer thickness due to the presence of nanotubes, and the very high aspect ratio of CNTs.
**Significant Increase in the Turbulent Heat Transfer Coefficient** Xuan and Li (2003) were first to show a significant increase in the turbulent heat transfer coefficient. They found that at fixed velocities, the heat transfer coefficient of nanofluids containing 2.0 vol% Cu nanoparticles was improved by as much as 40% compared to that of water. The Dittus–Boelter correlation failed to predict the improved experimental heat transfer behavior of nanofluids. Recent unpublished work shows that the effect of particle size and shape and dispersion becomes predominant in enhancing heat transfer in nanofluids. Even greater heat transfer effects are expected for nanofluids produced by the one-step process. Therefore, there is great potential to “engineer” ultra-energy-efficient heat transfer fluids by choosing the nanoparticle material as well as by controlling particle size, shape, and dispersion.

**Decrease in the Natural Convection Heat Transfer Coefficient** Putra et al. (2003) were first to study natural convection in nanofluids. Using water with 130-nm Al$_2$O$_3$ and 90-nm CuO particles, they showed that the natural convective heat transfer is lower in nanofluids than in pure water and that this decrease in natural convection heat transfer coefficient increases with particle concentration. Interestingly, they attributed this deterioration to the slip between fluid and particle because the denser CuO particles show more deterioration. Wen and Ding (2005a) studied natural convection in water-based nanofluids containing TiO$_2$ particles and confirmed the deterioration of heat transfer discovered by Putra et al. (2003). However, they attributed this deterioration to convection driven by concentration gradient, particle–surface and particle–particle interaction, and modification of dispersion properties.

### 1.4.3. Milestones in Boiling Heat Transfer in Nanofluids

Most investigators observed deterioration of pool boiling in nanofluids. However, some experiments with nanofluids have shown a completely different picture by yielding up to a 40% increase in boiling heat transfer coefficient. The ability to greatly increase the critical heat flux (CHF), the heat flux limit in boiling systems, is of paramount importance to ultrahigh–heat-flux devices such as high-powered lasers and reactor components. The enhancement of CHF in nanofluids has been reported by all investigators.

**Boiling Heat Transfer Coefficient** Das et al. (2003) were first to study the pool boiling characteristics of water-based nanofluids containing 1, 2, and 4 vol% Al$_2$O$_3$ nanoparticles and unexpectedly, showed a deterioration of the boiling performance with particle concentration. Later, the same authors (Das et al., 2003) showed that that the deterioration of pool boiling heat transfer in nanofluids is less in small tubes than in large industrial tubes. Bang and Chang (2005) confirmed the deterioration of pool boiling in nanofluids. Furthermore, they observed that the Rohsenow correlation with effective nanofluid properties alone fails to predict...
their experimental data but with a combination of nanofluid properties and surface characteristics shows good agreement with their data.

In contrast to work by Das et al. (2003, 2003a) and Bang and Chang (2005), Wen and Ding (2005b) reported enhanced boiling heat transfer with nanoparticle concentration and heat flux in nanofluids. Their data show an increase as high as 40% in heat transfer coefficient at about 0.3 vol%, which cannot be explained by conductivity enhancement alone. This could be because Wen and Ding (2005b) conducted pool boiling experiments with nanofluids containing fewer nanoparticles than were used in previous studies. Liu and Qiu (2007) investigated the boiling of an impinging jet of CuO–water nanofluids on a flat surface and showed that nanofluids in jet impingement have poorer boiling characteristics than those of to pure water.

**Threefold Increase in CHF** You et al. (2003) measured the CHF in pool boiling of Al2O3-in-water nanofluids for the first time and discovered an unprecedented phenomenon: a threefold increase in CHF over that of pure water at the mass fraction O (10−5). The enhancement of CHF was confirmed further by Vassallo et al. (2004) with SiO2 nanoparticles in water despite some differences in nanoparticle materials and concentration range and heater geometry (silica nanoparticles between 2 and 9 vol%, in contrast to Al2O3 nanoparticles between ~0.001 and 0.013 vol%, and a horizontal 18-gauge NiCr wire versus the heating surface used by You et al.). Vassallo et al. (2004) also observed a thin coating of silica particles on the wire after boiling but concluded that the increase in roughness alone cannot explain such as unusual rise in CHF.

**1.5. MECHANISMS AND MODELS FOR ENHANCED THERMAL TRANSPORT**

The marvelous experimental discoveries described in Section 1.4 clearly offer theoretical challenges because they show the fundamental limits of conventional heat conduction, convection, or boiling models for solid–liquid suspensions. Most of the thermal properties of nanofluids measured greatly exceed the values predicted by classical macroscopic theories and models. For example, classical conductivity theories of solid–liquid suspensions used for traditional solid–liquid suspensions (Maxwell, 1873; Hashin and Shtrikman, 1962; Jeffrey, 1973; Jackson, 1975; Davis, 1986; Bonnecaze and Brady, 1990, 1991; Lu and Lin, 1996) cannot explain why low concentrations of nanoparticles can enhance the thermal conductivity of base fluids significantly larger than the theoretical prediction. The big gap between conductivity data measured and model predictions, particularly for copper and CNT nanofluids, which conduct heat 10 times faster than predicted possible, clearly suggests that conventional heat conduction models, developed for fluids containing relatively large particles (three to six orders of magnitude larger than nanoparticles), are inadequate for nanofluids. Other important thermal
phenomena in nanofluids, such as a threefold increase in CHF and a twofold increase in convection heat transfer, cannot be explained by conventional convection or boiling theories. In trying to understand the unexpected discoveries and so to overcome the limitations of the classical models, a number of investigators have proposed new physical concepts and mechanisms and developed new models for the enhanced thermal conductivity of nanofluids.

Although there is a substantial number of mechanisms proposed and modeling work related to enhanced conductivity, other important thermal phenomena, such as anomalous increases in CHF and the convection heat transfer coefficient, have not yet led to new mechanisms or models. These unexpected thermal phenomena in nanofluids also necessitate new physical concepts, mechanisms, and models. Therefore, when we realize that nanofluids contain a small quantity of tiny nanoparticles and yet show interesting but unexpected properties, nanofluid is still a mystery calling for new and comprehensive theories to explain these unexpected thermal features.

1.5.1. Milestones in Mechanisms and Models for Enhanced Thermal Conductivity

Conventional solid–liquid suspensions can be described as macroscopic continuum systems. Therefore, existing continuum models of the thermal conductivity of solid–liquid suspensions, all of which are based on the central assumption that the heat transport in each phase is governed by the diffusion equation, adequately represent conventional suspensions of micrometer or larger particles. In these models the particle volume fraction, shape, and orientation and the thermal conductivities of particle and liquid are the important factors controlling the thermal conductivity of conventional suspensions.

For nanofluids the existing continuum model predictions begin to diverge from the experimental data at low volume fractions (Lee et al., 1999; Eastman et al., 2001). As a result, continuum models developed for suspensions of millimeter- or micrometer-sized particles can no longer describe the enhanced thermal conductivity of nanofluids observed in most thermal conductivity measurements. Therefore, it appears that the thermal behavior of nanofluids with nanoscale solid–liquid interface structures or nanoscale particle motion is more complex than that of conventional solid–liquid suspensions and so cannot be explained by the diffusive heat transport mechanism alone. It is expected that energy transport mechanisms at the nanoscale would differ from macroscale mechanisms.

What intrigued nanofluids researchers most in the early days of nanofluids was the experimental discovery that nanofluids can conduct heat much faster than scientists had predicted possible at the low volume fractions of nanoparticles. In addition to this big gap between measured conductivity data and model predictions, the strongly temperature- and size-dependent conductivities of nanofluids have created a great need to understand the thermal transport mechanisms in nanofluids. The expectation that the traditional understanding of how heat is conducted based on the Fourier law of heat conduction could be refined by these
discoveries has motivated a number of nanofluids researchers to move to the frontiers of intense search for new mechanisms behind such dramatic property enhancement.

Wang et al. (1999) were first to propose new mechanisms behind enhanced thermal transport in nanofluids, such as particle motion, surface action, and electrokinetic effects. They suggested for the first time that nanoparticle size is important in enhancing the thermal conductivity of nanofluids. Xuan and Li (2000) suggested several possible mechanisms for enhanced thermal conductivity of nanofluids, such as the increased surface area of nanoparticles, particle–particle collisions, and the dispersion of nanoparticles. Years later, Keblinski et al. (2002) proposed four possible microscopic mechanisms for the anomalous increase in the thermal conductivity of nanofluids, which include Brownian motion of the particles, molecular-level layering of the liquid at the liquid–particle interface, the ballistic rather than diffusive nature of heat conduction in the nanoparticles, and the effects of nanoparticle clustering.

Modeling for the thermal conductivity of nanofluids typically falls into two broad categories: extension of existing conduction models and development of new models. Briefly, structural models such as nanolayer, fractal, or percolation structures and dynamic models such as Brownian motion-based collision of nanoparticles belong to the first category. Nanoconvection induced by Brownian motion of nanoparticles and near-field radiation belong to the second category. A number of investigators have proposed both static (or structural) and dynamic mechanisms and models in both categories to account for the anomalously high thermal conductivity enhancements reported in recent measurements. It is interesting to see that the shape of nanoparticles is critical in determining the key mechanism of heat transport in nanofluids. For example, it seems that dynamic mechanisms such as Brownian motion play a key role in nanofluids containing spherical nanoparticles, but structural mechanisms such as percolation are dominant in nanofluids containing CNTs. In some nanofluids there may be a synergistic effect of static and dynamic mechanisms.

**Structure-Based Mechanisms and Models** Major static or structural models are based on the concepts of nanolayers acting as thermal bridge, fractal structure of agglomerates, percolation structure of high-aspect-ratio nanotubes, cubic arrangement of spherical nanoparticles, interfacial thermal resistance, and surface charge state of nanoparticles. Although liquid molecules close to a solid surface are known to form a solidlike nanolayer, little is known about the connection between this nanolayer and the thermal properties of solid–liquid suspensions. Yu and Choi (2003) proposed for the first time a new mechanism in which, unlike that normally found in solid–solid composite materials, the nanolayer acts as a thermal bridge between a solid nanoparticle and a bulk liquid, so is a key structure-based mechanism of enhancing thermal conductivity of nanofluids. They then developed a renovated Maxwell model for the effective thermal conductivity of solid–liquid suspensions to include the effect of this ordered nanolayer. They extended this simple nanostructural model to nonspherical particles and renovated the Hamilton–Crosser model (Yu and Choi, 2004). The two
nanostructural models developed by Yu and Choi are not able to predict the nonlinear behavior of nanofluid thermal conductivity. Xue (2003) was the first researcher to model the nonlinear behavior of nanofluid thermal conductivity. He developed a structural model for nanofluid thermal conductivity based on the liquid layering mechanism and the average polarization theory.

Wang et al. (2003) were first to study the effect of particle clusters and cluster distribution and developed a fractal model for thermal conductivity of nanofluids. Xie et al. (2002a) were first to report the effects of the shape (spherical and cylindrical) of nanoparticles on the enhancement of the thermal conductivity of SiC nanofluids. Because carbon nanotubes have extremely high aspect ratios (or high values of shape factor \( n \)) in the Hamilton–Crosser model, they have more potential for thermal conductivity enhancement than do spherical nanoparticles. Nan et al. (2003) presented a simple model for thermal conductivity enhancement in CNT composites, taking the effective-medium approach. Nan et al. (2004) have developed a new model by incorporating interface thermal resistance with an effective-medium approach. Recently, Ju and Li (2006) and Xue (2006) considered the interfacial thermal resistance effect in their models for the effective thermal conductivities of carbon nanotube–based mixtures.

Xie et al. (2002b) showed first that the effective thermal conductivity of aqueous Al\(_2\)O\(_3\) nanofluids increases with the difference between the pH value and the isoelectric point of nanofluids. Lee et al. (2006) studied the effect on thermal conductivity of the surface charge state of nanoparticles and showed strongly pH-dependent thermal conductivity. Yu and Choi (2005) were first to model the effective thermal conductivity of nanofluids with a cubic arrangement of spherical nanoparticles with shells and to show a nonlinear dependence on the particle-volume concentrations of the effective thermal conductivity of nanofluids containing spherical nanoparticles.

**Dynamics-Based Mechanisms and Models** The effective thermal conductivity of nanofluids depends not only on the nanostructures of the suspensions but also on the dynamics of nanoparticles in liquids. Nanofluids are dynamic systems, so the motion of nanoparticles and the interactions between dancing nanoparticles or between dancing nanoparticles and liquid molecules should be considered to develop more realistic models. Interestingly, the Brownian motion of nanoparticles was considered as a most probable mechanism. The studies of Wang et al. (1999) and Keblinski et al. (2002) clearly showed that Brownian motion is not a significant contributor to heat conduction based on the results of a time-scale study. However, it is important to understand that the heat transfer mechanism that Wang et al. (1999) and Keblinski et al. (2002) explored is heat conduction through particle–particle collisions caused by the Brownian motion of nanoparticles. Despite the work of Wang et al. (1999) and Keblinski et al. (2002), a few investigators did not drop the idea that Brownian motion of nanoparticles is a most probable mechanism. In fact, one of the key concepts used in most dynamic models is that nanoparticle motion is essential to enhanced energy transport in nanofluids. This is to address one of the most important thermal phenomena in nanofluids: the strongly temperature-dependent thermal conductivity of nanofluids.
Xie et al. (2002b) measured the thermal conductivity of aqueous Al$_2$O$_3$ nanofluids with varying particle sizes and showed for the first time that the thermal conductivity of nanofluids depends strongly on particle size. Xuan et al. (2003) were first to develop a dynamic model that takes into account the effects of Brownian motion of nanoparticles and fractals. However, their model has not correctly predicted the strongly temperature-dependent thermal conductivity data obtained by Das et al. (2003b).

Even though it had been stated earlier that Brownian motion is not a significant contributor to enhanced heat conduction (Wang et al., 1999; Keblinski et al., 2002), three dynamic models, all of which show the key role of Brownian motion in nanoparticles in enhancing the thermal conductivity of nanofluids, have been published (Bhattacharya et al., 2004; Jang and Choi, 2004; Hemanth et al., 2004). However, they show large discrepancies among themselves, and the validity of these competing theoretical models is hotly debated.

Yu et al. (2003) were first to develop a simplified one-dimensional drift velocity model of a nanofluid thermal conductivity. They assumed that in the presence of a temperature gradient, the thermophoretically drifting nanoparticles superimposed on their Brownian motion drag a modest amount of the surrounding fluid with them. However, this type of convection model failed to show the effect of nanoparticle size. Jang and Choi (2004) proposed the new concept that nanoscale convection induced by purely Brownian motion of nanoparticles without thermophoretically drifting velocity can enhance the thermal conductivity of nanofluids. Their new dynamic model, which accounts for the fundamental role of nanoconvection, predict strongly temperature- and size-dependent conductivity. Prasher et al. (2005) extended the concept of nanoconvection by considering the effect of multiparticle convection and developed a semiempirical Brownian model to show that nanoconvection caused by the Brownian movement of nanoparticles is primarily responsible for the enhanced conductivity of nanofluids. Recently, Patel et al. (2005) developed a microconvection model for evaluation of thermal conductivity of the nanofluid by taking into account nanoconvection induced by Brownian nanoparticles and the specific surface area of nanoparticles. Ren et al. (2005) considered kinetic theory–based microconvection and liquid layering in addition to liquid and particle conduction.

Koo and Kleinstreuer (2004) extended the convection model of Yu et al. (2003) to consider fluids dragged by a pair of nanoparticles. Furthermore, Koo and Kleinstreuer (2005) show that the role of Brownian motion is much more important than that of thermophoretic and osmophoretic motion and that particle interaction can be neglected when the nanofluid concentration is low (\(<0.5\%\)).

**Near-Field Radiation**  Recently, Domingues et al. (2005) proposed a new physical mechanism based on near-field heat transfer. When the volume fraction exceeds a few percent, the mean distance between particles in nanofluids is on the order of the particle diameter. This distance is much lower than the dominant wavelength of far-field radiation (i.e., when photons are emitted or absorbed), and near-field radiation (i.e., Coulomb interaction) may become important.
1.5.2. Milestones in Mechanisms and Models for Convection Heat Transfer

Experimental investigations have demonstrated a remarkable heat transfer enhancement when using nanofluids in forced convection: a 40% increase in turbulent convection heat transfer with the addition of 2.0 vol% of Cu nanoparticles in water and roughly a twofold increase in laminar convection heat transfer by the addition of 1.1 vol% CNTs in water (Xuan and Li, 2003; Faulkner et al., 2004). The enhancement of heat transfer coefficient measured is much higher than that of predictions based on enhanced effective thermal conductivity of nanofluids alone. Such dramatic enhancement of convective heat transfer has inspired several investigators to propose new mechanisms of enhanced convection heat transfer coefficient under both laminar and turbulent flow. In the flow of a nanofluid, thermal dispersion, particle migration, and Brownian diffusion may be some mechanisms of enhanced convection in nanofluids.

Xuan and Roetzel (2000) were first to employ the concept of thermal dispersion for modeling enhanced convection in nanofluids. This concept adds a fictitious conductivity called the thermal dispersion coefficient to the effective thermal conductivity of nanofluids by assuming that there is velocity slip between nanoparticle and liquid and that the nanoparticles induce a velocity and temperature perturbation. Xuan and Li (2000) advanced the concept of dispersion further by solving the energy equation under the assumption that axial dispersion is negligible. Khaled and Vafai (2005) investigated the effect of thermal dispersion on heat transfer enhancement of nanofluids and provided thermal dispersion as a possible explanation of the increased thermal conductivity of nanofluids.

Faulkner et al. (2004) were first to propose the concept that pseudoturbulence induced by the rolling and tumbling of CNT agglomerates results in microscale mixing, which nearly doubles the laminar heat transfer coefficient of CNT nanofluids flowing in a microchannel. Ding and Wen (2005) were first to develop a theoretical model to predict particle migration in pressure-driven laminar pipe flows of relatively dilute nanofluids. They showed that shear-induced, viscosity gradient–induced, and concentration gradient–induced particle migration results in the large radial variation of particle distribution, viscosity, and thermal conductivity. The results suggest the existence of an optimal particle size for enhanced thermal conductivity with little penalty on pressure drop.

Buongiorno (2006) considered seven possible mechanisms of fluid particle slip during the convection of nanofluids and showed that Brownian diffusion and thermophoresis are important mechanisms in laminar flow and in the viscous sublayer of turbulent flow, but are negligible in the turbulent region, where the nanoparticles are carried by turbulent eddies. Kim et al. (2004) studied convective instability in nanofluids and predicted enhanced heat transfer in natural convection of nanofluids where the Soret effect is significant. Later, Kim et al. (2007) considered both the Soret and Dufour effects in their study of convective instabilities in binary nanofluids for absorption application and derived the linear stability equation. They calculated the stability parameters for copper and silver nanofluids and showed that the Dufour and Soret effects make nanofluids unstable, but the Soret effect is more important for heat transfer.
Gosselin and da Silva (2004) were first to show that there are optimum particle loadings for the highest heat transfer in laminar and turbulent flow in nanofluids. Mansour et al. (2007) studied the effect of uncertainties in physical properties of nanofluids on forced convection heat transfer in nanofluids and showed that the estimated performance of nanofluids such as pumping power or heat exchanger sizing depends on the models of nanofluid properties. This work shows the importance of developing accurate models of nanofluid properties for practical applications.

### 1.6. FUTURE RESEARCH

Despite recent advances in the field of nanofluids, the mysteries of nanofluids are unsolved, presenting new opportunities and challenges for thermal scientists and engineers. Nanofluid research could lead to a major breakthrough in developing next-generation coolants for numerous engineering applications. Better ability to manage thermal properties translates into greater energy efficiency, smaller and lighter thermal systems, lower operating costs, and a cleaner environment.

Future research on nanofluids can be classified in two broad categories: basic research, and applied research including development and demonstration. However, basic research and applied research in nanofluids are not separate but go hand in hand. Therefore, a high level of interaction and integration between basic and applied research is required to advance not only nanofluid science but also nanofluid development and demonstration. Because the fundamental mechanisms for energy transport in nanofluids underlie heat transfer processes involving nanofluids, developing a new understanding of energy transport in nanofluids is vitally important for potential cooling applications of nanofluids in multibillion-dollar industries, including electronics, photonics, transportation, MEMS/NEMS, biological and chemical sensors, and biomedical applications. Basic nanofluid research would greatly enable creative development and application of future nanofluid technologies. For example, nanoscale phenomena and nanoscale transport mechanisms discovered or to be discovered in basic research would be very useful in the design of next-generation liquid coolants for a wide range of applications. In short, basic scientists will be able to explain the anomalous behavior of nanofluids, and application engineers will be able to design ultra-energy-efficient nanofluids. In this section we illustrate some challenges in basic and applied nanofluids research and give research directions for basic and applied research in order to create new understanding about the nanofluids and develop commercial nanofluids.

#### 1.6.1. Future Basic Research on Nanofluids

**Key Energy Transport Mechanisms** The goal of future basic research on nanofluids is to gain a fundamental understanding of the static and dynamic mechanisms of enhanced heat transfer in nanofluids. At present, understanding the
fundamental mechanisms of the enhanced thermal conductivity of nanofluids remains a key challenge in nanofluid research. The three main categories of new mechanisms proposed for enhanced thermal conductivity of nanofluids are conduction, nanoscale convection, and near-field radiation. Although these mechanisms have been proposed the validity of most of them remains a subject of debate, and there is no agreement in the nanofluids community about their use. Furthermore, there are few experimental data at the nanoscale level with which to test proposed nanoscale mechanisms such as nanoscale structures and dynamics. The true contribution of the proposed and potential new mechanisms can only be validated by highly sophisticated systematic experiments. Therefore, in the future, such experiments are needed to explore, for example, structure-enhanced energy transport and nanoparticle-mobility-enhanced energy transport. These future studies will reveal key energy transport mechanisms that are missing in existing theories and add to the understanding of the fundamental mechanisms of the thermal conductivity enhancement behind nanofluids. Understanding the fundamentals of energy transport in nanofluids is important not only for advancing basic nanofluid research, but also for validating competing theoretical models and ultimately for developing extremely energy-efficient nanofluids for a range of heat transfer applications.

In conjunction with experimental studies of fundamental energy transport mechanisms, we need to develop tools with high spatial and temporal resolution, for example, to measure the dynamic behavior of a single nanoparticle in suspension or to measure the thermal conductance between two nanoparticles that are suspended in liquid less than 50 nm apart. Development of a technique for temperature measurement at nanometer or subnanometer resolution and the application of x-ray methods to the determination of interface nanostructures would be very useful in advancing thermal physics of nanofluids. New tools and techniques are essential to better understand the physics and chemistry responsible for the anomalous increase in conductivity and to validate new mechanisms, such as nanoconvection or near-field radiation. If we can understand the mechanisms of enhanced thermal conductivity in nanofluids, we can control the thermal properties of nanofluids for nanoengineering of smart coolants.

When the size of an object or device is reduced down to nanometer scale, its surfaces and interfaces are very important. Understanding the thermal characteristics of interfacial nanolayers is important for the growing realm of nanotechnology in general and nanofluids in particular. To understand the laws of physics and chemistry that govern the interface structure and thermal properties, we need to measure the thickness and thermal conductivity of the interface nanolayer. Currently, very little information is available on the structure or chemical and physical properties of nanoparticle–liquid interfaces, and additional experimental studies are needed in this area. It has been observed that the modification of nanoparticle surfaces with surface-modifying additives such as surfactants has a strong influence on the thermal conductivity of nanofluids. For example, copper nanoparticle surfaces modified with thioglycolic acid can significantly increase the effective thermal conductivity of nanofluids (Eastman et al., 2001). Therefore,
particle size, and hence large surface area, is not the only important parameter controlling the thermal conductivity of nanofluids. There is growing evidence that particle surface charge, surface chemistry, and interface thermal resistance are important. The development of nanoparticle surface modification methods and materials for improved thermal interfaces as well as the stability of nanofluids would provide great opportunities for the design of next-generation liquid coolants.

Validity of Thermal Conductivity Data and Expansion of Properties and the Cooling Performance Database  A number of experimental nanofluid groups have shown that when uniformly dispersed and stably suspended in host liquids, nanoparticles can significantly increase the thermal conductivity of the host liquids. In almost all cases, a transient hot-wire method was used to measure the thermal conductivity of nanofluids. However, few groups have not observed any significant effect of suspended nanoparticles on thermal conductivity. For example, one group used a microscale beam deflection technique to measure the thermal conductivity of extremely dilute nanofluids and did not observe any significantly larger conductivity enhancement than the prediction of effective medium theory (Putnam et al., 2006). Thus, there is a new issue in nanofluids research regarding the validity of the conflicting experimental data. The structural characteristics of nanoparticles, such as the mean particle size, particle size distribution, and shape, depend on the synthesis method. At present it is not clear how many of the conflicting data are due to differences among the nanofluid samples produced by different synthesis techniques and how many are due to thermal conductivity measurement techniques used by the various groups. Therefore, this new issue would require use of at least two different methods to measure the thermal conductivity of the same nanofluid samples and check if data are different due to different methods. It would be vital to characterize and compare the thermal properties of a number of nanofluids accurately using new experimental techniques as well as the commonly used transient hot-wire technique.

In conjunction with this issue, test methods for measurement of thermal conductivities of nanofluids need to be standardized to provide nanofluid researchers with high-quality sample preparation and testing procedures for evaluating the thermal properties of nanofluids so that others can repeat the experiments, produce reliable results, and verify published data. When standardized test methods are established, the thermal properties database should be expanded for nanofluid applications. Furthermore, basic studies on single- and two-phase nanofluid flow and heat transfer in minichannels and microchannels should be conducted for cooling applications. In the future, nanofluid properties and cooling performance should be tested under potential service conditions.

Comprehensive Thermal Conductivity Models  In addition to basic experimental study of new mechanisms, we need integrated experimental, modeling, simulation, and theoretical studies. Classical models for the effective properties of solid–liquid suspensions account for the particle concentration, shape, orientation, and distribution, as well as the thermal conductivity of the particle and liquid.
These conventional continuum models should be modified based on a number of nanoscale transport mechanisms, such as interface structures, nanolayer chemistry, and nanoparticle dynamics related to temperature and nanoparticle size. New and comprehensive models of energy transport in nanofluids should then link microscopic parameters such as particle size, shape, polydispersity index, zeta potential, surface chemistry, particle motion, interface structure and properties, and other parameters to the macroscopic properties of nanofluids.

**Theory of Nanofluids**  One of the goals of theoretical research on nanofluids is to develop a theory of nanofluids to explain how nanoparticles change the thermal properties of nanofluids. A theory of nanofluids would also provide a theoretical foundation for physics- and chemistry-based predictive models. There are several reasons that a theory of thermal conductivity of nanofluids has not yet emerged. First, the thermal behavior of nanofluids is quite different from that of solid–solid composites or conventional solid–liquid suspensions. For example, the thermal conductivity of solid-solid composites is reduced when the grain size is reduced. In contrast, the effective thermal conductivity of nanofluids is increased when the nanoparticle size is reduced. Second, nanofluids and conventional solid–liquid suspensions are quite different not only in the magnitude of the thermal conductivity, but also in the dependence of thermal conductivity on temperature and particle concentration and size. Third, nanofluids comprise an emerging, highly interdisciplinary field combining some aspects of such traditional fields as materials science, colloidal science, physics, chemistry, and engineering. So a full understanding of nanofluids requires some knowledge of each field. Therefore, developing a theory of nanofluids is very challenging.

There are two major theoretical approaches to the thermal conductivities of materials: (1) first-principles atomistic simulations, such as equilibrium and nonequilibrium dynamic simulations, and (2) continuum kinetics, such as the Boltzmann transport equation. Atomistic simulations have been employed to determine diffusion coefficients, viscosities, and thermal conductivities for fluids. The Boltzmann equation has been used for various solids. However, there is still no satisfactory extension of the Boltzmann equation to fluids with collisions of more than two bodies.

The theories of thermal conductivity of pure liquids are not well developed. Some old models are based on the assumption that liquid molecules are arranged in a cubic lattice and that energy is carried by phonons from one lattice plane to another with the speed of sound (Bridgman, 1923; Horrocks, 1960). Predictions of the thermal conductivity of liquids based on old theoretical liquid models do not agree well with experimental data for pure liquids. So predictions would get worse when nanoparticles are suspended in a liquid because they would interact with each other or with lattice to allow electromagnetic or particle–lattice heat transfer on top of the lattice vibrational heat transfer of the liquid models.

Therefore, a theory of thermal conductivity of nanofluids may be developed initially by considering two distinctive parts: one that is given in terms of static
mechanisms such as the nature of interface layering and thermal resistance, and a second that is given in terms of dynamic mechanisms such as nanoparticle motion and nanconvection. Later, other mechanisms may be considered. For example, near-field radiation in nanofluids appears to be a really attractive and interesting hypothesis at this stage.

The theoretical result obtained for thermal conductivity should be tested against experimental data available on nanofluids in the literature and from future nanoscale experiments. Theoretical predictions should be in good agreement with experiments with regard to concentration, particle size, and temperature dependence. One proposed theory or model of nanofluids may not be able to explain all experimental data, and only realistic theories can guide the formulation of optimized nanofluids. However, it should be noted that the subject of nanofluids is a continuing study, and it is likely that several generations of theories will be required to arrive at a model that can explain all the data satisfactorily. This is how we advance scientific knowledge. No theory or model is perfect. Each time we take one small new step in developing a theory or model, we move it closer to reality.

**New Mechanisms and Models of Enhanced Convection and Critical Heat Flux**

It seems that investigators are having difficulty in understanding the anomalous behavior of nanofluids in regard to the enhanced convection heat transfer coefficient and critical heat flux since little work on the mechanisms and models of enhanced convection and CHF has appeared in the literature. In fact, such a large enhancement in heat transfer and CHF of nanofluids cannot be explained by the classical theories and models currently used for traditional solid–liquid suspensions. Therefore, we need to understand the underlying fundamentals of the role of nanoparticles in convection heat transfer and CHF, such as nanoscale mixing, bubble growth, and bubble dynamics by discovering missing heat transfer and CHF enhancement mechanisms at the nanoscale.

**1.6.2. Future Applied Research on Nanofluids**

Experiments have shown that a number of nanofluids provide extremely desirable thermal properties, such as higher thermal conductivity, convection heat transfer coefficients, and CHF compared to their base liquids without dispersed nanoparticles. These key thermal features of nanofluids, together with excellent nanoparticle suspension stability, would open the door to a wide range of engineering applications, such as engine cooling and microelectronics cooling, and biomedical applications, such as cancer therapy. Nanofluid research presents us with very promising opportunities for applications, but there are still a number of technical issues on the road to commercialization. In this connection, in this section we identify some technical barriers facing the development of commercially available nanofluid technology and suggest research needed to overcome the barriers and to achieve cost-effective, high-volume production of nanofluids.
Volume Production of Nano fluids

Production of nanofluids is currently limited to laboratory-scale research. Therefore, high-volume low-cost production of well-dispersed nanofluids is one of the most serious technical barriers to the development and commercial use of nanofluids.

Barriers and Challenges in the Two-step Process

An advantage of the two-step technique in terms of eventual commercialization of nanofluids is that the inert-gas condensation technique has already been scaled up to produce tonnage quantities of nanoparticles economically (Romano et al., 1997). Therefore, nanoparticles produced in bulk at low prices can be used to make nanofluids by the two-step method. Because these nanoparticles are commercially available in volume orders and relatively cheap, the two-step method is very attractive for industrial applications of nanofluids. However, nanofluids produced by the two-step process contain large aggregates and require high-volume concentrations of oxide nanoparticles (approximately 10 times those of metallic nanoparticles produced and dispersed by the one-step process) to achieve comparable thermal conductivity enhancement. Although the problem of aggregation of nanoparticles is particularly severe at particle concentrations greater than 20 vol%, it often occurs in nanofluids, depending on the characteristics of nanoparticles and the liquid environment. Therefore, it is important to minimize aggregation in nanofluids. Some surface-treated nanoparticles show excellent dispersion and thermal properties. The challenge is to develop innovative ways to improve the two-step process to produce well-dispersed nanofluids in volume. In fact, some nanoparticles are available commercially in the form of liquid suspensions. Ceramic suspensions are available in large quantities in the market. Therefore, the real challenge appears to be significant cost reduction in nanofluid production using the two-step process.

Barriers and Challenges in the One-Step Process

Although the two-step technique works well for oxide nanoparticles, it is not as effective for metal nanoparticles such as copper. For nanofluids containing high-conductivity metals, it is clear that the single-step technique is preferable to two-step processing. However, although the one-step physical method developed by Argonne is excellent for research, it is not likely to become the mainstay of nanofluid production because the process would be hard to scale up, for two reasons: Processes that require a vacuum slow the production of nanoparticles and nanofluids significantly, and the production of nanofluids by this one-step physical process is expensive.

Recently, an alternative one-step chemical method for making copper nanofluids has been reported (Zhu et al., 2004). Nearly monodisperse copper nanoparticles less than 20 nm in diameter were produced and dispersed in ethylene glycol by the reduction of a copper salt by sodium hypophosphite. Poly(vinylpyrrolidone) was added as a protective polymer and stabilizer that inhibited particle aggregation. Copper nanofluids produced by this one-step chemical method show nearly the same thermal conductivity enhancement as the nanofluids produced by the
one-step physical method. Although this new one-step chemical process was used only to produce small quantities of nanofluids in a laboratory, with some development it appears that it has the potential to produce large quantities of nanofluids faster than the one-step physical process. Therefore, it is needed to study the potential of the new one-step chemical method of making stable nanofluids and scaling up to commercial production. Since a one-step chemical method can minimize nanoparticle agglomeration, it can produce well-dispersed nanofluids containing monosized nanoparticles. However, a significant limitation to the application of this technique is that the volume fractions of nanoparticles and quantities of nanofluids that can be produced are much more limited than with the two-step technique. Unlike the two-step process, these one-step processes are not yet available commercially. Therefore, the challenge is to develop innovative ways to improve the one-step chemical process to produce large quantities of nanofluids economically. It should be noted that the current one-step physical or chemical production systems run in batch mode with limited control over a number of important parameters, including those that control nanoparticle size. The one-step physical and chemical processes are likely to have commercial potential if they allow making nanofluids in a continuous process.

Future focus should be on identifying promising methods that do not require a vacuum and that provide continuous fluid feed and extraction capabilities in a production system. New technologies for making stable nanofluids which do not require a vacuum and utilize a semicontinuous or continuous process will probably replace current methods of producing nanofluids. In the future, these methods could lead to the ability to make nanofluids much faster and cheaper than can be accomplished using current methods. The critical technical breakthroughs in industrial-scale production of nanofluids to bring nanofluids to commercialization are expected to be achieved through continued support of nanofluids R&D and collaboration with industrial partners.

**Long-Term Stability** In addition to the production-scale-up issue, we need to address a number of concerns related to the use of nanofluids, including clogging, fouling, corrosion, abrasion, compatibility, and long-term stability. Making stable nanofluids containing monosized nanoparticles is challenging in lab-scale research. But long-term stability of the nanofluids could be a practical issue in the commercialization of nanofluids. Long-term stability of nanoparticle suspensions, by making small (1- to 10-nm) nanoparticles and dispersing them without agglomeration using special mechanical dispersing techniques and the creative use of chemical dispersants, is critical to fully appreciate the benefits of nanofluids.

**Green Nanoﬂuids** Nanotechnology is a compelling solution to our urgent need for the more efficient use of energy in general and for the faster cooling of devices and systems in particular. However, we now face public concerns and challenges to make sure that nanotechnology is safe. We need to address public concerns about potential health and environmental hazards of nanotechnology.
Nanoparticles are very different from micro- or macro-sized materials. Because it is not known yet if nanoparticles of certain materials and size would have undesirable effects on the environment and health, we should care about the potential negative impact of nanoparticles on humans or the environment.

Systematic research into potential risks and benefits of nanofluids would require the development of methods for evaluating the health and environmental impact of nanofluids and models for predicting the potential health and environmental impact of nanofluids. The public needs to be informed of research findings on nanofluid risks and benefits. Looking forward, it seems prudent for nanofluid engineers to think about and develop green nanofluids by choosing nontoxic nanoparticles that would pose no environmental, safety, and health danger so that nanofluids could be produced in large quantities and used widely in industrial and consumer thermal management applications. Biodegradable nanoparticles could be used in making nanofluids for biomedical applications. Low-cost, high-volume production of green nanofluids would be one of the most challenging future research directions.

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INTRODUCTION


