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Review on Enhanced Thermal Conductivity of Colloidal Suspension of Nanosized Particles (Nanofluids)

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Abstract

The dispersion of ultrafine nanoparticles(normally smaller than 100 nm) in base fluid can remarkably enhance the thermal conductivity over the base fluids and thus can offer very high advantage in applications such as industrial cooling, space vehicles, nuclear reactors, electronic components etc. over conventional cooling fluids. But major problem before commercialization of such fluids lies in their short term stability, disagreements between the results of various researchers, increased cost due to increased pumping power. Present paper mainly concentrate on disperse experimental data obtained by various researchers in their study on nanofluids and summarizes various models used by them to calculate the various thermophysical properties of the nanofluids.

1. Introduction

A particle is defined as a small object that behaves as a whole unit with respect to its transport and properties.particle are further classified according to diameter. Coarse particles cover a range between 2,500 and 10,000 nanometer Fine particles are sized between 100 and 2,500 nanometers. Ultrafine particles, or nanopartical, are between 1 and 100 nanometers in size. Particles of nanometer dimensions dispersed in base liquids are called nanofluids. This term was first introduced by Choi in 1995 at theArgonne National Laboratory.

2. The Cooling Challenge

One of the chief motivations in the initial development of nanofluids is the pressing need, in many industrial technologies, for better cooling systems. Heat rejection requirements are continually increasing **for such devices as micro- and nano electromechanical systems (MEMS and NEMS), power electronics,** light emitting diodes (LEDs), integrated circuits, and semiconductor lasers... At the macro scale, the problem is also acute for internal combustion engines. However, with extended-surface thermal control technologies _such as fins and microchannels_ stretched to their limits, new technologies with potential to improve the thermal properties of cooling fluids are of great interest.

3. Characterizing Nanofluids

Good methods for characterizing nanofluids are critical to a correct understanding of their novel properties. Characterization Of nanofluids includes determination of colloidal stability, particle size and size distribution, concentration, and elemental composition as well as measurements of thermophysical properties. For some applications, measurement of the electrical conductivity of nanofluids is required. Some of the most commonly used tools for characterization include transmission electron microscopy _TEM_imaging and dynamic light scattering _DLS_. One of the most measured thermophysical properties is the thermal conductivity of nanofluids. Generally, methods are used to measure the thermal conductivity of nanofluids: the transient hot wire method, and the laser flash method.

4. Novel Thermal Transport Phenomena

Several pioneering experiments with nanofluids showed that nanofluids have unprecedented thermal transport phenomena that show remarkable enhancement in thermal properties compared with the base fluid. These phenomena surpass the fundamental limits of macroscopic theories of suspensions and provide avenues to exciting new coolants for a variety of applications. The enhanced transport properties and heat transfer have been studied with varying degrees of thoroughness.

4.1 High Thermal Conductivity at Low Concentrations

The early proof-of-concept experiments were conducted with oxide nanofluids produced by two-step methods. Although these fluids showed enhanced performance, the improvement could be predicted by existing models. Thus, oxide nanofluids failed to generate great interest. However, when copper nanofluids produced by a one-step method showed up to a 40% increase at a particle concentration of 0.3 vol% _5_, researchers took notice! These results are shown in Fig. 3. This measured enhancement is anomalous, according to calculations with the weighted average model. This discovery is especially significant because the concentration is reduced by one order of magnitude at comparable enhancement compared with oxide nanofluids_10_.

Liu et al. _8_ synthesized Cu nanofluids using the chemical reduction method with no surfactant; in this study thermal conductivity was enhanced by up to 23.8% at 0.1 vol%. Jana et al. _11_ showed that Cu-water nanofluids have a 74% increase in conductivity at 0.3 vol%, far exceeding the previous record of40%. However, Zhang et al. _12_ and Putnam et al. _13_ found no anomalous enhancement. These contradictory data highlight the need for more accurate characterization of nanofluids

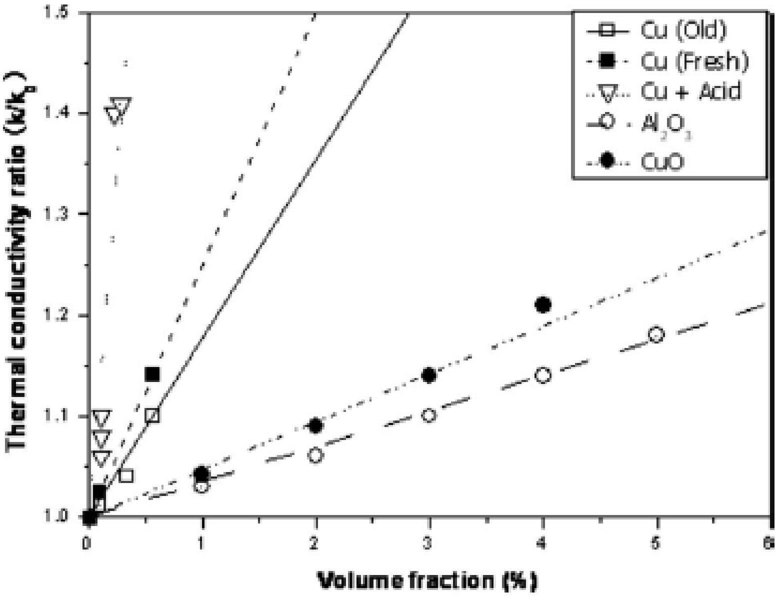


Fig. 3: The thermal conductivity of nanoffluids depends on nanoparticle concentration and synthesis method.

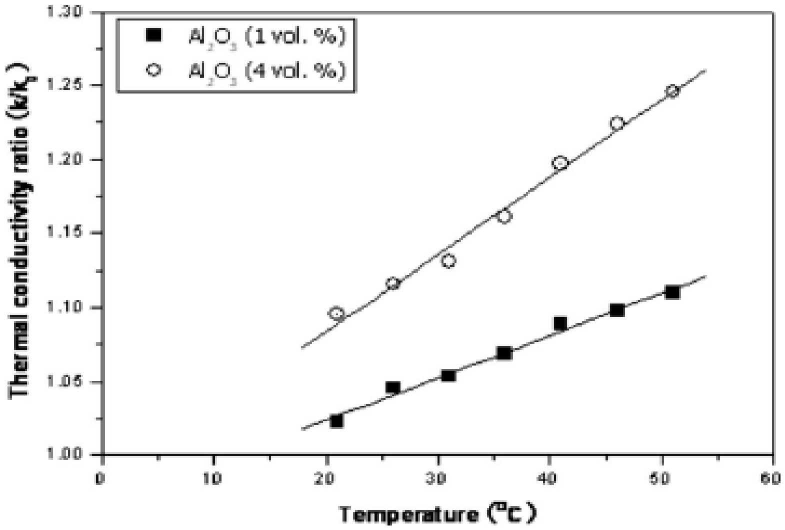


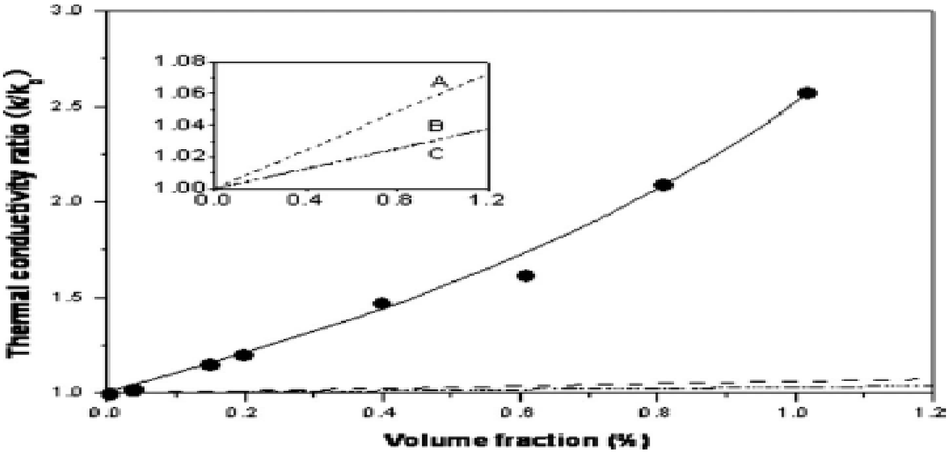
Fig. 5: the strong temperature dependence of thermal con-ductivity of mamofluids.

4.2 Nonlinear Increase in Conductivity With Nanoparticle Concentrations

Nanofluids have shown unexpected nonlinearity in several properties. Nonlinearity was first observed in the thermal conductivity of a fluid with carbon nanotubes _CNTs_ dispersed in a matrix material, first prepared by Choi et al. _14_. CNTs, the most thermally conductive material known, yield the highest enhancement ever achieved in liquid _150% increase in conductivity of oil at _1 vol%_. The measured thermal conductivity is_1_ an order of magnitude greater than predicted by existing models and _2_ nonlinear with volume fraction, while predictions show a linear relationship _Fig. 4_. Shaikh et al. _15_ confirmed independently the largest increase in the thermal conductivity of the MWNT-PAO nanofluids Choi et al. reported six years ago _14_. This nonlinear behavior is not limited to CNTs with a high aspect ratio. Murshed et al. _16_, Hong et al. _17_, and Chopkar et al. _6_ showed that nanofluids containing spherical nanoparticles also have strong nonlinear behavior.

4.3 Strongly Temperature-Dependent and Size-Dependent Conductivity.

Das et al. _18_ discovered that nanofluids have strongly temperature-dependent thermal conductivity _Fig. 5_.



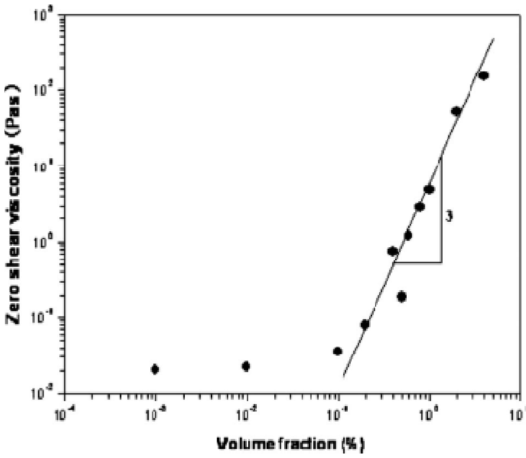
The conductivity enhancement of Al2O3 or CuO nanofluids is twice to four times that of the base fluid over a small temperature range between 20°C and 50°C. Li and Peterson _19_ found that the temperature effect is stronger compared with the data of Das et al. The discovery is significant because it raises an exciting possibility to develop smart nanocoolants that “sense” their thermal environment, making them a very attractive solution for preventing hot spots.A similar trend was soon predicted _20_ for nanoparticle size. Chopkar et al. _6_ measured the thermal conductivity of Al70Cu30 nanofluids as a function of particle size to show strongly size dependent conductivity. Chon et al. _in two studies_ _21,22_, Hong et al. _23_, and Kim et al. _24_ also showed size-dependent conductivity. Strong size effects in nanofluids are significant for practical applications. These effects are so pronounced that strong temperature and size dependences of the thermal conductivity have been accepted as the criteria for classifying a given suspension as a nanofluid.

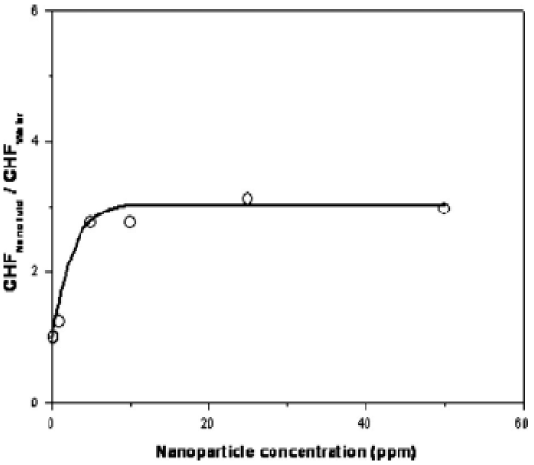
4.4 Nonlinear Rheological Properties

Das et al. _25_ and Prasher et al. _26_ showed linearity and Newtonian behavior; other investigators have reported nonlinearity with concentration _27–29_. A size factor may also need to be considered: Jang et al. _30_ discovered that the viscosity of Al2O3 nanofluids not only increases nonlinearly with concentration but also depends on then size of nanoparticles relative to the tube size. Kwak and Kim _4_ discovered that the zero shear viscosity of CuO-ethylene glycol nanofluids changes abruptly when particle volume fraction becomes larger than 0.2% _Fig. 6_; hence this volume fraction is regarded as the dilute limit. Substantial enhancement in thermal conductivity is attainable only when particle concentration is below the dilute limit. For concentrations above the dilute limit, where both rotational and translational Brownian motions are restricted, there is no additional increase in conductivity beyond the predictions of effective medium theory. The viscosities of CuO ethylene glycol nanofluid show that particles exist in aggregated form. It has a strong effect on both the viscosity and thermal conductivity of nanofluid.

4.5 Little or Modest Increase in Pressure Drop

Microparticle suspensions have much higher viscosity than their base fluids and require large pumping power to get the same thermal performance as their base fluids. Most nanofluids have flow properties similar to those of a single-phase base liquid and have little or modest increase in turbulent pressure drop _28,31_. This flow behavior is attractive for application engineers. An exception is the type of oxide nanofluids studied by Pak and Cho _32_, which had high viscosities. To be successful in practical applications, nano-fluids must be engineered to enhance heat transfer without much penalty in pressure drop. This requires an accurate selection of the particle shape, size, materials, and concentrations.





4.6 Single-Phase Convection Heat Transfer: Laminar Flow

Ding et al. _33_ showed that the laminar heat transfer coefficient of CNT nanofluids increases rapidly at the highest values of the Reynolds number up to a 150%

enhancement. They also showed that this coefficient increases with the nondimensional axial distance $\tilde{x}D$. Faulkner et al. _34_ showed that the laminar heat transfer coefficient of CNT nanofluids nearly doubled at the upper end of the Reynolds number range tested; it also decreased with increasing concentration in the concentration range from 1.1 vol % to 4.4 vol %.

4.7 Single-Phase Convection Heat Transfer: Turbulent Flow

Pak and Cho _32_ studied heat transfer in oxide nanofluids and showed that, even though the Nusselt number increased, the turbulent heat transfer coefficient actually decreased by 3–12%. Xuan and Li _35_ showed that the turbulent heat transfer coefficient of Cu-water nanofluids increased by ~40% at 2 vol %. The friction factor is not affected by the particle concentration for a given Reynolds number in both laminar and turbulent flow conditions. The MIT group _36_ showed that, as far as single-phase convective heat transfer and pressure drop are concerned, their alumina-water and zirconia-water nanofluids behave like pure fluids, provided that the temperature and loading dependence of the thermophysical properties are measured and used in the Re, Pr, and Nu definitions.

4.8 Size-Dependent Single-Phase Convection Heat Transfer

He et al. _28_ showed that the conductivity increases with decreasing particle size, but nanoparticle size _in the range of 95–210 nm_ has a marginal effect on the heat transfer coefficient. However, recent work shows the opposite trend. This finding is consistent with recent results for turbulent flow by Nguyen et al. _37_, who showed size-dependent heat transfer coefficients in turbulent forced convection. The discovery that nanofluids have sizedependent heat transfer coefficients in both laminar and turbulent flows is significant.

4.9 Pool Boiling Heat Transfer

Most experiments on the pool boiling of nanofluids show that nanoparticles deteriorate the boiling heat transfer coefficient _38,39_. However, Wen and Ding _40_, using dilute nanofluids __0.32 vol %_, showed that alumina nanoparticles can enhance boiling heat transfer _by up to 40%_. Furthermore, the enhancement increases with particle concentration. Interestingly, Nnanna _41_ also showed that heat transfer in buoyancy-driven single-phase nanofluids is augmented for small volume fraction __2%_ but suppressed for large volume fraction __2%_. Therefore, the nanoparticle concentration is an important factor. Dilute nanofluids are desirable for both single phase, buoyancy-driven heat transfer and two-phase boiling heat transfer.

5. Mechanisms and Models

Great discoveries such as those described above show the fundamental limits of conventional models of heat conduction, convection, and boiling for solid/liquid suspensions. For example, various macroscopic models have been based on the assumption that heat conduction in suspensions occurs by diffusion. However, some nanofluids show greater thermal conductivity than predicted by Fourier heat conduction theory. Expecting that these discoveries could change the traditional understanding of energy transport in nanofluids, several investigators have searched for new concepts and mechanisms behind such dramatically enhanced properties. They have proposed both static _or structural_ and dynamic mechanisms and models to account for the anomalously enhanced thermal properties. Hot debates are ongoing in the nanofluids community on the validity of proposed mechanisms and models of heat conduction in nanofluids. Some of these proposed approaches are discussed below.

5.1 Ordered Nanolayer of Liquid Molecules

Yu and Choi _48_ proposed a new mechanism that, unlike in solid-solid composites, an ordered liquid layer _or nanolayer_ acts as a thermal bridge between a nanoparticle and a bulk liquid. They developed a renovated Maxwell model to include the effect of this ordered nanolayer. They further extended this structural model to nonspherical particles and renovated the Hamilton and Crosser model. However, their two static models do not predict the nonlinear behavior of nanofluid conductivity. Xue _49_ was the first to model this nonlinear behavior. Although these models predict well the measured thermal conductivity data, both the thickness and conductivity of the liquid layer have to be assumed.

5.2 Percolation like Behavior

Carbon nanotubes have extremely high aspect ratio. Foygel et al. _50_ performed Monte Carlo simulations to show that the percolation regime starts at a surprisingly low critical concentration of 0.01 vol %. The new percolation theory accounts for the two features of the thermal conductivity data for CNT nanofluids, namely, the nonlinear increase with CNT concentration and the significant increase in thermal conductivity.

5.3 Interfacial Thermal Resistance

Experiments show that adding 1 vol % of CNTs to synthetic oil _14_ or polymer epoxy _51_ can increase the conductivity of the matrix material more than twofold. Huxtable et al. _52_ used a pump-probe method to measure heat transfer across the particle-liquid interface. They showed that the exceptionally large interface thermal resistance, i.e., the Kapitza resistance, can significantly reduce the thermal conductivity of nanofluids. Nan et al. _53_ developed a model for thermal conductivity enhancement in CNT composites by incorporating the Kapitza resistance in the effective medium approximation.

5.4 Brownian Motion of Nanoparticles

The static models, such as the liquid layering model and the interface thermal resistance model, cannot explain the strong temperature dependence of the conductivities of nanofluids. Effective medium theory models, such as the Maxwell–Garnett, Bruggeman, Hamilton–Crosser, and Jeffrey and Davis models, do not take particle motion into consideration. A nanofluid is a dynamic system because the nanoparticles are in motion even if the fluid is stationary. Several dynamic models have been developed in combination with static models. Xuan et al. _31_ developed a dynamic model that takes into account the effects of Brownian motion of nanoparticles and fractals. They showed, probably for the first time, that the conductivity of nanofluids increases with the square root of fluid temperature. However, their model did not predict the linear increase of thermal conductivity with temperature, as obtained by Das et al._18_.

5.5 Nanoconvection

All the static and dynamic models developed with conduction-based mechanisms still fail to predict the magnitude and trends of the experimental data. Nanoparticle diffusion, which is orders of magnitude slower than heat diffusion, has little effect on the k of nanofluids. Jang and Choi _20_ proposed the concept of nanoconvection induced by Brownian motion of nanoparticles assuming that energy transport in nanofluids is by nanoscale flow of fluids around Brownian nanoparticles. They developed a theoretical model that takes into account nanoconvection. Though the new model makes simplifying assumptions, it generates useful results for interpreting experiments _Fig. 8_. Whereas Maxwell-type theories fail to capture the temperature-dependent conductivity, calculations with the new model agree with temperature-dependent data and predict sizedependent conductivity. Xuan et al. _54_ developed, based on the Green–Kubo theorem, a conductivity model consisting of the static and dynamic terms. This model accounts for the Kapitza resistance and nanoconvection, nanoparticle size and concentration, and fluid temperature. Their model shows that the contribution of the nanoconvection effect increases rapidly when the nanoparticle size is smaller than 30 nm. Several other studies have considered various aspects of nanoconvection. Prasher et al. _55_ extended the concept of nanoconvection by considering for the first time the effect of multiparticle convection. Koo and Kleinstreuer _56_ developed a microconvection model for evaluation of conductivity of a nanofluid by taking into account nanoconvection induced by Brownian nanoparticles theoretical model that takes into account the effects of fluids dragged by nanoparticles and mixing. Patel et al. _57_ developed a and the specific surface area of nanoparticles.

Finally, Ren et al. _58_ considered kinetic-theory-based microconvection and liquid layering in addition to liquid and particle conduction. Several other groups have questioned the importance and mechanisms of nanoconvection. For example, Evans et al. _59_ and Vladkov and Barrat _60_ conducted molecular dynamicsb simulations _MDS_ of model nanofluids to show that the effect of nanoconvection is negligible. However, Sarkar and Selvam _61_ also used MDS to show that the conductivity enhancement is mostly due to the increased movement of liquid atoms in the presence of nanoparticle. Most recently, Eapen et al. _62_ measured the conductivity of silica and Teflon suspensions to show that microconvection does not influence the conductivity of their nanofluids. The debate over the role of Brownian nanoparticles in the enhanced conductivity of nanofluids will continue

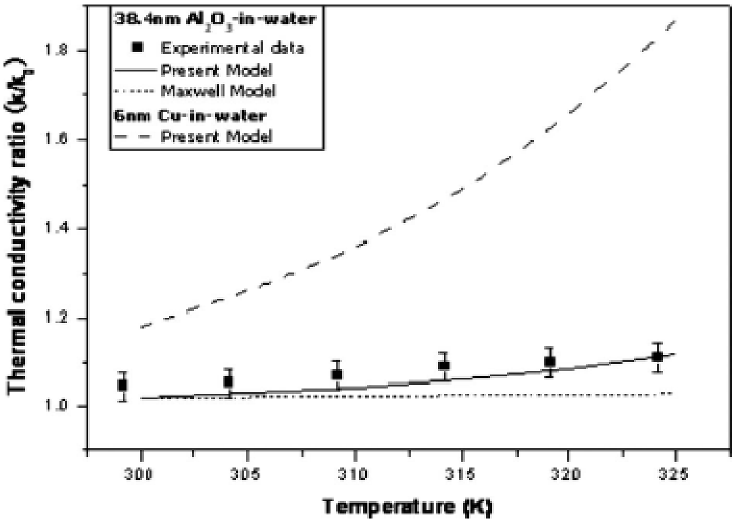


Fig. 8: Experimental data from das et al. [18] and predictions from jang and chol's [20] new model based on nonocorvection induced by Brownian motion.

5.6 Surface Charge Model

Lee et al. _63_ presented the surface charge state as a new key parameter for the anomalous enhancement of the conductivity of nanofluids. They showed that the effective thermal conductivity increases by a factor of 3 as *p*H decreases from 8 to 3.

5.7 Molecular-Level Mechanisms of Enhanced Conductivity

Eapen et al. _64_ considered three fluctuation modes in the microscopic heat flux and showed a molecular-level mechanism for enhanced conductivity of nanofluids. A number of mechanisms and models of enhanced conductivity have been proposed, but none has gained universal support.

5.8 Heat Transfer Models

- Models of heat transfer in nanofluids come in three varieties at present.
- *Homogeneous flow.* Choi _1_ assumed that traditional heat transfer correlations can be used for nanofluids, provided that their enhanced thermophysical properties are used.
- *Dispersion.* Xuan and Roetzel _65_ were the first to employ the concept of thermal dispersion, assuming that velocity slip induces a velocity and temperature perturbation.
- *Particle migration.* Ding and Wen _66_ were the first to use the concept of particle migration in nanofluids and developed a theoretical model to predict particle migration in pressure-driven laminar pipe flows of relatively dilute nanofluids.

- *Brownian diffusion and two-component nonhomogeneous equilibrium.* Buongiorno _67_ was the first to show that Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. Based on this finding, he developed a two-component nonhomogeneous equilibrium model for mass, momentum, and heat transport in nanofluids. He explained that the abnormal heat transfer behavior of nanofluids is due to a significant decrease in viscosity within the boundary layer _67_.

6.9 Mechanisms and Models of Viscosity

Ding and Wen _66_ developed a theoretical model to examine particle migration in pressure-driven laminar pipe flows of nanofluids. The model considers particle migration due to spatial gradients in viscosity and shear rate and Brownian motion. The results show that particle migration can result in nonuniform particle concentration, thermal conductivity, and viscosity. However, nanofluids have Peclet numbers _10 _because Pe_*dp*3_ and thus concentration and viscosity distributions are uniform over the pipe cross section. Most recently, Jang et al. _30_ showed that, when nanoparticles have a nonzero slip velocity, the viscosity of Al2O3 nanofluidsn flowing through micro- and minitubes increases nonlinearly with concentration even in the range of 0.02–0.3 vol % and depends strongly on the nanoparticle diameter to the tube diameter ratio.

6.10 Pool Boiling Heat Transfer Mechanisms

Narayan et al. _68_ observed that with a rough heater _Ra=524 nm_, heat transfer is significantly enhanced by up to ~70% at 0.5 wt % and with a smooth heater _Ra=48 nm_, heat transfer is significantly deteriorated by up to ~45% at 2 wt %. Furthermore, they observed that a new parameter, which is the ratio of average size of the particle to the average roughness value of the heater, can explain the reported controversy in the pool boiling behavior of nanofluids.

6. Applications of Nanofluids

Nanofluids can be used in a wide range of applications wherever improved heat transfer or efficient heat dissipation is required. Major examples include electronics, automotive, and nuclear applications. The following examples give a picture of the versatility of this technology. Nanofluids are a promising candidate for microelectronics cooling. Nanofluids have a plethora of potential applications in many automotive parts and functions, including engine coolant, automatic transmission fluid, power steering fluid, fan clutches, engine oil, power electronics, brake fluid, gear lubrication, and greases. The results show that CuO nanofluids have the lowest temperature distribution and accordingly the best heat transfer performance. Nuclear applications of nanofluids appear to be very promising—perhaps the most promising of currently envisaged uses. Nanofluids could be used in primary systems, emergency safety systems, and severe accident management systems, with resulting benefits such as power uprates in commercial pressurized water reactors _PWRs_ and enhanced safety margins during design-basis events and severe accidents. In general, nanofluids could enhance economics and safety of nuclear reactors _74,75_. They also have great potential as a coolant for safer and smaller nuclear generators in the future. Beyond these somewhat concrete possibilities lies a broad expanse of potential applications, wide open to the engineering imagination. A few ideas to provoke further thought include cooling

and lubrication of drill bits for deep-hole drilling _76_, drug delivery and nanofluids-based control of biological functions _because the size of nanoparticles is similar to that of biomolecules_, process intensification in the chemical and metallurgical industry, efficiency optimization in the heating, ventilation and air conditioning _HVAC_ industry, production of nanostructured materials, engineering of complex fluids, lubricant-based nanofluids _nanolubricants_, and enhanced quenching performance.

7. Future Directions

7.1 Future Basic Research

To understand the fundamental physics of energy transport in nanofluids, systematic experiments are needed, as are tools with a high spatial and temporal resolution. Another need is for comprehensive thermal conductivity models that consider transport mechanisms at multiscale levels. Theoretical predictions should be evaluated in terms of agreement with experiments regarding concentration, particle size, and temperature dependence.

7.2 Future Applied Research

- Equally interesting challenges await the applied researcher who chooses to pursue questions related to nanofluids. The following are three of the most pressing issues.
- *Volume production.* Production of stable nanofluids with nonagglomerated nanoparticles is currently limited ton laboratory-scale research. Future work should focus on identifying methods that provide volume production for commercial applications.
- *Stability.* Long-term physical and chemical stability of nanofluids is an important practical issue for commercialization of nanofluids.
- *Environmental issues.* Nanofluids offer compelling solutions for energy efficiency, but we also face public concerns about their safety, both in production and in use. Nanofluids engineers would be prudent to pursue green designs by choosing nontoxic or biodegradable nanoparticles. In summary, low-cost, high-volume production of stable green nanofluids is one of the most challenging directions for future applied research.

8. Conclusions

Nanofluids are an exciting new class of nanotechnology-based heat transfer fluids. Scientists and engineers are being challenged to discover the many unexpected thermal properties of these fluids. In short, nanofluids have emerged as a new field of scientific research, especially in thermal sciences and engineering. Much more work is necessary in every area, from fundamentals to formulation to large-scale production. When the mysteries of nanofluids are solved we could imagine nanofluids designed to have novel properties. Consider what possibilities could open up if conductivity increased two- to threefold, effective specific heat increased two- to threefold, CHF increased three- to fourfold, and heat transfer coefficients increased two- to threefold. These are the kinds of visionary possibilities that can guide future research. However, the novel character of nanofluids demands not only new science but also a new approach to science, one that is uniquely interdisciplinary and collaborative. This point is especially important in considering the training of young scientists.. Perhaps the only path to master this field is a multidisciplinary one that includes both basic science and engineering knowledge. Above all, the study of nanofluids is an interdisciplinary field that challenges researchers to consider the fundamentals of nanofluids from a more integrated perspective.

9. Acknowledgment

This paper is based on the works of pioneering scientists and engineers who have achieved important milestones in the research and development of nanofluids, including the novel concept, production methods, exceptional discoveries of unprecedented thermal transport phenomena, new mechanisms behind the enhanced thermal properties, unconventional models, and innovative potential applications of nanofluids.

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Nomenclature

a = nanoparticle diameter (m)
D = tube diameter (m)
h =heat transfer coefficient (W̃m2 K)
k = thermal conductivity (W̃m K)
$\tilde{P}Po$ = pumping power ratio
T =temperature (C or K)

Greek Symbol

μ =viscosity (Pa s)
Subscript
o = base fluid

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