

Heat Transfer Intensification Using Nanofluids[†]

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Abstract

This paper summarises some of our recent work on the heat transfer of nanofluids (dilute liquid suspensions of nanoparticles). It covers heat conduction, convective heat transfer under both natural and forced flow conditions, and boiling heat transfer in the nucleate regime. The results show that, despite considerable data scattering, the presence of nanoparticles enhances thermal conduction under macroscopically static conditions mainly due to nanoparticle structuring / networking. The natural convective heat transfer coefficient is observed to decrease systematically with increasing nanoparticle concentration, and the deterioration is partially attributed to the high viscosity of nanofluids. However, either enhancement or deterioration of convective heat transfer is observed under the forced flow conditions and particle migration is suggested to be an important mechanism. The results also show that the boiling heat transfer is enhanced in the nucleate regime for both alumina and titania nanofluids, and the enhancement is more sensitive to the concentration change for TiO₂ nanofluids. It is concluded that there is still some way to go before we can tailor-make nanofluids for any targeted applications.

Keywords: Nanofluids, Thermal conduction, Natural convective heat transfer, Forced convective heat transfer, Boiling heat transfer, Mechanisms

1. Introduction

Nanofluids are dilute liquid suspensions of nanoparticles with at least one critical dimension smaller than ~100nm. Much attention has been paid in the past decade to this new type of composite material because of its enhanced properties and behaviour associated with heat transfer (Masuda et al. 1993; Choi 1995), mass transfer (Krishnamurthy et al. 2006, Olle et al. 2006), wetting and spreading (Wasan and Nikolov 2003) and antimicrobial activities (Zhang L et al. 2007), and the number of publications related

to nanofluids increases in an exponential manner. The enhanced thermal behaviour of nanofluids could provide a basis for an enormous innovation for heat transfer intensification, which is of major importance to a number of industrial sectors including transportation, power generation, micro-manufacturing, thermal therapy for cancer treatment, chemical and metallurgical sectors, as well as heating, cooling, ventilation and air-conditioning. Nanofluids are also important for the production of nanostructured materials (Kinloch et al. 2002), for the engineering of complex fluids (Tohver et al. 2001), as well as for cleaning oil from surfaces due to their excellent wetting and spreading behaviour (Wasan & Nikolov 2003).

Despite considerable research effort and significant progress in the past decade, our fundamental understanding of nanofluids is limited. This is indeed reflected in the significant scattering / disagreement of published data and less convincing arguments in interpreting the data (see Sections 2-4). It is fair to

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say that there is a long way to go before we can actually tailor-make nanofluids for targeted applications. This paper aims to provide a brief overview of the thermal properties and behaviour of nanofluids. The focus will be on our own work on conduction, convection and phase change heat transfer of nanofluids, though a brief review of the literature is also carried out where appropriate. Discussions will be made on possible mechanisms of heat transfer enhancement. Formulation of nanofluids and the flow behaviour of nanofluids will not be included. Interested parties are referred to recent publications by, for example, Kwak and Kim (2005), Prasher et al. (2006a) and Ding et al. (2007).

The paper is organised in the following manner. Section 2 presents the work on the thermal conduction of nanofluids under macroscopically static conditions. Section 3 is devoted to the heat transfer of nanofluids under forced and natural convection conditions. Section 4 will discuss boiling (phase change) heat transfer. Finally, concluding remarks are made in Section 5.

2. Thermal Conductivity of Nanofluids

The thermal conductivity of nanofluids has dominated the literature in the past decade, though this pattern has changed slightly over the last few years; see Koblinski et al. (2005), Das et al. (2006) and Wang and Mujumdar (2007) for recent reviews. Note that the term 'thermal conductivity' refers to the 'effective thermal conductivity', as nanofluids are two-phase mixtures. For simplicity, we shall not differentiate the two terms in the paper.

2.1 Experimental data

The published data of the thermal conductivity of nanofluids are mostly obtained at room temperature with two methods, namely the hot-wire method and the conventional heat conduction cell method (Choi 1996; Lee et al. 1999; Eastman et al. 2001; Choi et al. 2001; Wen and Ding 2004a). There are also a few recent reports on the measurements using the 3ω method (Yang and Han 2006). The hot-wire method is well known and will not be described here. The 3ω method is relatively new and accurate, and uses a metal wire suspended in nanofluids. The wire acts as both a heater and a thermometer. A sinusoidal current at frequency ω is passed through the metal wire and generates a heat wave at frequency 2ω . The temperature rise at frequency 2ω in the metal wire can be deduced by the voltage component at frequency

3ω . The thermal conductivity of the fluid is determined by the slope of the 2ω temperature rise of the metal wire.

Fig. 1 summarises the room temperature data from our own work (Wen and Ding 2004a, 2004b, 2005a, 2005b, 2006; Ding et al. 2006; He et al. 2007) and those reported in the literature (Lee et al. 1999; Eastman et al. 2001; Choi et al. 2001; Xie et al. 2002a & 2002b; Biercuk et al. 2002; Das et al. 2003a; Patel et al. 2003; Kumar et al. 2004; Assael et al. 2004; Zhang X. et al. 2007). The data shown in **Fig. 1** include aqueous, ethylene glycol, minerals oil and polymer-based composite materials and are classified according to the material type of nanoparticles. One can see a significant degree of data scattering. In spite of the scatter, the presence of nanoparticles in fluids can substantially enhance the thermal conductivity and the extent of enhancement depends on the nanoparticle material type and volume fraction.

Note that the particle size is not included in **Fig. 1**. The main reason is that almost all publications only give the primary size of nanoparticles obtained by electron microscopes. It is well known that nanoparticles are prone to agglomerating and/or aggregating, and, as will be discussed later, it is the nanoparticle structuring that gives rise to the thermal conduction enhancement. Nanoparticles used in our own work include multi-walled carbon nanotubes supplied by Prof W. Fei of Tsinghua University, China (20-60nm in diameter, a few micrometres long), alumina purchased from Nanophase Technologies, USA (primary particle diameter 27-56 nm, but they are in the aggregate form with a diameter of ~150nm), and titania purchased from Degussa, Germany (primary particles ~25nm in diameter, they are in aggregate form with a size ranging from 95 – 210nm depending on the processing method). Except where otherwise mentioned, titania aggregates with an average size of 120nm are used in this work.

An inspection of **Fig. 1** suggests that the data points can be approximately divided into two groups separated by a demarcation band. The data points on the left-hand side of the band are for nanofluids made of metal nanoparticles and carbon nanotubes, whereas those on the right-hand side of the band are for nanofluids made of metal oxide and carbide nanoparticles. The width of the band represents overlapping between the two groups. Broadly speaking, the demarcation band seems to indicate that nanofluids made with high thermally conductive materials give a higher effective thermal conductivity. There are, however, deviations within each of the two re-

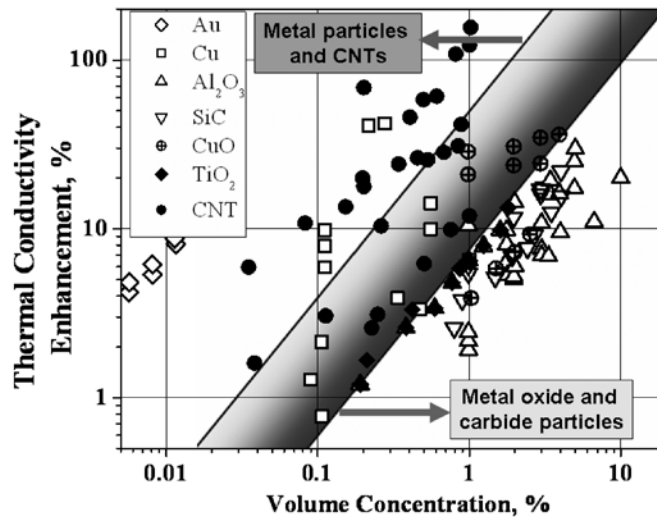


Fig. 1 Thermal conductivity of nanofluids: data taken from Lee et al. (1999), Eastman et al. (2001), Choi et al. (2001), Xie et al. (2002a & 2002b), Biercuk et al. (2002), Das et al. (2003a), Patel et al. (2003), Kumar et al. (2004), Wen and Ding (2004a, 2004b, 2005a, 2005b, 2006), Assael et al. (2004), Ding et al. (2006), He et al. (2007) and Zhang X et al. (2007).

gions separated by the band. For example, at room temperature, the thermal conductivities of gold and copper are 317 and 401 W/K.m, respectively, whereas the thermal conductivity of carbon nanotubes is observed to be between 3000 and 6000 W/K.m (Kim et al. 2001; Berber et al. 2000). The sequence of the three materials as shown in the left-hand side of band in **Fig. 1** is gold, carbon nanotubes and copper. On the other hand, the thermal conductivities of CuO, alumina and SiC at room temperature are 20, 40 and 120 W/K.m, respectively. **Fig. 1** shows that copper oxide nanofluids give the highest enhancement and little difference is seen between SiC and alumina nanofluids.

The experimental data shown in **Fig. 1** are compared with various macroscopic models proposed for suspensions and composite materials as listed in Table 1. These models were developed based on the so-called effective medium theory, which has been detailed by Choy (1999). The models have been shown to be applicable under various conditions as indicated in the last column of **Table 1**. It has been shown that, for spherical particles, all the models give a predicted line that is slightly lower than the lower bound of the demarcation band, and there is a very small difference between these models within the range of particle concentration as shown in **Fig. 1**. This indicates that the conventional way of using macroscopic models gives an underprediction for most nanofluids, particularly for Au, Cu and CuO nanofluids. For carbon nanotube nanofluids, the models provide an overprediction, mainly because the interfacial resistance in

not considered in the model; see Section 2.2 for more details.

2.2 Mechanisms of the thermal conduction enhancement

A number of mechanisms have been proposed for interpreting the experimentally observed thermal conduction enhancement including Brownian motion of nanoparticles, the interfacial ordering of liquid molecules on the surface of nanoparticles, the ballistic transport of energy carriers within individual nanoparticles and between nanoparticles that are in contact, as well as the nanoparticle structuring / networking (Kebllinski et al. 2002; Wang et al. 2003; Nan et al. 2003; Yu and Choi 2003; Patel et al. 2003; Kumar et al. 2004; Shenogin et al. 2004a & 2004b; Prasher et al. 2006b). There has been much debate on these mechanisms over the past few years and the focus of debate has been on the role of Brownian motion (Kumar et al. 2004; Koo and Kleinstreuer 2005; Kebllinski and Cahill 2005; Evans et al. 2006) and interfacial ordering (Yu and Choi 2003; Shenogin et al. 2004a & 2004b; Prasher et al. 2005). A brief discussion will be made in the following text on the two much-debated mechanisms.

The role of Brownian motion The Brownian motion of nanoparticles could contribute to the thermal conduction enhancement through two ways, a direct contribution due to motion of nanoparticles that transport heat, and an indirect contribution due to micro-convection of fluid surrounding individual nanoparticles. The direct contribution of Brownian motion has been

Table 1 A list of the most frequently used models for effective thermal conductivity

Model	Expressions	Remarks
Maxwell (1873)	$\frac{K_{eff}}{K_L} = \frac{K_s + 2K_L + 2(K_s - K_L)\phi_s}{K_s + 2K_L - (K_s - K_L)\phi_s}$	Spherical particles ϕ_s – solids volume fraction
Hamilton & Crosser (1962)	$\frac{K_{eff}}{K_L} = \frac{K_s + (n-1)K_L - (n-1)\phi_s(K_L - K_s)}{K_s + (n-1)K_f + \phi_s(K_L - K_s)}$	n depends on particle shape and K_s/K_L , $n=3/\psi$ for $K_s/K_L > \sim 100$, $n=3$ for other cases, ψ - sphericity
Jeffrey (1973)	$\frac{K_{eff}}{K_L} = 1 + \frac{3\phi_s(K_s/K_L - 1)}{K_s/K_L + 2} + 3\phi_s^2 \left(\frac{K_s/K_L - 1}{K_s/K_L + 2}\right)^2 \cdot [1 + \frac{1}{4} \left(\frac{K_s/K_L - 1}{K_s/K_L + 2}\right) + \frac{3}{16} \left(\frac{K_s/K_L - 1}{K_s/K_L + 2}\right) \left(\frac{K_s/K_L + 2}{2K_s/K_L + 3}\right) + \dots]$	High order terms represent pair interactions of randomly dispersed particles
Davis (1986)	$\frac{K_{eff}}{K_L} = 1 + \frac{3(K_s/K_L - 1) \cdot [\phi_s + f \cdot \phi_s^2 + O(\phi_s^3)]}{(K_s/K_L + 2) - (K_s/K_L - 1)\phi_s}$	High order terms due to pair interactions of randomly dispersed spheres, $f=2.5$ & 0.5 for $K_s/K_L=10$ and ∞ , respectively
Bruggeman (1935)	$\frac{K_{eff}}{K_L} = [(3\phi_s - 1) \frac{K_s}{K_f} + (2 - 3\phi_s) + \sqrt{\Delta}] / 4$ $\Delta = (3\phi_s - 1)^2 (K_s/K_L)^2 + (2 - 3\phi_s)^2 + 2(2 + 9\phi_s - 9\phi_s^2)(K_s/K_L)$	Spherical particles, interactions between particles considered, applicable to high concentrations

shown theoretically to be negligible as the time scale of the Brownian motion is about 2 orders of magnitude larger than that for the thermal diffusion of the base liquid (Kebinski et al. 2002). The indirect contribution has also been shown to play a minute role by theoretical analysis (Evans et al. 2006). Furthermore, nanoparticles are often in the form of agglomerates and/or aggregates. The Brownian motion should therefore play an even less significant role. In the following text, further experimental evidence of the minor role of the Brownian motion is presented.

Fig. 2 shows the thermal conductivity enhance-

ment as a function of temperature for nanofluids made of three types of metal-oxide nanoparticles. One can see that, except for the data of Das et al. (2003a) for CuO/H₂O nanofluids, the thermal conductivity enhancement is a very weak function of temperature. The weak temperature dependence suggests that the Brownian motion of nanoparticles is not a dominant mechanism of the enhanced thermal conductivity of nanofluids under the conditions of this work and other recent studies such as Kabelac and Kuhnke (2006) and Zhang X. et al. (2007). **Fig. 3** shows the results of alumina nanofluids made from

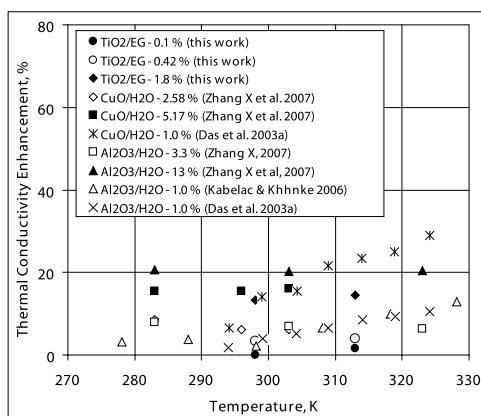


Fig. 2 Effect of temperature on the thermal conductivity enhancement: data source see the legend.

three base liquids with very different viscosities. No clear trend in the dependence of the thermal conductivity enhancement on the base liquid viscosity again suggests the minor role of the Brownian motion.

The role of liquid molecular layering At the solid-liquid interface, liquid molecules could be significantly more ordered than those in the bulk liquid. By analogy to the thermal behaviour of crystalline solids, the ordered structure could be a mechanism of thermal conductivity enhancement (Kebllinski et al. 2002). On such a basis, a number of macroscopic models have been proposed to interpret the experimental data; see for example, Yu and Choi (2003) and Wang et al. (2003). It is now clear that the liquid-nanoparticle interface is one of the main factors that decrease (rather than increase) the effective thermal conductivity due to the so-called Kapitza interfacial resistance (Shenogin et al. 2004a & 2004b, Nan et al. 2003; Gao et al. 2007). The experimental data for carbon nanotube nanofluids as presented in Section 2.1 agrees with this argument.

It should be noted that the effect of interfacial resistance on the overall effective thermal conductivity depends on the particle size (Kebllinski et al. 2005; Prasher et al. 2005; Putnam et al. 2006; Gao et al. 2007). When particle size is relatively small in comparison with the characteristic length scale due to the interfacial resistance, nanoparticles act as insulators. This leads to deterioration of the thermal conduction of nanofluids.

The last standing mechanism The above discussion indicates that neither Brownian motion nor interfacial liquid layering can be a dominant mechanism. As the ballistic transport of energy carriers in nanofluids has been excluded as a dominant mechanism, the last

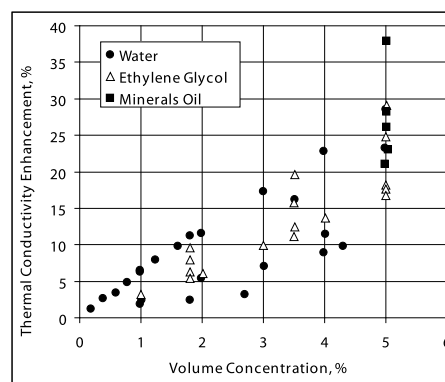


Fig. 3 Effect of base liquid property on thermal conductivity enhancement for alumina nanofluids: data taken from Lee et al. (1999), Eastman et al. (2001), Xie et al. (2002a), Das et al. (2003b) and Wen and Ding (2004b).

mechanism standing is the nanoparticle structuring / networking (Prasher et al. 2006b, Kebllinski 2007). This has actually been validated by our experimental results and theoretical analyses of ethylene-glycol-based titania nanofluids. We found that the size of the aggregates is approximately 3.5 times that of the primary nanoparticles (**Fig. 4**). By using the Maxwell model for aggregate suspensions and the Bruggeman model for aggregates (**Table 1**), a nanoparticle structuring model is formulated which gives a fairly good agreement with the experimental data (**Fig. 5**, Chen et al. 2007a).

3. Convective Heat Transfer of Nanofluids

Convective heat transfer refers to heat transfer between a fluid and a surface due to the macroscopic motion of the fluid relative to the surface. The sur-

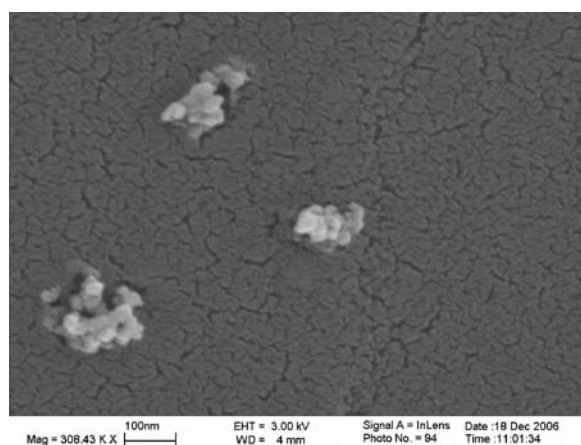


Fig. 4 SEM image of based TiO₂ nanofluids: Degussa P25 TiO₂ with primary particle diameter ~ 25nm.

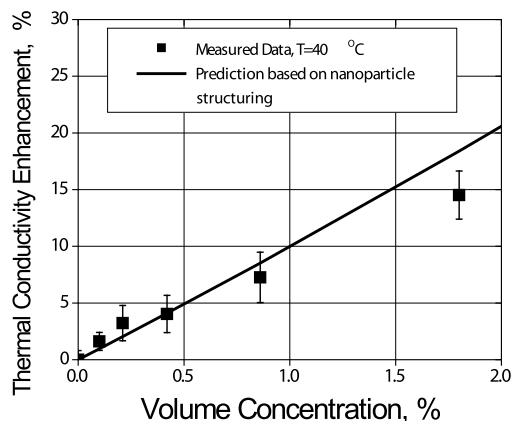


Fig. 5 Comparison of measured thermal conductivity enhancement with the model based on nanoparticle structuring: based TiO₂ nanofluids.

face can be a solid wall or an interface with another liquid. We are interested in the solid surface due to its great industrial significance. Convective heat transfer can be divided into two types, natural convective heat transfer where fluid motion is induced by buoyancy, and forced convective heat transfer where fluid is forced to flow through a confined region or across a confining wall.

3.1 Natural convective heat transfer

Very few studies have been found in the literature on nanofluids heat transfer under natural convection conditions. By using the numerical technique, Khanafer *et al.* (2003) predicted that nanofluids enhanced natural convective heat transfer. The enhancement was also observed experimentally by Nnanna *et al.* (2005) for Cu / ethylene glycol nanofluids and by Nnanna and Routhu (2005) for alumina / water nanofluids. In contrast, Putra *et al.* (2003) found experimentally that the presence of nanoparticles in water systematically decreased the natural convective heat transfer coefficient. Interestingly, the decrease in the natural convective coefficient was also reported by Nnanna *et al.* (2005) for alumina / water nanofluids, which is in contradiction to the observation of Nnanna and Routhu (2005). Our work was therefore aimed to investigate the controversy (Wen & Ding 2005b & 2006) and the details are presented in the following text.

Materials and experimental techniques Aqueous-based TiO₂ nanofluids were formulated for the work by dispersing dry titania nanoparticles in distilled water without the use of any dispersant/surfactant. The size of the titania nanoparticles was given in Section 2. A high-shear mixer was used to break agglomer-

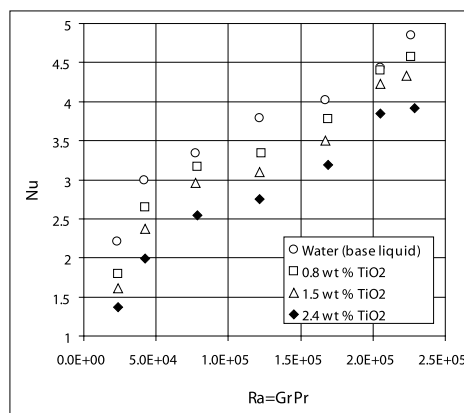


Fig. 6 Effect of nanoparticle concentration on the convective heat transfer under natural convection conditions.

ates of nanoparticles, and electrostatic stabilisation was used to stabilise the suspensions. The experimental system used in the work consisted of two horizontally positioned aluminium discs of diameter 240mm and thickness 10mm, separated by a 10mm gap through a short insulating PTFE cylinder. A silicon rubber flexible heater was attached to the lower surface of the bottom disc. Six type J thermocouples and two surface heat flux sensors were mounted on the aluminium surfaces to measure temperatures and heat fluxes, which allowed calculation of the natural convective heat transfer coefficient.

Experimental data Fig. 6 shows the convective heat transfer coefficient (h) in the form of a Nusselt number (Nu) as a function of the product of the Grashof number (Gr) and Prandtle number (Pr) defined as $Nu = hd_g/K_f$, $Pr = \nu_f/\alpha$, $Gr = g\beta\Delta T d_g^3/\nu_f^2$, respectively, with d_g representing the separation between the two discs, K_f the thermal conductivity of the fluid, ν_f the kinematic viscosity of the fluid, α the thermal diffusivity of the fluid, g the gravitational acceleration, β the volume expansion coefficient of the fluid and ΔT the temperature difference between the two disc surfaces. The product of the Gr and Pr numbers is also termed as the Rayleigh number defined as $Ra = g\beta\Delta T d_g^3/(\nu_f\alpha)$. One can see clearly that the Nusselt number decreases with increasing nanoparticle concentration. Possible reasons are discussed in the following text.

Why the observed deterioration? It is known that the natural convective heat transfer coefficient depends not only on the properties of the fluid and geometry under consideration, but also on other factors such as method of heating, configuration and orientation of the heater, as well as the properties of the heating

and cooling surfaces. Given the experimental system and nanofluids used in this work, the Nusselt number takes the following form (Wen and Ding 2006):

$$Nu = c' \left[\frac{\rho_f C_{Pf} \beta \Delta T}{\nu_f K_f} \right]^n \quad (1)$$

where c' and n are constants, ρ_f is the fluid density and C_{Pf} is heat capacity of the fluid. The constant n lies between 1/4 and 1/3. Equation (1) indicates that the physical properties of nanofluids that affect their heat transfer behaviour include heat capacity, thermal conductivity, density and viscosity. The effects of density and heat capacity are expected to be small due to small concentrations of nanoparticles. The maximum enhancement of thermal conductivity and increment of the viscosity are ~5% and 20% under the conditions of this work, respectively. This brings to a maximum Nusselt number a decrease of ~8%, which is much smaller than the experimentally observed 30% decrease. Thus, there must be other factors that play roles. More work is needed in identifying these factors.

3.2 Forced convective heat transfer

There are a limited number of published studies on the forced convective heat transfer. Most of the reported studies show the enhancement of convective heat transfer by using nanofluids (Lee and Choi 1996; Xuan and Roetzel 2000; Li and Xuan 2002; Xuan and Li 2003; Jang and Choi 2006; Heris 2007). A few studies show inconsistencies, i.e. enhancement under certain conditions but little enhancement under other conditions (Pak and Cho 1998; Chein and Chuang 2007; Lee and Mudawar 2007). There are also studies that show little enhancement or even a decrease in the convective heat transfer coefficient when nanoparticles are added to the base liquids (Yang et al. 2005). Our work has aimed to understand and interpret the controversies through both experimental work and simple analyses using various nanofluids (Wen and Ding 2004b; Ding et al. 2006; He et al. 2007; Chen et al. 2007b; Ding et al. 2007).

Materials and techniques Five types of nanomaterials, alumina, titania, titanate nanotubes, carbon nanotubes and nano-diamond particles were used in our work. Titania and alumina nanofluids were formulated by using dry nanoparticles manufactured by Degussa (Germany) and Nanophase Technologies (USA), respectively. The carbon nanotubes were supplied by Prof F. Wei of Tsinghua University (China). The nano-diamond and titanate nanotubes were synthesised by our collaborators in Newcastle and Bath Uni-

versities, respectively. Details of these materials and preparation methods can be found in Wen and Ding (2004b), Ding et al. (2006), He et al. (2007), Chen et al. (2007b) and Ding et al. (2007). Distilled water was used as the base liquid for formulating most of the nanofluids, whereas a few titania nanofluids were made with ethylene glycol. Two experimental systems were used for the forced convective heat transfer studies, one for a horizontal arrangement and the other one for a vertically oriented pipe. **Fig. 7** shows the schematic diagrams of the two experimental systems and the details can be found elsewhere (Wen and Ding 2004b; Ding et al. 2006; He et al. 2007).

Experimental data Experiments on the forced convective heat transfer were carried out on all the nanofluids formulated under various flow conditions. Pure base liquids were tested first for use as a basis for comparison. The results are summarised as follows:

- In general, the convective heat transfer coefficient of nanofluids has the highest value at the entrance but decreases with axial distance and reaches a constant value in the fully developed region. The entrance length depends on the properties and behaviour of nanofluids. For a given nanofluid, the entrance length at low flow rates, e.g. laminar flow for Newtonian fluids, is longer than that at high flow rates, e.g. turbulent flow for Newtonian fluids.

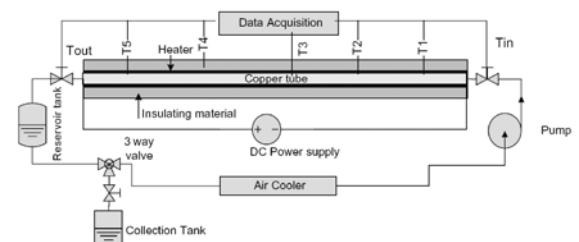


Fig. 7(a): Horizontal system

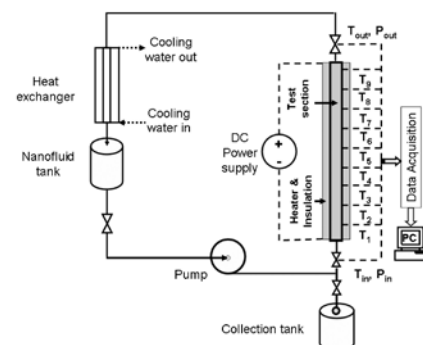


Fig. 7(b): Vertical system

Fig. 7 Experimental systems for forced convective heat transfer studies.

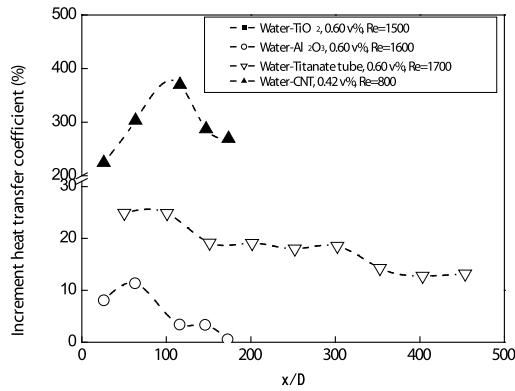


Fig. 8 Enhancement of forced convective heat transfer coefficient as a function of axial position from the inlet of the test section: carbon nanotube (CNT) and alumina nanofluids tested in the rig as shown in **Fig 7(a)**; titanate and titania nanofluids measured with the system shown in **Fig 7(b)**.

- At given particle concentrations and flow conditions, aqueous-based carbon nanotube nanofluids give the highest enhancement of convective heat transfer coefficient, followed by (in descending order) aqueous-based titanate nanofluids, aqueous-based titania nanofluids, aqueous-based alumina nanofluids, ethylene-glycol-based titania nanofluids and aqueous-based nano-diamond nanofluids. **Fig. 8** shows some experimental data in the form of enhancement as a function of the axial position (x) normalised by the tube diameter (D). As the ethylene-glycol-based titania nanofluids and aqueous-based nano-diamond nanofluids did not show enhancement, they are not included in **Fig. 8**.
- For aqueous-based alumina, titania, and titanate and carbon nanotube nanofluids, the convective heat transfer coefficient generally increases with increasing flow rate or increasing particle concentration, and the enhancement exceeds by a large margin the extent of the thermal conduction enhancement, indicating that thermal conduction enhancement is not the dominant mechanism for the

convective heat transfer enhancement. However, if one takes into account the enhancement of the thermal conductivity, deterioration of the convective heat transfer is found for ethylene-glycol-based titania and aqueous-based nano-diamond nanofluids. The exact reason for this has been a subject of our recent investigation. Some of the findings are discussed later in this section.

- For titania nanofluids, we found no clear trend in the effect of particle size on the convective heat transfer coefficient for particles between 95 and 210nm (He et al. (2007)).
- The data for the aqueous-based titania and titanate nanofluids seem to indicate that particle shape plays an important role in the convective heat transfer enhancement given other conditions, i.e. larger aspect ratios (length/diameter) give a higher enhancement. This is also supported by comparing the results of this work on carbon nanotube nanofluids with those by Yang et al. who found no enhancement of convective heat transfer using water-based disc-like graphite nanofluids (Yang et al. 2005).
- For nanofluids made of particles with large aspect ratios, e.g. carbon nanotubes, there seems to be a relationship between the rheological behaviour and the convective heat transfer behaviour. For example, for aqueous-based carbon nanotube nanofluids, a drastic increase in the convective heat transfer coefficient occurs at a flow rate corresponding to a shear rate where the shear viscosity is close to the minimum (Ding et al. 2006).

Why enhancement in some cases but deterioration in other cases? The experimental observations can be examined from both macroscopic and microscopic aspects. Considering a flow with uniform velocity and temperature distributions through a pipe, the flow has a different temperature from the wall temperature (**Fig. 9**). Due to friction between the fluid and the pipe wall, a hydrodynamic boundary layer will

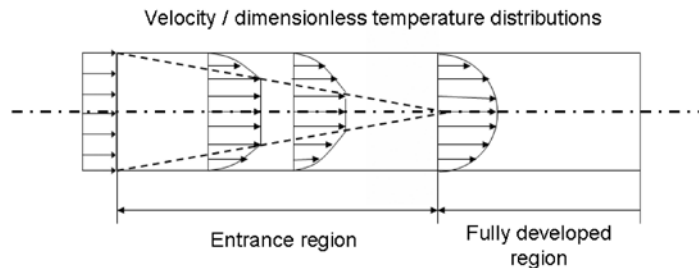


Fig. 9 Boundary layer development in a pipe flow in the laminar flow regime; for turbulent flow, the entrance region is much shorter and the boundary layer thickness is thinner.

form at the wall region in which the flow velocity increases from zero at the wall to maximum in a radial position depending on the axial position from the entrance. At a certain axial position from the entrance, the thickness of the boundary layer approaches constant, and the flow is regarded as fully developed. Similarly, due to the different temperatures of the fluid and the pipe wall, a thermal boundary layer is developed, though its thickness and the entrance length can be different. Macroscopically, the forced convective heat transfer coefficient, h , is given by $h = K_f / \delta_t$, with δ_t representing the local thickness of thermal boundary layer and K_f the local effective thermal conductivity of nanofluids adjacent to the wall surface. This simple expression indicates that either an increase in K_f and a decrease in δ_t , or both, can result in an increase of the convective heat transfer coefficient. This explains why the entrance region gives a higher convective heat transfer coefficient. As nanofluids have a higher thermal conductivity in comparison with the base liquid, the simple expression also partially explains the enhanced convective heat transfer coefficient. The expression, however, cannot provide an adequate explanation of the experimental observations that, in some cases, the convective heat transfer coefficient enhancement is much higher than the thermal conduction enhancement, while in other cases, there is no convective heat transfer enhancement despite considerable thermal conduction enhancement, e.g. aqueous-based nano-diamond and ethylene-glycol-based titania nanofluids (Ding et al. 2007). This may be explained from the microscopic point of view; see below.

Microscopically, nanofluids are inhomogeneous. There are at least two possible reasons for the inhomogeneity (Ding et al. 2006, Ding et al. 2007). One is the presence of agglomerates in nanofluids, which can be associated with either sintering during nanoparticle manufacturing or solution chemistry during nanofluids formulation. The former is often seen in processes involving elevated temperatures, e.g. aerosol reactors. The resulting agglomerates are very strong and are difficult to break down to primary nanoparticles even with prolonged high-shear processing and ultrasonication. The latter is due to the attraction between nanoparticles, e.g. van der Waals' attractive force and depletion phenomena. The agglomerates (aggregates) can be controlled by adjusting the solution chemistry and applying shear. The second reason is particle migration due to viscosity and velocity gradients. Experimental evidence of particle migration is the longer entrance length of

nanofluids as discussed above and in a recent experimental study by Merhi et al. (2005). There are also plenty of theoretical studies on particle migration; see, for example Phillips et al. (1992), Frank et al. (2003) and Ding and Wen (2005). If particles are very small, Brownian motion is strong and the effect of the above-mentioned particle migration is negligible. If particles are large, e.g. aggregates of hundreds of nanometres, the contribution of the Brownian motion is small, and a particle depletion region may exist at the wall region, which gives non-uniform distributions of particle concentration, viscosity and thermal conductivity. The direct results of particle migration are lower particle concentration at the wall region and a thinner boundary thickness due to disturbance by the moving particles. This, according to $h = K_f / \delta_t$, can lead to three possible scenarios: (i) h is enhanced if the decrease in δ_t exceeds the decrease in K_f ; (ii) h does not change if the decrease in δ_t is equal to the decrease in K_f ; and (iii) h is reduced if the decrease in δ_t is lower than the decrease in K_f . This qualitatively explains the experimental results. However, quantitative explanation requires understanding of how nanoparticles behave under shear and how they interact with each other and with fluid in the boundary layer.

4. Phase Change (boiling) Heat Transfer of Nanofluids

There are a limited number of studies on the phase change heat transfer (Das et al. 2003b & 2003c; Tsai et al. 2003; You et al. 2003; Tu et al. 2004; Vassallo et al. 2004; Bang and Chang 2005; Kim H et al. 2006; Kim S. et al. 2006). The results of these studies show that the presence of nanoparticles in liquid enhances Critical Heat Flux (CHF). The mechanism of the CHF enhancement is attributed to the deposition and sintering of nanoparticles on the boiling surfaces so that the surface area is increased. Experimental results also show that the properties of nanofluids affect the extent of the enhancement (Kim H et al. 2006; Kim S. et al. 2006). However, there is a disagreement in boiling heat transfer of nanofluids in the nucleate regime. Our work was therefore aimed at understanding and interpreting boiling heat transfer in the nucleate regime (Wen and Ding 2005a; Wen et al. 2006).

Materials and experimental techniques Aqueous-based alumina and titania nanofluids were used in the work. No dispersant / surfactant was used in the formulation. The experimental system consisted of a boiling vessel with 160mm inner diameter and 300mm

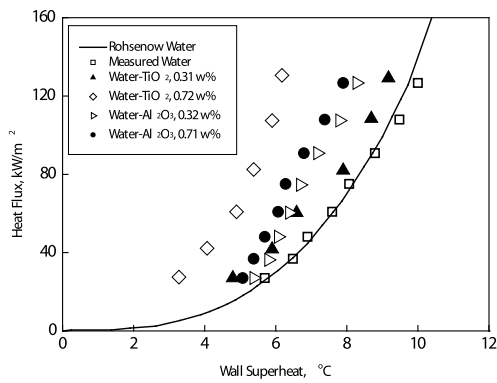


Fig. 10 Heat flux as a function of the wall superheat.

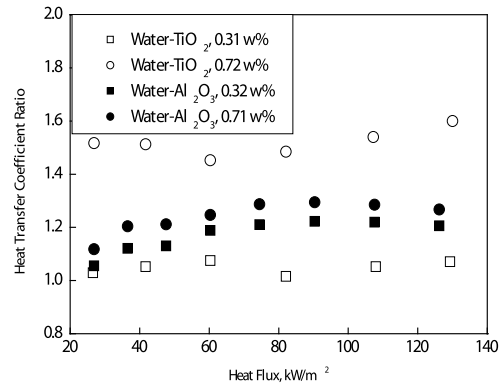


Fig. 11 Heat transfer coefficient ratio as a function of heat flux.

height, a heating and measuring unit and a data acquisition unit. The boiling surface was situated at the bottom of the vessel, which was the upper side of a polished stainless steel disc with 150mm diameter. A ring heater with a maximum power of 2.4 kW was attached to the back surface of the stainless steel disc, and heat flux was controlled through varying the voltage. By measuring the temperatures of the boiling surface and the bulk liquid, and the voltage and heater resistance, one can calculate the heat transfer coefficient.

Experimental results and discussion Fig. 10 shows the heat flux as a function of the wall superheat (temperature difference between the bulk fluid and the boiling surface), together with the prediction by the classical correlation of Rohsenow (1952) for pool boiling. One can see that the experimental data for water agree well with the Rohsenow correlation. The data of nanofluids deviate from the Rohsenow equation and the deviation increases with nanoparticle concentration.

The data shown in Fig. 10 are processed to give the heat transfer coefficient. Fig. 11 shows the results in the form of the ratio of heat transfer coefficient of nanofluids to that of pure water given other conditions. Enhancement of the boiling heat transfer is significant for both alumina and titania nanofluids in the nucleate regime, and the enhancement cannot be entirely attributed to the thermal conduction enhancement (data shown in Figs. 1-3). Fig. 11 also shows that the heat transfer enhancement increases with nanoparticle concentration and the enhancement for titania nanofluids is more sensitive to the change of particle concentration in comparison with that for alumina nanofluids. The different heat transfer behaviour of alumina and titania nanofluids indicates that the nanofluid properties have an influence

on the boiling heat transfer in the nucleate regime.

The experimental results of this work as presented above agree with that of You et al. (2003) and Tu et al. (2004). Our results, however, disagree with those of Das et al. (2003b & 2003c), Bang and Chang (2005) and Kim S et al. (2006), who observed deterioration of boiling heat transfer in the nucleate regime. The exact reason for the discrepancy is unclear. Possible reasons are discussed in the following text:

- Thermal conductivity and viscosity affect the heat transfer behaviour of nanofluids in opposite ways. As a result, a combination of thermal conductivity enhancement and increment of the viscosity can give either enhancement or deterioration of the heat transfer coefficient. However, there is too little information in the published studies to permit making a conclusive assessment.
- Stability of nanofluids and the presence of a dispersant / surfactant affect the behaviour of nanofluids, which are often not provided in the published studies. For example, settling of nanoparticles in nanofluids with poor stability can change the properties of the boiling surface, and surfactants / dispersants may fail at elevated temperatures.
- Boiling heat transfer consists of a number of sub-processes in parallel and/or series, including unsteady-state heat conduction, growth and departure of bubbles, and convection due to bubble motion and liquid re-filling. These sub-processes are affected by parameters such as heater geometry, properties of the boiling surface, orientation of the heater, liquid sub-cooling, system pressure, and the mode in which the system is operated. Among these, the boiling surface properties are among the key factors that influence

the boiling heat transfer. The surface properties include surface finish (roughness), surface wettability, and surface contamination, as they all influence the number and distribution of active nucleation sites for bubbles and their subsequent growth. In the published studies, however, surface roughness is the most often-used parameter, and interpretation of the effect of surface roughness on the boiling heat transfer has been based on the size of the suspended particles relative to the surface roughness. For example, Bang and Chang (2005) used a boiling surface of nanometre-scale roughness, hence sedimentation of the particles was regarded to effectively increase the roughness of the surface, whereas a commercial cartridge heater with a micron-scale surface roughness was employed by Das et al. (2003b, 2003c) onto which sedimentation of the nanoparticles was thought to decrease the effective surface roughness.

- Different temperature measurement methods may lead to the different experimental results obtained by different investigators. For example, all thermocouples were welded on the outer surface of the cartridge heater by Das et al. (2003b & 2003c). This would inevitably influence the surface characteristics of the boiling surface, as bubbles have a tendency to nucleate on the welded positions and the measured temperature may not be representative of the boiling surface. Vassalao et al. (2004) used fine resistance wires for temperature measurements. Large uncertainties are expected for this sort of method as temperature is converted from the measured resistance of the heating wire against the standard temperature-resistance curve. Indeed, for boiling with pure water, more than 10°C deviance of superheat was observed under a fixed heat flux condition in different runs; see **Fig. 1** of Vassalao et al. (2004). It may be sensible for a qualitative comparison of the critical heat flux (CHF), but it may not be adequate for a quantitative comparison of nucleate boiling heat transfer.

Obviously, the above discussion is crude and on a qualitative basis. Nevertheless, these points provide possible ways towards interpreting the controversies in the literature.

5. Concluding Remarks

This paper summarises some of our work on nanofluids over the past few years. It covers conduction,

convection under both natural and forced convective heat transfer conditions, and boiling heat transfer in the nucleate regime. A brief review of the state-of-the-art developments in these aspects is also given. The following conclusions are obtained:

- Despite considerable scattering, the presence of nanoparticles enhances thermal conduction under macroscopically static conditions, and direct application of the conventional thermal conductivity models for suspensions and composite materials does not provide an adequate prediction of the experimental observations. The enhancement is a function of particle concentration, particle material type and particle shape. The effect of temperature is weak, whereas the effects of the base liquid properties and particle size are unclear. Over the many possible mechanisms proposed for the thermal conductivity enhancement, nanoparticle structuring / networking seems to be the last mechanism standing.
- The natural convective heat transfer coefficient systematically decreases with increasing nanoparticle concentration. Although the exact reason is still unclear, the deterioration can be partially attributed to the high viscosity of nanofluids.
- Either enhancement or deterioration can occur in the forced convective heat transfer of nanofluids. The exact reason is unclear but particle migration is shown to be an important mechanism.
- Enhancement of the boiling heat transfer is observed in the nucleate regime for both alumina and titania nanofluids, and the enhancement is more sensitive to the concentration change for TiO₂ nanofluids.

Nanofluids research has been carried out for over 10 years. Significant progress has been made over the years, particularly in the past few years. However, there is still some way to go before we can tailor-make nanofluids.

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List of symbols

c'	constant in Eq.(1)
C_{Pf}	heat capacity
d_g	separation between the two discs
D	pipe diameter
f	interaction coefficient
g	gravitational acceleration
Gr	Grashof number
h	heat transfer coefficient
K_{eff}	effective thermal conductivity
K_f	fluid thermal conductivity
K_L	liquid thermal conductivity
K_s	solid thermal conductivity
n	shape factor
n'	constant in Eq.(1)
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
ΔT	temperature difference
x	axial distance

Greek

α	thermal diffusivity
β	thermal expansion coefficient
ρ_f	fluid density
ϕ_s	solid volume fraction
δ_i	thermal boundary layer thickness
ψ	shape factor of particles

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Author's short biography



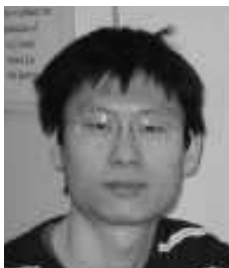
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Professor Haisheng CHEN

Professor Haisheng CHEN *BEng PhD* is a visiting research fellow in Institute of Particle Science and Engineering, University of Leeds and an associate professor in Institute of Engineering Thermophysics, Chinese Academy of Sciences. His research experience covers micro/nano scale flow and heat transfer, energy storage using phase change materials, aerodynamics and trajectories of aerocrafts, internal flow of turbomachinery and complex ventilation systems. His research has led to over 50 technical papers and 10 patents.



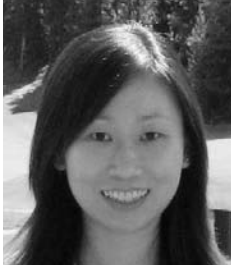
Mr Wei Yang

Mr Wei Yang *BEng MRes* is currently a PhD student in the Institute of Particle Science & Engineering at the University of Leeds. He received his BEng in Chemical Engineering from Beijing University of Chemical Technology (July 2000) and MRes in Chemistry from University of York (September 2004). His research focuses on developing a novel method for fine particle classification and characterization.



Professor Yurong He

Professor Yurong He (1976-) *BEng MSc PhD* is currently an associate professor of Chemical Engineering Processing and Mechanics in the School of Energy Science and Engineering at Harbin Institute of Technology, P.R. China. She spent a year in Twente University (Netherlands) and two years at Leeds University (UK) before taking her current post. Professor He's current research focuses on gas-liquid-solid three-phase flow and heat transfer. She has published over 50 technical papers on these topics.



Dr Wai Peng LEE

Dr Wai Peng LEE *BEng PhD* is currently a postdoctoral research fellow with the Institute of Particle Science and Engineering at the University of Leeds in the group of Professor Yulong Ding having obtained her PhD from the University of Sheffield. Her research interest includes film formation from polymer colloids, nanoparticle interactions and behaviour in confined geometry.



Miss Ran Huo

Miss Ran Huo *BEng MSc* is a PhD student in the Institute of Particle Science and Engineering at the University of Leeds. Her MSc was on heat transfer in nanofluids composed of different nanoparticles and base liquids. She is currently working on nanoemulsion production and crystallization, during which she developed a novel method for producing organic nanoparticles with potential applications in the food, pharmaceutical, cosmetics, and home and personal care products.