A REVIEW ON NANOFLUIDS - PART II: EXPERIMENTS AND APPLICATIONS

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Abstract - Research in convective heat transfer using suspensions of nanometer-sized solid particles in base liquids started only over the past decade. Recent investigations on nanofluids, as such suspensions are often called, indicate that the suspended nanoparticles markedly change the transport properties and heat transfer characteristics of the suspension. This second part of the review covers fluid flow and heat transfer characteristics of nanofluids in forced and free convection flows and potential applications of nanofluids. Opportunities for future research are identified as well.
Keywords: Nanofluids; Nanoparticles; Heat transfer; Thermal conductivity.

PREPARATION OF NANOFLUIDS

Preparation of nanofluids is the first key step in experimental studies with nanofluids. Nanofluids are not simply liquid-solid mixtures. Some special requirements are essential, e.g., even and stable suspension, durable suspension, negligible agglomeration of particles, no chemical change of the fluid, etc. Nanofluids are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol (EG), oils, etc. In the synthesis of nanofluids, agglomeration is a major problem. There are mainly two techniques used to produce nanofluids: the single-step and the two-step method. The single-step direct evaporation approach was developed by Akoh et al. (1978) and is called the VEROS (Vacuum Evaporation onto a Running Oil Substrate) technique. The original idea of this method was to produce nanoparticles, but it is difficult to subsequently separate the particles from the fluids to produce dry nanoparticles. A modified VEROS process was proposed by Wagener et al. (1997). They employed high pressure magnetron sputtering for the preparation of suspensions with metal nanoparticles such as Ag and Fe. Eastman et al. (1997) developed a modified VEROS technique, in which Cu vapor is directly condensed into nanoparticles by contact with a flowing low-vapor-pressure liquid (EG).

Zhu et al. (2004) presented a novel one-step chemical method for preparing copper nanofluids by reducing $CuSO_4 \cdot 5H_2O$ with $NaH_2PO_2 \cdot H_2O$ in ethylene glycol under microwave irradiation. Results showed that the addition of $NaH_2PO_2 \cdot H_2O$ and the adoption of microwave irradiation are two significant factors which affect the reaction rate and the properties of Cu nanofluids.

A vacuum-SANSS (submerged arc nanoparticle synthesis system) method has been employed by Lo et al. (2005) to prepare Cu-based nanofluids with different dielectric liquids such as de-ionized water, with 30%, 50%, 70% volume solutions of ethylene glycol and pure ethylene glycol. They found that the different morphologies that are obtained are mainly influenced and determined by the thermal conductivity of the dielectric liquids. CuO, Cu_2O, and Cu based nanofluids can also be efficiently

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prepared by this technique. An advantage of the one-step technique is that nanoparticle agglomeration is minimized, while the disadvantage is that only low vapor pressure fluids are compatible with such a process. Recently, a Ni nano-magnetic fluid and silver nanofluid were also produced by Lo et al. (2006) using the SANSS method. The spherical silver nanoparticle formed in the ethylene glycol and the mean particle size is about 12.5 nm, which more closely resembles Newtonian fluids.

The two-step method is extensively used in the synthesis of nanofluids considering the available commercial nanopowders supplied by several companies. In this method, nanoparticles are first produced and then dispersed in the base fluids. Generally, ultrasonic equipment is used to intensively disperse the particles and reduce the agglomeration of particles. For example, Eastman et al. (1997), Lee et al. (1999), and Wang et al. (1999) used this method to produce Al_2O_3 nanofluids. Also, Murshed et al. (2005) prepared TiO_2 suspension in water using the two-step method. Other nanoparticles reported in the literature are gold (Au), silver (Ag), silica and carbon nanotubes. As compared to the single-step method, the two-step technique works well for oxide nanoparticles, while it is less successful with metallic particles.

While most nanofluid productions to date have used one of the above-described (one-step or two-step) techniques, other techniques are available depending on the particular combination of nanoparticle material and fluid. For example, nanoparticles with specific geometries, densities, porosities, charge, and surface chemistries can be fabricated by templating, electrolytic metal deposition, layer-by-layer assembly, microdroplet drying, and other colloid chemistry techniques. Another process, the chemical vapor condensation technique, appears to offer advantages in terms of control of particle size, ease of scalability, and the possibility of producing novel core-shell nanostructures (Srdic et al, 2001). Still another technique is the shape- and size-controlled synthesis of nanoparticles at room temperature (Cao et al, 2006). The structural characteristics of nanoparticles such as the mean particle size, particle size distribution, and shape depend on the synthesis method, and there is potential for good control. These characteristics for nanoparticles in suspensions are not easily measured. This fact could account for some of the discrepancies in thermal properties reported in the literature among different experiments.

Except for the use of ultrasonic equipment, some other techniques, such as control of pH or addition of surface active agents, are also used to attain stability of the suspension of the nanofluids against sedimentation. These methods change the surface properties of the suspended particles and thus suppress the tendency to form particle clusters. It should be noted that the selection of surfactants should depend mainly on the properties of the solutions and particles. Xuan and Li (2000) chose salt and oleic acid as the dispersant to enhance the stability of transformer oil-Cu and water-Cu nanofluids, respectively. Oleic acid and cetyltrimethylammonium bromide (CTAB) surfactants were used by Murshed et al. (2005) to ensure better stability and proper dispersion of TiO_2-water nanofluids. Sodium dodecyl sulfate (SDS) was used by Hwang et al. (2005) during the preparation of water-based multi-walled carbon nanotube (MWCNT) nanofluids since the fibers are entangled in the aqueous suspension.

Li et al. (2007) prepared Cu/water nanofluids with nanoparticle sizes typically of 1-100 nm using the two-step method. Results showed that zeta potential and absorbency are important bases for selecting conditions for dispersing particles. Furthermore, the observed sediment photographs and particle size distribution showed better dispersion behavior in the suspension with the addition of dispersant. The effect of pH on the stability of the copper suspension was critical.

Hwant et al. (2007) prepared various nanofluids (nanoparticle: MWCNT, fullerence, copper oxide, and silicon dioxide; base fluid: DI water, ethylene glycol, and oil) and examined their stability using UV-vis spectral analysis. They claimed that the stability of nanofluid is strongly affected by the characteristics of the suspended particle and base fluids such as the particle morphology, the chemical structure of the particles and base fluid. Furthermore, addition of surfactant can improve the stability of the suspensions.

In general, methods such as change of pH value, addition of dispersant, and ultrasonic vibration aim at changing the surface properties of suspended particles and suppressing formation of particle clusters to obtain stable suspensions. However, the addition of dispersants can affect the heat transfer performance of the nanofluids, especially at high temperature.

EXPERIMENTAL INVESTIGATIONS

Measurement of Thermal Conductivity

Since thermal conductivity is the most important parameter responsible for enhanced heat transfer, many experimental works have been reported on this

aspect. The transient hot wire method (Kestin and Wakeham, 1978), the steady-state parallel-plate technique (Wang et al, 1999) and the temperature oscillation technique (Das et al, 2003c) have been employed to measure the thermal conductivity of nanofluids. Among these the transient hot wire method has been used most extensively. Because in general nanofluids are electrically conductive, it is difficult to apply the ordinary transient hot-wire technique directly. A modified hot-wire cell and electrical system was proposed by Nagasaka and Nagashima (1981) by coating the hot wire with an epoxy adhesive which has excellent electrical insulation and heat conduction. However, Das et al. (2003c) pointed out that possible concentration of ions of the conducting fluids around the hot wire may affect the accuracy of such experimental results.

The oscillation method was proposed by Roetzel et al. (1990) and further developed by Czarnetski and Roetzel (1995). This method is purely thermal and the electrical components of the apparatus are removed from the test sample. Hence ion movement should not affect the measurement.

Alumina (Al_2O_3) and copper oxide are the most common and inexpensive nanoparticles used by many researchers in their experimental investigations. All the experimental results have demonstrated the enhancement of the thermal conductivity by addition of nanoparticles. Eastman et al. (1997) measured the thermal conductivity of nanofluids containing Al_2O_3, CuO, and Cu nanoparticles with two different base fluids: water and HE-200 oil. A 60% improvement of the thermal conductivity was achieved as compared to the corresponding base fluids for only 5 vol% of nanoparticles. They also showed that the use of Cu nanoparticles (using the one-step method) results in greater improvements than that of CuO (using the two-step method).

Lee et al. (1999) suspended CuO and Al_2O_3 (18.6 and 23.6 nm, 24.4 and 38.4 nm, respectively) in two different base fluids: water and ethylene glycol (EG) and obtained four combinations of nanofluids: CuO in water, CuO in EG, Al_2O_3 in water and Al_2O_3 in EG. Their experimental results showed that nanofluids have substantially higher thermal conductivities than the same liquids without nanoparticles. The CuO/EG mixture showed enhancement of more than 20% at 4 vol% of nanoparticles. In the low volume fraction range (<0.05% in test), the thermal conductivity ratios increase almost linearly with volume fraction. Results suggest that not only particle shape but size is considered to be dominant in enhancing the thermal conductivity of nanofluids.

Wang et al. (1999) measured the effective thermal conductivity of nanofluids by a steady-state parallel-plate technique. The base fluids (water, ethylene glycol (EG), vacuum pump oil and engine oil) contained suspended Al_2O_3 and CuO nanoparticles of 28 and 23 nm average diameters, respectively. Experimental results demonstrated that the thermal conductivities of all nanofluids were higher than those of their base fluids. Also, comparison with various data indicated that the thermal conductivity of nanofluids increases with decreasing particles size. Results demonstrated 12% improvement of the effective thermal conductivity at 3 vol% of nanoparticles as compared to 20% improvement reported by Masuda et al. (1993) and 8% reported by Lee et al. (1999) at the same volume fraction of particles.

Xuan and Li (2000) enhanced the thermal conductivity of water using Cu particles of comparatively large size (100 nm) to the same extent as has been found using CuO particles of much smaller dimension (36 nm). An appropriate selection of dispersants may improve the stability of the suspension. They used oleic acid for transformer oil-Cu nanofluids and laurate salt for water-Cu suspension in their study and found that Cu particles in transformer oil had superior characteristics to the suspension of Cu particles in water.

Xie et al. (2002b) investigated the effects of the pH value of the suspension, the specific surface area (SSA) of the dispersed Al_2O_3 particles, the crystalline phase of the solid phase, and the thermal conductivity of the base fluid on the thermal conductivity of nanofluids. They found that the increase in the difference between the pH value and isoelectric point (the pH at which a molecule carries no net electrical charge) of Al_2O_3 resulted in enhancement of the effective thermal conductivity. Also, the thermal conductivity enhancements were highly dependent on the specific surface area (SSA) of the nanoparticles. The crystalline phase of the nanoparticles did not appear to have any obvious effect on the thermal conductivity of the suspensions.

Eastman et al. (2001) used pure Cu nanoparticles of less than 10 nm size and achieved a 40% increase in thermal conductivity for only 0.3% volume fraction of the solid dispersed in ethylene glycol. They indicated that the increased ratio of surface to volume with decreasing size should be an important factor. Also, they showed that the additive acid may stabilize the suspension and thus increase the effective thermal conductivity.

A Fe-nanofluid was prepared by Hong and Yang (2005) with ethylene glycol; Fe nanoparticles with

mean size of 10 nm were produced by a chemical vapor condensation process. They found that Fe nanofluids exhibited higher enhancement of thermal conductivity than Cu nanofluids. Their result indicated that the material with high thermal conductivity is not always the best candidate for the suspension to improve the thermal characteristics of base fluids. Also, they concluded that the thermal conductivity of nanofluids increased non-linearly with the solid volume fraction. Hong et al. (2006) also investigated the effect of the clustering of Fe nanoparticles on the thermal conductivity of nanofluids. They found that the thermal conductivity of nanofluids is directly related to the agglomeration of Fe nanoparticles, which caused the nonlinear relation between the Fe volume fraction and thermal conductivity of nanofluids due to rapid clustering of nanoparticles in condensed nanofluids.

Murshed et al. (2005) investigated TiO_2 nanoparticles of rod-shape ($\varnothing 10 \times 40$) and spherical shape ($\varnothing 15$) dispersed in deionized water. They observed nearly 33% and 30% enhancements of the effective thermal conductivity for TiO_2 particles of $\varnothing 10 \times 40$ and $\varnothing 15$, respectively. Both particle size and shape influenced the thermal conductivity of nanofluids.

Xie et al. (2001; 2002a) prepared and measured the thermal conductivities of 26 nm and 0.6 µm SiC suspensions in deionized water and EG using a transient hot-wire method. Different from the experimental results of Lee at al. (1999), they found that the nanofluids with the same solid particles in different base fluids had the same improvement in the effective thermal conductivity. Furthermore, results showed that the HC model (Hamilton and Crosser, 1962) is capable of predicting the thermal conductivity of 0.6 µm SiC suspensions, while it under-predicted that of 26 nm particles.

Das et al. (2003c) examined the effect of temperature on thermal conductivity enhancement for nanofluids containing Al_2O_3 (38.4 nm) or CuO (28.6 nm) through an experimental investigation using the temperature oscillation method. They observed that a 2 to 4-fold increase in thermal conductivity can take place over the temperature range of 21°C to 52°C. The results suggest the application of nanofluids as cooling fluids for devices with high energy density where the cooling fluid is likely to work at a temperature higher than room temperature. They also mention that the inherently stochastic motion of nanoparticles could be a probable explanation for the thermal conductivity enhancement since smaller particles show greater enhancements of thermal conductivity with temperature than do larger particles.

Li and Peterson (2006) conducted an experimental investigation to examine the effects of variations in the temperature and volume fraction on the effective thermal conductivity of CuO (29 nm) and Al_2O_3 (36 nm) water suspensions. Results demonstrated that nanoparticle material, diameter, volume fraction and bulk temperature have significant effects on the thermal conductivity of the nanofluids. For example, for Al_2O_3/water suspensions, increase in the mean temperature from 27 to 34.7°C results in an enhancement of nearly three times. They also derived two simple two-factor linear regressions for the discussed nanofluids (Al_2O_3/water:

$(k_{eff} - k_b)/k_b = 0.764\phi + 0.0187(T-273.15) - 0.462$, CuO/water:

$(k_{eff} - k_b)/k_b = 3.761\phi + 0.0179(T-273.15) - 0.307$. However, additional investigations are necessary to verify the impact of the temperature on the effective thermal conductivity of nanofluids.

Patel et al. (2003) studied gold (Au) and silver (Ag) nanoparticles with thoriate and citrate as coatings in water- and toluene-based fluids. The nanofluids were prepared to check the conductivity enhancement effect at low concentrations They found 5%-21% enhancement of the thermal conductivity of nanofluids for water with citrate in the temperature range 30–60°C at a very low loading of 0.00026 vol% of Ag particles. For a loading of 0.011% of Au particles, the improvement of thermal conductivity was around 7%-14%. Such interesting phenomena indicate that, except for particle size, there exist important factors related to the motion of particles. Also, the increments in thermal conductivity of the nanofluids were found to be nonlinear with temperature and almost linear with particle volume fraction. Chemical factors such as the need for direct contact of the metal surface with the solvent medium have important effects on the resulting effective thermal conductivity.

However, it is very difficult to understand why nanofluids would have such a high thermal conductivity. Furthermore, there are large differences among the thermal conductivities reported by different researchers. Putnam et al. (2006) did not observe significant enhancement in the thermal conductivity of nanofluids with small volume fractions of nanoparticles such as C_{60}-C_{70} and Au ($\phi \ll 1$). The observed largest increase in thermal conductivity for 4 nm Au particles is 1.3%±0.8%, which conflicts with the anomalous results of Patel et al. (2003). Keblinski et al. (2005)

also pointed out that the most exciting experimental results have not been reproducible.

Recently, Zhang et al. (2007) measured the effective conductivity and thermal diffusivity of Au/totuene, Al_2O_3/water, TiO_2/water, CuO/water nanofluids using the transient short-hot-wire (SHW) technique, which was developed from the conventional transient hot wire (THW) technique and is based on the numerical solution of two-dimensional transient heat conduction for a short wire with the same length-to-diameter ratio and boundary conditions as those used in the actual measurements. The diameters of Au, Al_2O_3, TiO_2 and CuO spherical particles were 1.65, 20, 40 and 33 nm, respectively. The effective thermal conductivities of the nanofluids show no anomalous enhancement and can be predicted accurately by the equations of the Hamilton and Crosser model.

The largest increases in thermal conductivity have been observed in suspensions of carbon nanotubes, which have a very high aspect ratio and very high thermal conductivity. The first report on the synthesis of nanotubes was conducted by Iijima (1991). Later, nanotube (multiwalled carbon nanotubes or MWNTs)-oil (α-olefin) mixtures were investigated by Choi et al. (2001) to measure their effective thermal conductivity. Results showed that the measured thermal conductivity was anomalously greater than the theoretical predictions and was nonlinear with nanotube loadings. As compared to other nanostructured materials discussed previously, the nanotubes achieved the highest conductivity enhancement and provided wide opportunities for effective management applications. Xie et al. (2003) also proposed a method to produce stable and homogeneous suspensions of multiwalled carbon nanotubes (CNTs) in deionized water (DW), ethylene glycol (EG), and decene (DE). They introduced oxygen-containing functional groups on CNT surfaces to form more hydrophilic surfaces. Experimental data indicated that the thermal conductivity enhancement increased with an increase in nanotube loading, but decreased with thermal conductivity increase of the base fluid.
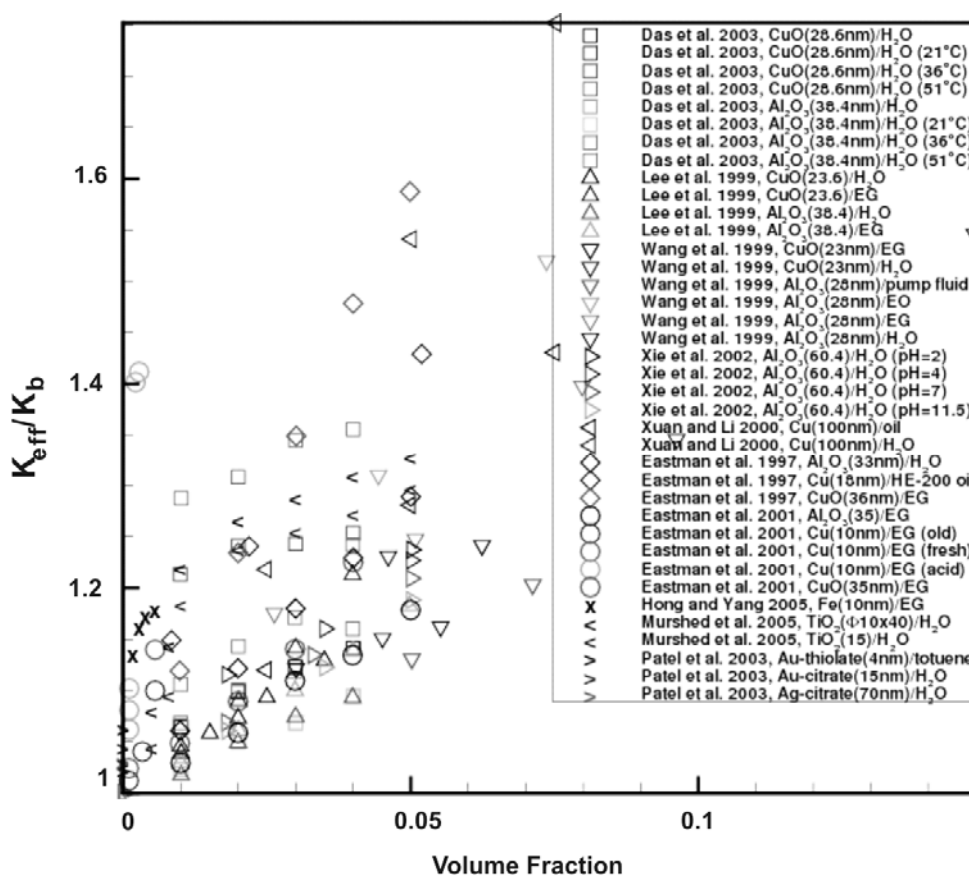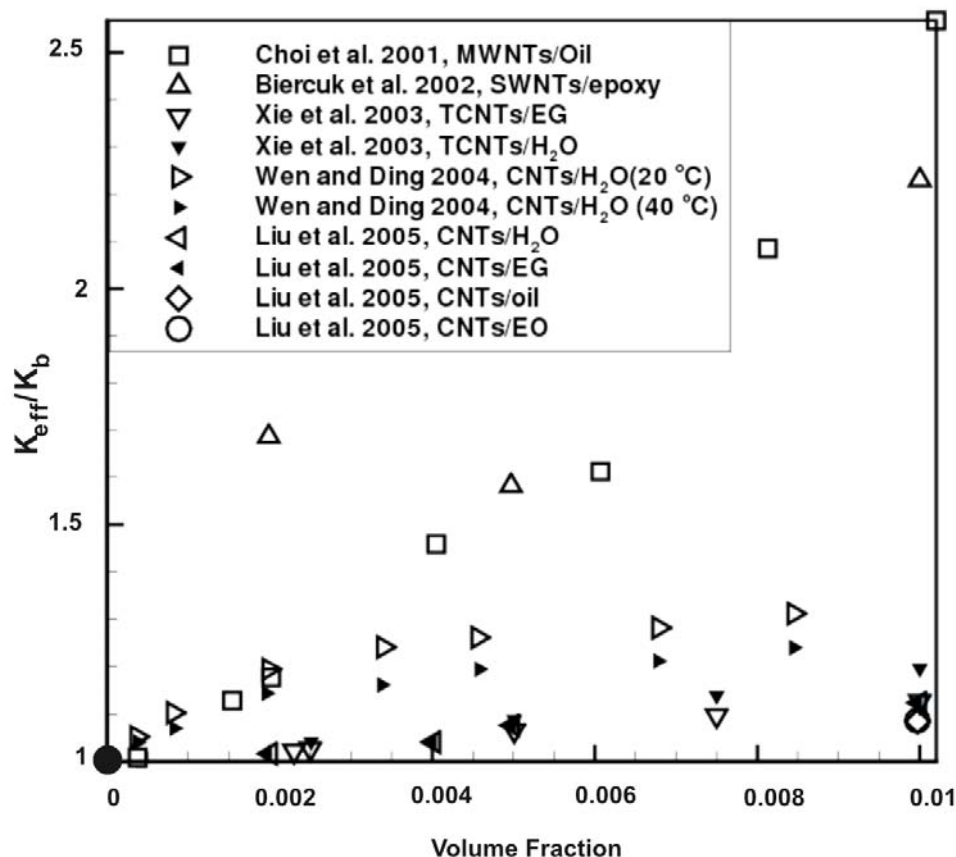

Figure 1: Comparison of experimental data on thermal conductivity of nanofluids.

Figure 2: Comparison of some experimental data on thermal conductivity
for carbon nanotube-based nanofluids.

Biercuk et al. (2002) measured the effective thermal conductivity of suspensions of single wall carbon nanotubes (SWNTs) and vapor grown carbon fibers (VGCF) in epoxy using a comparative method (Llaguno et al, 2001). Results showed 125% and 45% improvements for 1.0 wt% SWNTs and VGCF, respectively. Choi et al. (2003) found that thermal properties of SWNTs-epoxy composites showed similar improvement of the thermal conductivity. They pointed out that the bundling of nanotubes could be an important factor for thermal transport characteristics.

Wen and Ding (2004a) investigated the effect of temperature on the thermal conductivity of MCNT (20-60 nm in diameter and a few tens of micrometers in length)/water nanofluids. For temperatures lower than 30°C, an approximately linear dependence of thermal conductivity enhancement on temperature was obtained. However, the dependence leveled off when the temperature was higher than 30°C. Ding et al. (2005) also showed that the effective thermal conductivity increases with increasing temperature in CNT-water suspensions. They found that the improvement of the thermal conductivity is slightly higher than that reported by Assael et al. (2003), Xie et al. (2003), and Wen and Ding (2004a), but much lower than that found by Choi et al. (2001). The discrepancy among the different groups may reflect the properties of CNTs used, the aspect ratio, the inclusion of dispersants, and the experimental errors involved.

Assael et al. (2003; 2004) experimentally studied the enhancement of the thermal conductivity of carbon-multiwall nanotube (C-MWNT)-water suspensions with 0.1 wt% sodium dodecyl sulfate (SDS) as dispersant. They found that the maximum thermal conductivity enhancement was 38% for a 0.6 vol% suspension. Results showed that the SDS interacts with C-MWNT, the outer surface being affected. Later, Assael et al. (2005) repeated similar measurements using carbon-multiwall nanotubes (C-MWNTs) and carbon double-walled nanotubes (C-DWNTs), but using hexadecyltrimethyl ammonium bromide (CTAB) and nanosphere AQ as dispersants instead. The maximum thermal conductivity enhancement obtained was 34% for a 0.6 vol% C-MWNT-water suspension with CTAB. They also discussed the effect of surfactant concentration on the effective thermal conductivity of the suspensions

and found that CTAB is better for C-MWNTs and C-DWNTs.

Recently, Liu et al. (2005) measured the thermal conductivities of nanofluids containing CNTs dispersed in ethylene glycol and a synthetic engine oil. The increase of thermal conductivity is up to 12.4% for CNT-ethylene glycol suspensions at 1.0 vol% and 30% for CNT-synthetic engine oil suspensions at 2 vol%. The results of Liu (Liu et al, 2005) are relatively lower than other data, as shown in Fig. 2. It can be seen that the data from different groups vary widely and it is difficult to get a regression directly from the available data for CNT. One possible reason for this is that the thermal conductivity is highly dependent on important factors such as the structure of the CNTs, clustering, temperature, etc. Further systematic research is necessary to obtain a whole map for the thermal conductivities of CNTs.

Hwang et al. (2005) compared the thermal conductivity of four kinds of nanofluids such as MWCNTs in water, CuO in water, SiO_2 in water, and CuO in ethylene glycol. They found that the thermal conductivity of MWCNT nanofluid was increased up to 11.3% at 1 vol%, which is relatively higher than that of the other groups of nanofluids.

Recently, Zhang et al. (2007) investigated the effective thermal conductivity and thermal diffusivity of CNT/water nanofluids using the transient short-hot-wire technique. The average length and diameter of CNTs are 10 μm and 150 nm, respectively. However, the measured results demonstrate that the effective thermal conductivities of the nanofluids show no anomalous enhancements and can be predicted accurately by the unit-cell model equation of Yamada and Ota (1980) for carbon nanofibers.

From the aforementioned discussion, we find that the available experimental data from different research groups vary widely, as shown in Fig. 2. Further investigations are necessary to clarify the current predicament.

Table 1: Summary of experimental studies on thermal conductivity of nanofluids.

Investigator	Particles	Size (nm)	Fluids	Observations
Eastman et al (1997)	Al_2O_3/CuO/Cu	33/36/18	water,HE-200 oil	60% improvement for 5 vol% CuO particles in water.
Lee et al (1999)	Al_2O_3/CuO	24.4,38.4/18.6,23.6	water,EG	20% improvement for 4 vol% Cuo/EG mixture.
Wang et al (1999)	Al_2O_3/CuO	28/23	water,EG,PO,EO	12% improvement for 3 vol% Al_2O_3/water nanofluids.
Das et al (2003c)	Al_2O_3/CuO	38.4/28.6	water	2-4 fold increase over range of 21^oC to 52^oC.
Xie et al (2002b)	Al_2O_3	12.2–302	water,EG,PO	pH value, SSA, crystalline phase
Li and Peterson (2006)	Al_2O_3/CuO	36/29	water	enhancement with volume fraction and temperature
Xuan and Li (2000)	Cu	100	water,oil	successful suspension of relatively big metallic nanoparticles
Eastman et al (2001)	Cu	<10	EG	40% increase for 0.3 vol% Cu-based nanofluids
Hong et al (2005)	Fe	10	EG	18% increase for 0.55 vol% Fe/EG nanofluids.
Patel et al (2003)	Au, Ag	4, 15/70	water, toluene	Size, temperature, and chemical characteristics.
Murshed et al (2005)	TiO_2	Ø10×40,Ø15	DW	33% and 30% increase at 5 vol% for Ø10×40 and Ø15, respectively.
Xie et al (2001, 2002b)	SiC	Ø26, 600	water, EG	15.8% increase at 4.2 vol% for Ø26 SiC-H_2O and 22.9% at 4 vol% for Ø600 SiC-H_2O
Choi et al (2001)	MWNTs	Ø25×50μm	oil	exceed 250% at 1.0 vol%.
Biercuk et al (2002)	SWNTs	Ø3-30	epoxy	125% at 1.0 wt%.
Xie et al (2003)	TCNTs	Ø15×30 μm	DW,EG,DE	19.6%, 12.7%, and 7.0% increase at 1.0 vol% for TCNT/DE, EG, and DW, respectively.
Choi et al (2003)	SWNTs	Ø20-30×200	epoxy	300% at 3 wt% SWNT loading.
Assael et al (2003, 2004, 2005)	MWNTs, DWNTs	Ø130×10 μm	water	34% increase for 0.6 vol% suspension.
Liu et al (2005)	CNTs	Ø20-30 μm	EG,EO	12.4% for EG at 1 vol%, 30% for EO at 2 vol%.

Note: EG: ethylene glycol; PO: pump oil; EO: engine oil; DW: deionized water; DE: decene.

Measurement of Viscosity

Compared with the experimental studies on thermal conductivity of nanofluids, there are limited rheological studies reported in the literature. Li et al. (2002) measured the viscosity of water with CuO nanoparticle suspensions using a capillary viscometer. Results showed that the apparent viscosity of nanofluids decreased with increasing temperature. However, as they pointed out, the capillary tube diameter may influence the apparent viscosity for higher nanoparticle mass fractions, especially at lower temperatures.

Wang et al. (1999) also measured the relative viscosity of Al_2O_3-water and Al_2O_3-ethylene glycol nanofluids. Results showed a similar trend of increase of relative viscosity with increasing solid volume fraction for the two nanofluids. That means that the desirable heat transfer increase may be offset by the undesirable increase in pressure drop.

Das et al. (2003a) also measured the viscosity of Al_2O_3-water nanofluids against shear rate. Their results showed an increase of viscosity with increased particle concentrations. There is a strong possibility that nanofluids may be non-Newtonian, even viscoelastic in some cases. Further experimental studies are needed to define the viscosity models of nanofluids so they can be used in simulation studies.

The viscosity of CNT-water nanofluids as a function of shear rate was measured by Ding et al. (2005) recently. They observed that the viscosity of nanofluids increased with increasing CNT concentration and decreasing temperature. Also, the shear thinning behavior was found by the authors. That means the nanofluids can provide better fluid flow performance due to the higher shear rate at the wall, which results in low viscosity there.

Convective Heat Transfer

The past decade has seen many research activities in the experimental heat transfer characteristics of various nanofluids. For forced convective heat transfer, Lee and Choi (1996) studied the heat transfer behavior in parallel channels using an unspecified nanofluid and observed a reduction in thermal resistance by a factor of 2. Xuan and Li (2003) experimentally investigated flow and convective heat transfer characteristics for Cu-water based nanofluids through a straight tube with a constant heat flux at the wall. Results showed that the nanofluids give substantial enhancement of the heat transfer rate compared to pure water. They also

claimed that the friction factor for the nanofluids at low volume fraction did not produce an extra penalty in the pumping power.

Wen and Ding (2004b) reported experimental results for the convective heat transfer of γ-Al_2O_3 (27-56 nm)/water based nanofluids flowing through a copper tube (D = 4.5 mm, L = 970 mm) in laminar regime. They found that the inclusion of Al_2O_3 particles can significantly enhance the convective heat transfer coefficient, which increases with increasing Reynolds number and particle concentrations. Furthermore, the improvement of the heat transfer coefficient was particularly large in the entrance region, and decreased with the axial distance. Apart from the improved effective thermal conductivity, they also attributed the improvement of heat transfer to particle migration, which caused a non-uniform distribution of thermal conductivity and viscosity field along the cross-section in the tube.

Heris et al. (2006) investigated laminar flow of CuO/water and Al_2O_3/water nanofluids through a 1 m annular copper tube with 6 mm inner diameter and with 0.5 mm thickness and 32 mm diameter outer stainless steel tube, where saturated steam was circulated to create a constant wall temperature boundary condition rather than the constant heat flux condition employed by other researchers. Comparison of experimental results showed that the heat transfer coefficient enhanced with increasing volume fraction of nanoparticles, as well as Peclet number, while Al_2O_3/water showed more enhancement. Heris et al. (2007) claimed that the heat transfer enhancement of nanofluids is not only caused by the thermal conductivity increase, but also attributed to other factors such as dispersion and chaotic movement of nanoparticles, Brownian motion and particle migration, and so on.

Chien et al. (2003) investigated gold (17 nm)/water nanofluids flowing in a disk-shaped miniature heat pipe with diameter of 9 mm and height of 2 mm. Their data showed that the thermal resistance of the heat pipe fell appreciably with increased nanoparticle concentration. Tsai et al. (2004) also employed aqueous solutions of various-sized (2-35 nm and 15-75 nm) gold nanoparticles, which were prepared by the reduction of $HAuCl_4$ with trisodium citrate and tannic acid. They found a large decrease of thermal resistance of the heat pipe with nanofluids as compared with de-ionized water. The thermal resistance of the circular heat pipe ranged from 0.17 to 0.215 K/W with different nanoparticle solutions. The reason is that the included nanoparticles can bombard the vapor during

the bubble formation. Hence, the reduction of thermal resistance was obtained due to the smaller resulting bubble size. Results indicated the high potential of nanofluids as working medium to replace the conventional fluids in heat pipes. Ma et al. (2006) combined nanofluids with an oscillating heat pipe (OHP) to develop an ultrahigh-performance cooling device. Experimental results showed that the diamond nanofluid could reduce the temperature difference between the evaporator and the condenser from 40.9 to 24.3°C for 80 W input power.

Ding et al. (2005) investigated the heat transfer performance of CNT nanofluids in a tube with 4.5 mm inner diameter. They found that the observed enhancement of heat transfer coefficient is much higher than the increase in the effective thermal conductivity. They associated the possible reasons with the improved thermal conductivity, shear-induced enhancement in flow, reduced boundary layer, particle re-arrangement, and high aspect ratio of CNTs. These observations suggest that the aspect ratio should be associated with the high enhancement of heat transfer performance of CNTs-based nanofluids.

However, there are some inconsistent reports on nanofluid behavior in forced convection. Pak and Cho (1998) studied heat transfer performance of γ -Al$_2$O$_3$ (13 nm) and TiO$_2$ (27nm) water based nanofluids in tubes. They found that the convective heat transfer coefficient of the nanofluids at ϕ = 3 vol% was 12% lower than that of pure water for a constant average velocity. The possible reason is that the suspensions have higher viscosity than that of pure water, especially at high particle volume fractions.

Similar trends were observed by Yang et al. (2005), who investigated the convection heat transfer characteristics of the graphite nanofluids in laminar flow through a circular tube with diameter of 4.57 mm and length of 457 mm. Note that the particles they used are disc-like (the average diameter is 1-2 μm with the thickness around 20-40 nm). Unexpectedly, the experimental results showed that the increase of the heat transfer coefficient of the system is much lower than the enhancement of the effective thermal conductivity itself. That means that apart from the effective thermal conductivities, particle shape or aspect ratio (0.02 here) of the nanoparticle should be an important factor in determining the thermal performance of nanofluids, which can also be seen in the CNT-based suspensions with very high aspect ratio (Ding et al, 2005) (>100). Further investigation is necessary to clarify this problem.

Previous studies with nearly spherical nanoparticles (aspect ratio, $\alpha \approx 1$) (Pak and Cho, 1998; Xuan and Li, 2003; Wen and Ding, 2004b) showed an enhancement of the convective heat transfer of up to 60%. Results on CNTs nanofluids ($\alpha \gg 1$) (Ding et al, 2005) increased the convective heat transfer coefficient over 350% at Re = 800 for 0.5 wt.% CNTs. However, the disc-shape nanoparticle (α=0.02) of Yang et al. showed a much lower increase of the convective heat transfer coefficient with respect to the effective thermal conductivity. What we can conclude from the available experimental data is that the particle shape or aspect ratio of the particle is a significant parameter affecting the thermal performance of nanofluids. However, it has not been well examined yet.

For natural convective heat transfer, relatively few investigations have been carried out. Furthermore, the conclusions from the few published results in the literature also seem to be controversial. As discussed previously in section 3.3, Khanafer et al. (2003) numerically investigated the heat transfer behavior of nanofluids in a two-dimensional horizontal enclosure. The nanofluids were assumed to be in a single phase, in thermal equilibrium and without velocity slip between base fluid and particle. It was shown that the heat transfer rate increased with the particle concentration at any given Grashof number. However, different experimental results have been observed by Putra et al. (2003) and Wen and Ding (2005b).

Putra et al. (2003) presented their experimental observations on natural convection of Al$_2$O$_3$ and CuO-water nanofluids inside a horizontal cylinder heated from one end and cooled from the other. Unlike the results of forced convection, they found a systematic and definite deterioration of the natural convective heat transfer, which was dependent on the particle density, concentration, and the aspect ratio of the cylinder. The deterioration increased with particle concentration and was more significant for CuO nanofluids. For example, at a Rayleigh number of 5×10^7, 300% and 150% decreases in the Nusselt number was found for 4 wt.% of CuO and Al$_2$O$_3$, respectively. Then, what caused the different results between the numerical results (Khanafer et al, 2003) and the experimental data (Putra et al, 2003)? It should be clarified that in the numerical study presented by Khanafer et al. (2003), some important factors were not included. These factors include the particle size, particle shape, and particle distribution, which could significantly influence the flow and heat transfer characteristics of nanofluids. However, these factors has not been investigated properly as far.

Table 2: Summary of experiments on convective heat transfer of nanofluids.

Investigator	Geometry	Nanofluids	Findings
Forced convective heat transfer:			
Lee and Choi (1996)	parallel channels	unspecified	reduction in thermal resistance by a factor of 2.
Xuan and Li (2003)	tube (D = 10, L = 800 mm),	Cu/water	turbulent, large enhancement of heat transfer coef. $Nu_{nf} = c_1 (1.0 + c_2 \phi^{m1} Pe_d^{m2}) Re_{nf}^{m3} Pr_{nf}^{0.4}$
Wen and Ding (2004b)	tube (D = 4.5, L = 970 mm)	Al_2O_3/water (27-56 nm)	laminar, enhancement increases with Reynolds number and particle concentration.
Chien et al (2003)	disk-shaped heat pipe (D = 9, H = 2 mm)	Au/water (17 nm)	significant reduction of thermal resistance.
Tsai et al (2004)	heat pipe (D = 6, L = 170 mm)	Au/water (2-35, 15-75 nm)	high potential to take place conventional fluids in heat pipe applications.
Ding et al (2005)	tube (D = 4.5, L = 970 mm)	CNT/water	significant enhancement of convective heat transfer, which depends on the flow condition, CNT concentration and the pH level
Pak and Cho (1998)	tube	Al_2O_3 (13 nm), TiO_2 (27 nm)/water	h with $\phi = 0.03$ vol% was 12% lower than that of pure water for a given average fluid velocity.
Yang et al (2005)	tube (D = 4.57, L = 457 mm)	graphite nanofluid	the enhancement of h is lower than the increase of the effective thermal conductivity.
Heris et al (2006)	annular tube (D_{in} = 1 mm, D_{out} = 32 mm, L = 1m)	Al_2O_3(20 nm), CuO (50-60 nm)/water	enhancement of h with ϕ and Pe. Al_2O_3 showed more enhancement than CuO.
Natural convective heat transfer:			
Putra et al (2003)	horizontal cylinder	CuO (87.3 nm), Al_2O_3 (131.2 nm)/water	a systematic and significant deterioration in natural convective heat transfer.
Wen and Ding (2005b)	two horizontal discs (H = 10, D = 240 mm)	TiO_2/water (30-40 nm)	deterioration increases with particle concentrations.

Wen and Ding (2005b) also addressed the problem of natural convective heat transfer of TiO_2 (30-40 nm)/water nanofluids in a vessel which was composed of two horizontal aluminum discs of diameter 240 mm and thickness 10 mm separated by a 10 mm gap. They investigated both the transient and steady-state heat transfer coefficients for various concentrations of nanofluids. Similar to Putra et al. (2003), they also found that the natural convective heat transfer coefficient decreased as compared to that of pure water. Furthermore, such deterioration increased with nanoparticle concentrations. They proposed several possible mechanisms for their observations such as the convection caused by concentration difference, particle-fluid and particle-particle interactions, and modifications of the dispersion properties.

Tiwari and Das (2007) numerically studied mixed convection in a two-sided lid-driven differentially heated square cavity filled with a Cu/water nanofluid. The results agreed well with previously published work since the same single phase model was employed.

Considering the limited experimental studies on the natural convection heat transfer in nanofluids, firm conclusions can not be drawn yet. However, it has been clearly shown by the available results that the heat transfer behavior of nanofluids is very complex and the application of nanofluids for heat transfer enhancement should not be decided only by their effective thermal conductivity. Many other factors such as particle size, shape and distribution, micro-convection, pH value, and the particle-fluid interactions should have important influence on the heat transfer performance of the nanofluids in natural convective heat transfer, which should be identified further in future work.

Boiling Heat Transfer

Continuous advances in semiconductor miniaturization and manufacturing are bringing power densities to increasingly higher levels. For example, at the upper limit of future applications, high-end military and aerospace band-gap amplifiers will produce a waste heat flux on the order of 1000 W/cm². Only two-phase (boiling) liquids are suitable for such high dissipation rates. Faulkner et al. (2003) tried to achieve a 1000 W/cm² cooling flux using boiling with ceramic/water nanofluids. Their maximum heat flux dissipation was only 125 W/cm² for saturated boiling and 280 W/cm² for sub-cooled boiling. From their results we can see the high potential of boiling of nanofluids in cooling systems.

Witharana (2003) investigated the boiling heat transfer coefficients (HTC) of Au (unspecified size)/water, SiO_2 (30 nm)/water, and SiO_2/ethylene glycol nanofluids in a cylindrical vessel with 10 cm

in diameter and 10 cm in height. The bottom of the vessel was supplied with a fixed heat flux and the top was open to the atmosphere. Results of Au/water nanofluids ($\phi = 0.0002\ 0.001$ wt.%) showed that the HTC of nanofluids was higher than that of pure water, and increased with increasing gold particle concentrations. For example, the enhancement of HTC was above 11% in the intermediate heat flux (3 W/cm^2) and as high as 21% in the extreme case (4 W/cm^2). However, the SiO_2/water and SiO_2/ethylene glycol nanofluids recorded decreased HTC as compared to the base fluids, which was somewhat contrary to expectations. The author did not explain such strange phenomena. Possibly re-examination of the experiments might be a good choice. Li et al. (2003) also observed deteriorated pool boiling heat transfer for CuO/water nanofluids. They attributed this to a decrease in active nucleation sites due to nanoparticle sedimentation.

Das et al. (2003a) carried out an experimental study of pool boiling characteristics of Al_2O_3 nanofluids under atmospheric conditions in a tube with diameter of 20 mm. They found that the inclusion of nanoparticles degraded the boiling performance by increasing the wall superheat for a given heat flux. The deterioration in boiling performance increased with increasing particle concentration and surface roughness. This means there should be additional effects that degrade the boiling characteristics such as the changed surface features of the nanoparticles. Since the surface tension and latent heat were unaffected and the only unfavorable change was the increased viscosity, the heat transfer characteristics during pool boiling were expected to be enhanced considering the significant increase of thermal conductivity, which had active effects on the major factors in heat transfer during pool boiling such as micro-layer evaporation and reformation of the thermal boundary layer. They attributed it to the affected surface roughness during pool boiling of nanofluids. For higher particle concentration and higher surface roughness, the uneven surface can trap the particles more easily and make the surface smoother, which can cause the degradation of the boiling performance.

Das et al. (2003b) also studied the pool boiling performance in tubes with small diameter (4, 6.5 mm) where the bubble size and tube diameter are of the same order. They observed that deterioration for the narrow tubes was lower than that in the large tube (D = 20 mm). The small tube results in a large curvature of the surface to induce direct departure rather than sliding of larger bubbles. From the discussion above, apart from the increased effective thermal conductivity, there should be some other factors that affect the boiling performance of nanofluids.

Bang and Chang (2004; 2005) studied boiling of Al_2O_3-water nanofluids on a 100 mm square surface at high heat fluxes and observed that the surface roughness after boiling increased with nanoparticle concentration. However, the critical heat flux (CHF) (the peak heat flux, under which a boiling surface can stay in the nucleated boiling regime) performance was enhanced to ~32% and ~13% for both a horizontal flat surface and a vertical flat surface in the pool, respectively. They claimed that the increased roughness caused by the deposition of nanoparticles will cause a fouling effect and deteriorate the boiling heat transfer performance.

On the other hand, however, significant pool boiling heat transfer enhancement was found for Al_2O_3/water nanofluids by Tu et al. (2004). You et al. (2003) investigated the boiling curve and the CHF of Al_2O_3/water nanofluids in pool boiling with various nanoparticle concentrations ranging from 0 g/l to 0.05 g/l. They found that the boiling heat transfer coefficients of all the various concentrations, as well as of pure water, were the same, which demonstrated that the nucleated boiling heat transfer efficiency was not affected by the inclusion of nanoparticles. They also found that the size of bubbles increased with addition of nanoparticles to water. Correspondingly, the frequency of bubble departure degraded substantially. They claimed that there were some unknown key factors in the increase of the CHF in nanofluids, which need further investigation.

Vassallo et al. (2004) confirmed that the CHF increases for nanofluids (silica-water). They conducted experiments for both nano- and micro-solutions at the same solid volume fraction on a 0.4 mm diameter horizontal NiCr wire at atmospheric pressure. A heat transfer enhancement was not found in the nucleate boiling regime, but the CHF was increased significantly for both nano- and micro-particles. Addition of nanoparticles resulted in a maximum heat flux of about three times that of pure water and almost twice that of the micro-particle/water mixture.

Zhou (2004) investigated experimentally the heat transfer characteristics of copper/acetone based nanofluids with and without acoustic cavitation. Results showed that the copper nanoparticles and acoustic cavitation had significant influence on heat transfer in the fluid. However, the addition of nanoparticles did not affect the dependence of the heat transfer on acoustic cavitation and fluid sub-cooling. As compared to the experimental results of Das et al. (2003a; 2003b), the pool boiling heat transfer did not reduce with increased particle volume fractions in the absence of the acoustic field. While in an acoustic field, the boiling heat transfer of nanofluids was enhanced and the boiling hysteresis disappeared.

Table 3: Experiments on boiling heat transfer of nanofluids.

Investigator	Geometry	Nanofluids	Results
Witharana (2003)	cylindrical vessel (ϕ 10 × 10 cm)	Au, SiO_2 (30 nm)/water, EG	Au/water nanofluids displayed increased h, but SiO_2/water, SiO_2/EG caused decreased h.
Li et al (2003)	-	CuO/water	Deteriorated pool boiling heat transfer.
Das et al (2003a)	tube (D = 20 mm)	Al_2O_3/water	Nanoparticles deteriorated boiling performance and the degradation was found to increase with particle concentrations.
Das et al (2003b)	tube (D = 4, 6.5 mm)	Al_2O_3/water	the deterioration in narrow tube is less
Tu et al (2004)	-	Al_2O_3/water	significant pool boiling enhancement.
You et al (2003)	cartridge	Al_2O_3/water	enhancement of CHF 200% for pool boiling, no change for nucleate boiling.
Vassallo et al (2004)	NiCr wire (D = 0.4 m)	SiO_2/water	remarkable increase of CHF for both nano- and micro-solutions, but no significant differences for powers less than CHF.
Zhou (2004)	horizontal copper tube	Cu/acetone (80-100 nm)	Effects of acoustical parameters, nanofluids concentration, and fluid subcooling on heat transfer enhancement.
Wen and Ding (2005a)	cylindrical boiling vessel (D = 160 mm, H = 300 mm)	Al_2O_3/water	significant enhancement of the boiling heat transfer, ~ 40% at 1.25 wt% suspensions.
Bang and Chang (2004, 2005)	horizontal heater in a vessel	Al_2O_3/water	decrease of pool nucleate boiling heat transfer, but enhancement of CHF performance.

Wen and Ding (2005a) conducted experiments on pool boiling heat transfer using γ-Al_2O_3-water nanofluids, which were produced through an electrostatic stabilization method with the aid of a high shear homogenizer. They found that the presence of alumina in the nanofluid can enhance the boiling heat transfer significantly, by ~40% for a 1.25 wt% concentration of the particles. Considering the controversies from previous studies, they proposed some possible reasons such as the extra thermal resistance to the boiling surface caused by the sedimentation of nanoparticles, effect of surfactant, and interaction between boiling surface and nanofluids. The aggregation of nanofluids should be an important factor affecting the boiling performance, which needs to be clarified quantitatively further.

Kim et al. (2007) studied the pool boiling characteristics of dilute dispersions of Al_2O_3, ZrO_2 and SiO_2 nanoparticles in water. Consistent with other nanofluid studies, it was found that a significant enhancement in CHF can be obtained at modest nanoparticle concentration (<0.1 vol%).

The currently available experimental data on boiling heat transfer of nanofluids are limited. However, conflicting results were observed from these limited data as far as the effect of nanoparticles on the boiling heat transfer performance is concerned. The inconsistencies indicate that our understanding of the thermal behavior of nanofluids related to boiling heat transfer is still poor. Further detailed and valuable investigations are necessary for us to understand the phenomenon of boiling of nanofluids. As we know, pool boiling will be affected by surface properties such as surface roughness, surface wettability, and surface contamination. In the reviewed studies, however, only the surface roughness is the most often considered parameter. Systematic studies should be carried out to include the interaction between the surface and nanofluids (wettability), as also suggested by Wen and Ding (2005a).

APPLICATION OF NANOFLUIDS

Nanofluids can be used to improve heat transfer and energy efficiency in a variety of thermal systems. Much of the work in the field of nanofluids is being done in national laboratories and academia and is at a stage beyond discovery research. Recently, the number of companies that see the potential of nanofluid technology and are in active development work for specific industrial applications is increasing. In the transportation industry, GM and Ford, among others, have ongoing nanofluid research projects.

Transportation

An ethylene glycol and water mixture, the nearly universally used automotive coolant, is a relatively poor heat transfer fluid compared to water alone. Engine oils perform even worse as a heat transfer medium. The addition of nanoparticles to the standard engine coolant has the potential to improve automotive and heavy-duty engine cooling rates. Such improvement can be used to remove engine heat with a reduced-size coolant system. Smaller coolant systems result in smaller and lighter radiators, which in turn benefit almost every aspect of car and

truck performance and lead to increased fuel economy. Alternatively, improved cooling rates for automotive and truck engines can be used to remove more heat from higher horsepower engines with the same size of coolant system.

A promising nanofluid engine coolant is pure ethylene glycol with nanoparticles. Pure ethylene glycol is a poor heat transfer fluid compared to a 50/50 mixture of ethylene glycol and water, but the addition of nanoparticles will improve the situation. If the resulting heat transfer rate can approach the 50/50 mixture rate, there are important advantages. Perhaps one of the most prominent is the low-pressure operation of an ethylene-glycol-based nanofluid compared with a 50/50 mixture of ethylene glycol and water. An atmospheric-pressure coolant system has lower potential capital cost. This nanofluid also has a high boiling point, which is desirable for maintaining single-phase coolant flow. In addition, a higher boiling point coolant can be used to increase the normal coolant operating temperature and then reject more heat through the existing coolant system. More heat rejection allows a variety of design enhancements. including engines with higher horsepower.

The results of nanofluids research are being applied to the cooling of automatic transmissions. Tzeng et al. (2005) dispersed CuO and Al_2O_3 nanoparticles into engine transmission oil. The experimental platform was the transmission of a four-wheel-drive vehicle. The transmission has an advanced rotary blade coupling, where high local temperatures occur at high rotating speeds. For that reason, improved heat transfer rates from the transmission fluid were important. The temperature distribution on the exterior of the rotary-blade-coupling transmission was measured at four engine operating speeds. For that reason, improved heat transfer rates from the transmission fluid were important. The temperature distribution on the exterior of the rotary-blade-coupling transmission was measured at four engine operating speeds (400, 800, 1200, and 1600 rpm), and the optimum composition of nanofluids with regard to heat transfer performance was investigated. The results showed that CuO nanofluids produced the lowest transmission temperatures at both high and low rotating speeds. Thus, use of nanofluid in the transmission has a clear advantage from the thermal performance viewpoint. As in all nanofluid applications, however, consideration must be given to such factors as particle setting, particle agglomeration, and surface erosion.

In automotive lubrication applications, surface-modified nanoparticles stably dispersed in mineral oils are reported to be effective in reducing wear and enhancing load-carrying capacity (Zhang and Que, 1997). Recent results from a research project involving industry and university points to the use of nanoparticles in lubricants to enhance tribological properties such as load-carrying capacity, wear resistance, and friction reduction between moving mechanical components. Such results are encouraging for improving heat transfer rates in automotive systems through the use of nanofluids.

Electronics Cooling

The power density of integrated circuits and microprocessors has increased dramatically in recent years. The trend should continue for the foreseeable future. Recently, the International Technology Roadmap for Semiconductors (ITRS) projected that, by 2018, high-performance integrated circuits will contain more than 9.8 billion transistors on a chip area of 280 mm^2 - more than 40 times as many as today's chips of 90-nm node size. Future processors for high-performance computers and servers have been projected to dissipate higher power, in the range of 100-300 W/cm^2. Whether these values actually become reality is not as significant as the projection that the general trend to higher power density electronics will continue. Existing air-cooling techniques for removing this heat are already reaching their limits, and liquid cooling technologies are being, and have been, developed for replacing them. Single-phase fluids, two-phase fluids, and nanofluids are candidate replacements for air. All have increased heat transfer capabilities over air systems, and all are being investigated.

Nanofluids have been considered as the working fluid for heat pipes in electronic cooling applications. Tsai et al. (2004) used a water-based nanofluid as the working medium in a circular heat pipe designed as a heat spreader to be used in a CPU in a notebook or a desktop PC. The results showed a significant reduction in thermal resistance of the heat pipe with the nanofluid as compared with deionized water. The measured results also showed that the thermal resistance of a vertical meshed heat pipe varies with the size of nanoparticles. In a related study, Ma et al. (2006) investigated the effect of nanofluids on the heat transport capability of an oscillating heat pipe. Experimental results showed that, at the input power of 80 W, a nanofluid containing 1 vol.% nanoparticles reduced the temperature difference

between the evaporator and the condenser from 40.9°C to 24.3°C.

Nguyen et al. (2007) experimentally investigated the behaviour and heat transfer enhancement of an Al_2O_3/water nanofluid flowing inside a closed system that is used for cooling of micro-electronic components. Results showed that the inclusion of nanoparticles into distilled water produced a considerable enhancement of the cooling block convective heat transfer coefficient. For a 6.8 vol% concentration, the heat transfer coefficient has been found to increase as much as 40% compared to that of the base fluid. Experimental results also showed that a nanofluid with 36 nm particle size provides higher convective heat transfer coefficients than the ones given by a nanofluid with 47 nm particles. These positive results are promoting the continued research and development of nanofluids for such applications.

Recently, Lee and Mudawar (2007) explored microchannel cooling using Al_2O_3/water nanofluids. The high thermal conductivity of nanoparticles is only shown to enhance the single-phase heat transfer coefficient, especially for laminar flow. Higher heat transfer coefficients were achived mostly in the entrance region of microchannels. However, the enhancement was weaker in the fully developed region, proving that nanoparticles have an appreciable effect on thermal boundary layer development. Higher concentrations also produced greater sensitivity to heat flux. Despite this enhancement, the overall cooling effectiveness of nanoparticles was quite miniscule because of the large axial temperature rise associated with the decreased specific heat for the nanofluid compared to the base fluid. For two-phase cooling, nanoparticles cause catastrophic failure by depositing into large clusters near the channel exit due to localized evaporation once boiling commenced. These and other practical disadvantages bring into question the overall merit of using nanofluids in microchannel heat sinks.

Space and Defense

A number of military devices and systems require high-heat-flux cooling to the level of tens of MW/m^2. At this level, cooling with conventional fluids is challenging. Examples of military applications include cooling of power electronics and directed-energy weapons. Directed-energy weapons involve high heat fluxes (> 500 - 1000 W/cm^2), and providing adequate cooling of them and the associated power electronics is a critical need.

Nanofluids have the potential to provide the required cooling in such applications as well as in other military systems, including military vehicles, submarines, and high-power laser diodes. In some cases, nanofluid research for defense applications includes multifunctional nanofluids with added thermal energy storage or energy harvesting through chemical reactions.

Transformer cooling is important to the Navy as well as the power generation industry with the objective of reducing transformer size and weight. The ever-growing demand for greater electricity production can lead to the necessity of replacing and/or upgrading transformers on a large scale and at a high cost. A potential alternative in many cases is the replacement of conventional transformer oil with a nanofluid. Such retrofits can represent considerable cost savings. It has been demonstrated that the heat transfer properties of transformer oils can be significantly improved by using nanoparticle additives.

You et al. (2003) and Vassalo et al. (2004) have reported order of magnitude increases in the critical heat flux in pool boiling with naofluids compared to the base fluid alone. Such levels present the possibility of raising chip power in electronic components or simplifying cooling requirements for space applications. High critical heat fluxes allow boiling to higher qualities with increased heat removal and wider safety margin from film boiling. This feature makes nanofluids attractive in general electronic cooling as well as space applications where power density is very high.

Other Applications

The Massachusetts Institute of Technology has established an interdisciplinary center for nanofluid technology for the nuclear energy industry. Currently, they are evaluating the potential impact of the use of nanofluids on the safety, neutronic, and economic performance of nuclear systems.

Nanofluids and nanoparticles have many applications in the biomedical industry. For example, to circumvent some side effects of traditional cancer treatment methods, iron-based nanoparticles could be used as delivery vehicles for drugs or radiation without damaging nearby healthy tissue. Such particles could be guided in the bloodstream to a tumor using magnets external to the body. Nanofluids could also be used for safer surgery by producing effective cooling around the surgical region and thereby enhancing the patient's chance of survival and reducing the risk of organ damage. In a

contrasting application to cooling, nanofluids could be used to produce a higher temperature around tumors to kill cancerous cells without affecting nearby healthy cells (Jordan et al, 1999).

There are unending situations where an increase in heat transfer effectiveness can be beneficial to the quality, quantity, and/or cost of a product or process. In many of these situations, nanofluids are good candidates for accomplishing the enhancement in heat transfer performance. For example, nanofluids have potential application in building where increases in energy efficiency could be realized without increased pumping power. Such an application would save energy in a heating, ventilating, and air conditioning system while providing environmental benefits. In the renewable energy industry, nanofluids could be employed to enhance heat transfer from solar collectors to storage tanks and to increase the energy density. Nanofluid coolants also have potential application in major process industries, such as materials, chemical, food and drink, oil and gas, paper and printing, and textiles.

CONCLUDING REMARKS AND FUTURE WORK

This paper presents an overview of the recent developments in the study of heat transfer using nanofluids. Many important, complex and interesting phenomena involving nanofluids have been reported in the literature. Researchers have given much more attention to the thermal conductivity rather than the heat transfer characteristics. The use of nanofluids in a wide range of applications appears promising, but the development of the field faces several challenges: (i) the lack of agreement between experimental results from different groups; (ii) the often poor performance of suspensions; and lack of theoretical understanding of the mechanisms. Further theoretical and experimental research investigations are needed to understand the heat transfer characteristics of nanofluids and identify new and unique applications for these fields.

NOMENCLATURE

| k | thermal conductivity | W/m-K |
| T | temperature | K |

Greek Symbols

| α | aspect ratio of nanoparticles | (-) |
| ϕ | volume fraction of nanoparticles in suspension | (-) |

Subscripts

| b | base fluid | (-) |
| eff | effective | (-) |

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