

## Review

# A review of nanofluid heat transfer and critical heat flux enhancement—Research gap to engineering application

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## ABSTRACT

As a novel strategy to improve heat transfer characteristics of fluids by the addition of solid particles with diameters below 100 nm, nanofluids exhibit unprecedented heat transfer properties and are being considered as potential working fluids to be used in high heat flux systems such as electronic cooling systems, solar collectors, heat pipes, and nuclear reactors. The present paper reviews the state-of-the-art nanofluid studies on such topics as thermo-physical properties, convective heat transfer performance, boiling heat transfer performance, and critical heat flux (CHF) enhancement. It is indicated that the current experimental data of nanofluids thermal properties are neither sufficient nor reliable for engineering applications. Some inconsistent or contradictory results related to thermo-physical properties, convective heat transfer performance, boiling heat transfer performance, and CHF enhancement of nanofluids are found in data published in the literature. No comprehensive theory explains the energy transfer processes in nanofluids. To bridge the research gaps for nanofluids' engineering application, the urgent work are suggested as follows. (1) Nanofluid stability under both quiescent and flow conditions should be evaluated carefully; (2) A nanofluid database of thermo-physical properties, including detailed characterization of nanoparticle sizes, distribution, and additives or stabilizers (if used), should be established, in a worldwide cooperation of researchers; (3) More experimental and numerical studies on the interaction of suspended nanoparticles and boundary layers should be performed to uncover the mechanism behind convective heat transfer enhancement by nanofluids; (4) Bubble dynamics of boiling nanofluids should be investigated experimentally and numerically, together with surface tension effects, by considering the influences of nanoparticles and additives if used, to identify the exact contributions of solid surface modifications and suspended nanoparticles to CHF enhancement in boiling heat transfer. Once we acquire such details about the above key issues, we will gain more confidence in conducting application studies of nanofluids in different areas with more efficiency.

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## 1. Introduction

Energy concerns have ascended to the singular and most important problem for the world's scientists and engineers to cope with in the coming 50 years (Smalley, 2005). Whether using traditional or new energy resources, enhancing heat transfer and reducing energy losses are always the most efficient means to deal with problems of energy wastage and harvesting and environmental pollution.

Extended-surface thermal control technologies such as fins and microchannels are being stretched to their limits. Therefore, new technologies with the potential to improve the thermal properties of cooling fluids are of great interest to researchers. Nanofluids as a novel strategy to improve heat transfer characteristics of fluids by the addition of solid particles with diameters below 100 nm was proposed by Choi (1995) early in the 1990s. Very small amount of guest nanoparticles were found to provide dramatic improvements in thermal properties of base fluids in exhibiting superior thermal properties arising from strong temperature- and size-dependent thermal conductivities. A nonlinear relationship exists between nanofluid's thermal conductivity and its concentration and temperature. In addition, there has been a three-fold increase in the critical heat flux at small particle concentrations of order 10 ppm (Choi, 2009). Based on the current fruits from pioneering research,

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nanofluids are thus being considered as innovative and potential working fluids for heat transfer enhancement.

### 1.1. Potential applications of nanofluids in energy areas

By deliberately selecting base fluids with suitable nanoparticle materials, dispersion agents, nanoparticle sizes, and concentrations, nanofluids exhibiting these unprecedented thermal transport properties are in theory applicable to any thermal management systems requiring heat to be extracted more efficiently. However, it seems more urgent and efficient for suitable nanofluids to be used in high heat flux systems such as electronic cooling systems, solar collectors, heat pipes, and nuclear reactors to reduce the peak temperatures on the cooled wall, generate uniform temperature distributions, and assure better compactness of heat transfer systems without or with less pumping power increases penalty. To date, the diversity of investigations into the potential applications of nanofluids in different areas is evident in recent literature, as represented by Escher et al. (2011), Buongiorno and Hu (2009), Taylor et al. (2010), Liu and Zhu (2011), Wen et al. (2009).

### 1.2. Objectives of the work

On reviewing and analyzing fundamental nanofluid studies on topics such as thermo-physical properties, convective heat transfer performance, boiling heat transfer performance and CHF enhancement, the research gap and future directions will be suggested in the present paper. The long-term physical and chemical stability of nanofluids in both quiescent and flow conditions, the mechanism of convective heat transfer, and the critical heat flux (CHF) enhancement by nanofluids should be investigated carefully and thoroughly, to promote nanofluid engineering applications. Establishing a nanofluid database of thermo-physical properties is also essential for reliable applications in engineering thermal systems.

## 2. Current status of nanofluids fundamental research—review and analysis

### 2.1. Thermo-physical properties of nanofluids

Regarding the flow and heat transfer performance of thermal systems, the key thermo-physical properties of fluids include density, specific heat capacity, thermal conductivity, viscosity and surface tension. Thus, changes in the thermo-physical properties of nanofluids compared with base fluids need to be estimated first before nanofluids can be used in energy-efficient heat transfer systems. The density and specific heat capacity of nanofluids can be estimated according to the mixture model, which is applicable to conventional fluid–solid mixtures. However, the changes in thermal conductivity, viscosity, and surface tension of nanofluids are complicated but most interestingly unprecedented. These aspects are reviewed in the following.

#### 2.1.1. Thermal conductivity

Thermal conductivity is a property which has received the most attention in the nanofluid research community over the past few decades. It was found that, because of their higher thermal conductivity, stably dispersing metal or metal oxide nanoparticles in traditional heat transfer fluids (base fluids) lead to an increase in the thermal conductivity of these dilute suspensions. Suspensions containing small amounts of nanoparticles of metals (Cu and Ag, etc.), oxides ( $\text{Al}_2\text{O}_3$ , CuO,  $\text{TiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{ZrO}_2$  and  $\text{SiO}_2$ , etc.) and some other compounds (SiC, etc.) have been reported to have resultant increases in thermal conductivity. The host or base fluids usually include water, ethylene glycol, propylene glycol, engine oil, etc.

Eastman et al. (2001) used the transient hot-wire (THW) method to measure nanofluid thermal conductivity. The thermal conductivity of ethylene glycol containing approximately 0.3 vol. % Cu nanoparticles with mean diameter less than 10 nm was observed to increase by up to 40% comparing with the pure ethylene glycol. Xie et al. (2002) experimentally investigated the thermal conductivity behaviors of nano-sized  $\text{Al}_2\text{O}_3$  suspensions. Deionized water, ethylene glycol, and pump oil were used as base fluids. Nanoparticle suspensions containing a small amount of  $\text{Al}_2\text{O}_3$  were found to have substantially higher thermal conductivity than the base fluid. The enhancement increased with the volume fraction of  $\text{Al}_2\text{O}_3$ . For suspensions containing the same nanoparticles, the enhanced thermal conductivity ratio was reduced with increasing thermal conductivity of the base fluid. For the suspensions using the same base fluid, enhancements in the thermal conductivities were dependent on the specific surface area of the nanoparticle. The enhanced thermal conductivity was found to increase with an increase in the difference between the pH value of the aqueous suspension and the isoelectric point of  $\text{Al}_2\text{O}_3$  particles. This is quite interesting and deserves to be further investigated.

Moreover, the experimental results were found to be much higher than those predicted by theoretical models which are more suited to suspensions containing  $\mu\text{m}$  or mm size particles. This indicated that new heat transport mechanisms exist in nanofluids. Das et al. (2003a) presented experimental data on the temperature-dependent thermal conductivity of water-based  $\text{Al}_2\text{O}_3$  and CuO nanofluids within the temperature range of 21–51 °C. Specifically, for 1.0% particle volume concentration of CuO/water nanofluids, the thermal conductivity ratio was shown to have increased from 6.5% to 29%. Murshed et al. (2005) experimentally investigated the thermal conductivity of  $\text{TiO}_2$ /water nanofluids. There, the thermal conductivity of nanofluids increased remarkably with increasing volume fraction of nanoparticles. Particle size and shape also influenced the thermal conductivity enhancement of nanofluids. Chon et al. (2005) presented an experimental correlation for the thermal conductivity of  $\text{Al}_2\text{O}_3$ /water nanofluids as a function of nanoparticle size ranging from 11 nm to 150 nm nominal diameters over a wider range of temperature, from 21 to 71 °C; the thermal conductivity of nanofluids showed strong temperature- and size-dependence. Together with their previous theoretical work (Jang and Choi, 2004), it was concluded that Brownian motion of the nanoparticles constituted a key mechanism in the thermal conductivity enhancement with increasing temperature and decreasing nanoparticle sizes. Mintsa et al. (2009) presented new effective thermal conductivity data of  $\text{Al}_2\text{O}_3$ /water and CuO/water nanofluids with temperature range of 21–48 °C and particle volume fractions up to 18%. Particle sizes used in these suspensions were both 47 and 36 nm for the  $\text{Al}_2\text{O}_3$  nanofluid and 29 nm for the CuO nanofluid. Their results also showed that the effective thermal conductivity increased with increasing particle volume fraction and decreasing particle size. The relative increase in thermal conductivity was suggested to be of more importance at higher temperatures. Vajjha and Das (2009) experimentally determined the thermal conductivity of three nanofluids containing separately  $\text{Al}_2\text{O}_3$ , CuO, and ZnO as nanoparticles. A ethylene glycol–water mixture (60:40 by mass) was used as base fluid. Particle volume concentration tested was up to 10% and the experimental temperature range was from 25 to 90 °C. The same trends of volume concentration and temperature dependent thermal conductivity of nanofluids were found as for the nanofluids with single base fluid. Duangthongsuk and Wongwises (2009) experimentally examined the temperature-dependent thermal conductivity and viscosity of  $\text{TiO}_2$ /water nanofluids with volume concentrations between 0.2 and 2.0%. The data were collected for temperatures ranging from 15 °C to 35 °C. The results showed that the relative thermal

conductivity of nanofluids increased with increasing particle volume concentration and slightly decreased with increasing temperature. Various parameters such as particle size, particle preparation method (solution chemistry), measurement technique and even different particle sources, were presented as possible causes for the different measured data from different research groups.

So far, there are many other publications reporting on the enhanced thermal conductivity of different nanofluids under different conditions. The trends in the relationship between the thermal conductivity of nanofluid and its influence factors (temperature, size and volume concentration of nanoparticles) have been confirmed. Undoubtedly, these results provide interesting insights into nanofluids' heat transfer benefits. However, compared with base fluids, the current data are not only sparse in the expected application ranges, but also inconsistent in the thermal conductivity enhancement ratios. In brief, the current data are neither sufficient nor reliable for engineering applications of nanofluids in thermal management systems. For example, most experimental data are obtained at or slightly above atmospheric temperature; the data at higher temperatures (above 50 °C) are lacking. Indeed, temperatures could reach high levels in real thermal systems.

Inconsistencies or discrepancies in experimental results from different research groups could be due to the following factors. (1) Nanofluids reported in the literature may have been prepared by different dispersion methods each of which may influence the distribution and real size of nanoparticles in the base fluid. Meanwhile, this distribution and size may also be determined by factors such as whether surfactants or additives were used that were expected to improve the stability of the nanofluids. If used, the kind and concentration of surfactant or additive also influence the distribution and real size of the nanoparticles in the base fluid. (2) The size and/or distribution of nanoparticles in the tested nanofluid samples were often incompletely characterized or unclearly stated in the literature. Most of the time, we cannot obtain details on nanoparticle size (before and after dispersion) and its distribution in the base fluid. (3) Data from the literature refer to parameter ranges specific to the experiment; these include ranges for temperature and concentration with just single or few nanoparticle sizes. Thus, it is hard to directly compare experimental results from different groups, and of course hard to integrate these data to be a useful database for engineering applications.

Currently, agreement on a unified understanding of the mechanism underlying thermal conductivity enhancement has not yet been reached. To try to explain this spectacular enhancement, various theories have been proposed such as Brownian motion, the aggregation of suspended particles (Jang and Choi, 2004; Shukla and Dhir, 2008), the formation of an interfacial nano-layer around particles (Yu and Choi, 2003; Xie et al., 2005), the percolation-like behavior (Foygel et al., 2005), and the micro-convection and lattice vibration of nanoparticles (Gupta et al., 2006). Experimental confirmation of these mechanisms has been weak. Some models and/or empirical correlations have been proposed to predict the thermal conductivity (Xuan et al., 2003; Feng et al., 2007; Avsec, 2008; Murshed et al., 2009; Corcione, 2011). Most though are developed from data sets containing only a few experimental thermal conductivity values, limiting these models in predicting nanofluid thermal conductivities accurately over larger ranges.

Thus, efforts from the International Nanofluid Property Benchmark Exercise (INPBE) (Buongiorno et al., 2009) are very valuable because these provide more definitive answers on the characteristics of nanofluids through comparing the thermal conductivity data obtained by different experimental approaches for similar samples of various nanofluids, even if the data are preliminary and limited. In

the exercise, four different organizations provided test samples of nanofluids stating the particle materials, particle size and concentration, basefluid material, the additives/stabilizers used in the synthesis of the nanofluids and the material safety data sheets. This information was independently verified, to the extent possible, by the INPBE coordinators (MIT and Illinois Institute of Technology, IIT). Samples were also distributed to over 30 organizations worldwide to minimize spurious effects due to nanofluid preparation and handling. Measurements of thermal conductivities of samples were performed almost in a "semiblind" state as only minimal information about each sample was given to participants at the time of sample shipment. The minimum requirement to participate in the exercise was to measure and report the thermal conductivity of at least one test nanofluid at room temperature. The participants could also measure thermal conductivities at higher temperatures and/or various other nanofluid properties. The data were then reported in a standardized form to the exercise coordinator at MIT and posted, unedited, on the INPBE website. Participants at a workshop held on January 29–30th, 2009 in Beverly Hills, California presented and discussed the results. These showed that, everything else being the same, the thermal conductivity enhancement was higher at higher particle concentrations, and higher for elongated particles than for near-spherical particles. For samples with alumina nanorods, results showed that the enhancement was somewhat higher for the poly-alphaolefins lubricant (PAO) basefluids than for water, suggesting that the basefluid with lower thermal conductivity may gain more thermal conductivity enhancement by dispersing nanoparticles properly. For samples with gold nanoparticles, the results showed that the enhancement was slight as particle concentrations was very low (0.0009 vol. %), even if metal particles of high thermal conductivity were used. For samples with silica nanoparticles, the results showed that the enhancement was robust as particle concentrations were very high (26.0 vol. %), even if the particle material has a modest thermal conductivity. In Buongiorno et al. (2009), the effects of experimental approach on the thermal conductivity measurements were discussed. Choice of measurement technique does seem to affect the measured value. To ensure accurate determination of enhancement, it is important to measure both basefluid and nanofluid thermal conductivities using the same technique at the same temperature. A pitfall within this literature is that the stability of test nanofluid samples was not evaluated or described by the participants, as possibly the thermal properties of the samples were measured at different dates after being shipped to all participating organizations.

In general, it can be concluded that more collaborative experimental work, as exemplified by the INPBE (Buongiorno et al., 2009), needs to be conducted to establish and enlarge the nanofluid database of properties. The database will not only be valuable in validating proposed mechanisms and models, but also be necessary for theoretical analyses and numerical simulations of nanofluid heat transfer to achieve those goals set in engineering applications of nanofluids.

### 2.1.2. Viscosity

As mentioned already, the thermal conductivity of nanofluids has received more attention over the past few years. However, nanofluid viscosity also deserves the same attention for all thermal applications involving nanofluids. Namburu et al. (2007) experimentally investigated the rheological properties of nanofluid containing CuO nanoparticles with average diameter of 29 nm and 60:40 (by weight) ethylene glycol/water mixture. Copper oxide nanofluids exhibited Newtonian behavior in an ethylene glycol and water mixture for concentrations varying from 0% to 6.12%, and temperatures ranging from 35 °C to 50 °C. The viscosity increased with increasing volume concentration of nanoparticles, and

decreased exponentially with temperature. Nguyen et al. (2008) measured the viscosity of  $\text{Al}_2\text{O}_3$ /water nanofluids with different volume concentrations and temperatures, with particle-size of 36 nm or 47 nm, and various dispersing agents. The nanofluid viscosity was observed to considerably increase with increasing particle volume concentration, but clearly decrease with increasing temperature. The viscosity values obtained for the 36-nm and 47-nm particle sizes were relatively close, except when particle fractions were high. They also found the data from Wang et al. (1999) for a 28-nm particle size fell between their own data. Differences in nanofluid preparation and measurement technique could have been responsible for the inconsistency. Also, the Einstein formula and some others originating from classical linear fluid theory can greatly underestimate nanofluid viscosity, especially for those nanofluids with higher particle fraction (higher than 1.0 vol. %). There appears to exist a critical temperature beyond which viscosity starts to increase with increasing temperature. A more interesting hysteresis for viscosity has been observed. When the nanofluid was heated beyond this critical temperature, and then left to cool afterward, the measured values of the nanofluid viscosity at a given temperature during the cooling phase were remarkably higher than those collected during the heating phase. This suggested that irreversible changes seem to have developed within the particle suspension due to temperature exceeding this critical temperature. It is worthwhile performing more experimental work to confirm and/or understand such nanofluid behavior and characteristics, because these may be key factors having a direct impact on a reliable application of nanofluids in thermal management systems.

Phuoc and Massoudi (2009) presented some experimental observations on the effects of shear rates and particle volume fractions on the shear stress and the viscosity for  $\text{Fe}_2\text{O}_3$ /DW nanofluids with Polyvinylpyrrolidone (PVP) or Polyethylene oxide (PEO) as dispersant. The results showed that there existed a yield stress for these fluids. A non-Newtonian law exhibiting shear-thinning at volume fractions beyond 0.02 was observed, suggesting that shear viscosity depended on the shear rate and concentration. Lee et al. (2008)'s viscosity data for  $\text{Al}_2\text{O}_3$ /water nanofluids found a nonlinear relationship with concentration even at the low volume concentrations (0.01%–0.3%). Lee et al. (2011) experimentally investigated the thermo-physical properties of distilled water (DIW)-based SiC nanofluids for high-temperature heat transfer applications. The viscosity for SiC/DIW nanofluids increased with increasing particle volume fraction, and decreased with increasing temperature. Aladag et al. (2012) experimentally investigated the viscosity of carbon nanotubes (CNTs) and  $\text{Al}_2\text{O}_3$  water-based nanofluids at low temperatures. Results indicated that the nanofluid suspensions exhibited either Newtonian or non-Newtonian behavior, depending on shear rate.

At present, viscosity data from the literature are consistent in that nanofluid viscosity increases with increasing volume concentration. However, the underlying mechanism is not clear. A few studies have been reported on the relationship between the nanofluids viscosity and nanoparticle size. Classical models and/or formulae succeed in estimating nanofluid viscosities at low volume fractions, but fail at various temperature levels (Khanafer and Vafai, 2011). Data for nanofluid viscosity are still scarce and controversial, the reasons being the same as for thermal conductivity. Experimental data from different research groups lack a base for comparison. Models and/or correlations are developed from data sets containing only a few experimental viscosity values that are incapable of predicting viscosities accurately over an extended range. Therefore, additional experimental and theoretical studies are required to establish a database for nanofluid viscosity and to develop more reliable and accurate models and/or correlations, to

perform analyses or simulations of nanofluid heat-transfer and pressure variations more efficiently and accurately.

### 2.1.3. Surface tension

Although there is much controversy surrounding thermal conductivity enhancements and convective heat transfers for single-phase nanofluid flows, the significant CHF enhancement in boiling heat transfer of nanofluids, reviewed in Section 2.3, is undisputed. Surface tension is a very important parameter in boiling as well as other two-phase heat transfer phenomena. However, it has received less attention in past years compared with that given to thermal conductivity or even viscosity. Radiom et al. (2010) investigated the effects of nanoparticles on surface tension and equilibrium contact angle of DIW-based  $\text{TiO}_2$  nanofluids. The surface tension of the  $\text{TiO}_2$ /water nanofluids was found to depend weakly on nanoparticle concentration and strongly on surfactant concentrations. However, at higher nanoparticle concentrations, the surface tension was lower suggesting that the nanoparticles can function as a surfactant because nanoparticles could be absorbed onto the liquid–gas interface to reduce surface tension. Experimental measurements of contact angles of the  $\text{TiO}_2$ /water nanofluids sessile droplets on borosilicate glass slides exhibited strong nanoparticle dependence, and in general contact angle increased with nanoparticle concentration. Chen et al. (2011) measured the surface tension of three kinds of evaporating pendant nanofluid droplets containing separately laponite, silver, and  $\text{Fe}_2\text{O}_3$  particles in deionized water. For laponite and silver/water nanofluids without surfactant, the apparent surface tension of the droplet decreased with time because of the increase in particle concentration as the droplet evaporated. However, for a  $\text{Fe}_2\text{O}_3$ /water nanofluid with surfactant of 1%PVP for stability, surface tension remained constant during the lifetime of the evaporating droplets, and no conclusion was reached as to whether the surfactant canceled the effect of  $\text{Fe}_2\text{O}_3$  nanoparticles. Murshed and Nguyen (2008)'s experimental results showed that a nanofluid with  $\text{TiO}_2$  nanoparticles (15 nm) in deionized water exhibited substantially lower surface tension and oil-based interfacial tension than that of the base fluid. The surface and interfacial tensions of the nanofluid were found to decrease almost linearly with increasing temperature. The Brownian motion of nanoparticles in the base fluid was identified as a mechanism in reducing surface and interfacial tensions of nanofluid. Kumar and Milanova (2009)'s experimental results indicated that the relaxation of surface tension (defined as the surface tension difference between nanofluid and its base fluid) was the driving force in the postponement of burnout heat flux of CNT nanofluids in pool boiling. Further work needs to be conducted to realize optimum CNT and surfactant concentrations for maximum flux increase. Zhu et al. (2010)'s experimental results showed that the surface tension of  $\text{Al}_2\text{O}_3$ /water nanofluids were highly dependent on temperature. A maximum enhancement for the surface tension of only about 5% was obtained at a concentration of 1 g/L, as the nanoparticle concentration studied in this work was very low. Vafaei et al. (2009) investigated the effect of nanoparticle size and concentration on the effective gas–liquid surface tension of aqueous solutions with bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ) nanoparticles. The surface tension decreased as nanoparticle concentration increased up until a critical value of the concentration, beyond which the trend in surface tension reversed. In addition, at the same mass concentration, the nanofluid containing 2.5-nm nanoparticles had a smaller value of the surface tension than that containing 10.4-nm nanoparticle. The results showed that the liquid–gas surface tension could be controlled by the size and concentration of the dispersed nanoparticles.

Although the data of surface tension of nanofluids are scarce, the following information gained from the current research work is

very important. (1) Nanofluids surface tension is highly dependent on temperature. (2) The effect of nanoparticle concentration on the surface tension of nanofluids is not monotonic. (3) The effect of nanoparticle size on the surface tension of nanofluids needs to be investigated. (4) The combined effect of the nanoparticle and surfactant used on the surface tension of the nanofluid is a key factor in the boiling heat transfer and CHF of nanofluids. Thus, more innovative work on nanofluid surface tension needs to be conducted. Most important of all, surface tension measurements should be accompanied by studies of bubble dynamic behavior of nanofluid boiling heat transfer and the mechanism of CHF enhancement.

It should be noted that the special thermal properties of nanofluids are not merely of academic interest. The promising engineering applications of nanofluids in thermal management systems have spurred more and more research in regard to forced-convective and boiling heat transfers including CHF. So far, there are some exciting but even contradictory results on transfer performance in the current literature. In the following sections, the state-of-the-art studies on such topics will be reviewed and further work will be suggested.

## 2.2. Forced convective heat transfer of nanofluids

Nanofluids exhibiting enhanced thermal conductivity and negative viscosity gradients are naturally attractive and innovative to most thermal management systems. Forced convective heat transfer plays a significant role in almost all industrial sectors. Low concentration nanofluids are expected to be ideally suited to enhance the forced convective heat transfer in practical heat transfer systems, while bringing little or no penalty in pressure drop because the nanoparticles are ultrafine. Thus, the increasing studies on the performance of nanofluids forced heat transfer have been conducted in the past decade.

Xuan and Li (2003) experimentally investigated the characteristics of the fully developed convective heat transfer and flow for Cu/water nanofluids through a straight tube with inner diameter of 10 mm. A constant heat flux condition along the tube wall was imposed using DC heating. Results showed that the nanofluids gave substantial enhancement of heat transfer rate compared to pure water. They also claimed that friction for low-volume-fraction nanofluids did not produce extra penalty in pumping power.

Wen and Ding (2004) reported their experimental results on convective heat transfer of nanofluids, consisting of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> nanoparticles and de-ionized water flowing through a copper tube in the laminar flow regime. An enhancement was found to be particularly significant in the entrance region suggesting that it could not be solely attributed to an enhancement in the effective thermal conductivity. Particle migration was proposed as one of the reasons for the enhancement; this should result in a non-uniform distribution of thermal conductivity and viscosity field and reduce the thickness of thermal boundary layer. A similar conclusion was drawn in Kim et al. (2009a)'s experiment, in which the convective heat transfer coefficient for the amorphous carbonic/water nanofluid, under laminar flow, increased by 8% even if its thermal conductivity was similar to that of water.

Yang et al. (2005) measured the convective heat transfer coefficients of several nanofluids with non-spherical graphitic nanoparticles under laminar flow in a horizontal tube. The experimental results showed that the nanoparticles increased the heat transfer coefficient of the fluid system in laminar flow, but the increase was much less than that predicted by current correlation based on static thermal conductivity measurements. It was suggested that the type of nanoparticles, particle loading, base fluid chemistry, and process temperature were all important factors for high heat transfer coefficients.

Daungthongsuk and Wongwises (2007) reviewed the experimental and numerical investigation results on the convective heat transfer of nanofluids before 2005, and roughly listed the reasons for the forced convective heat transfer enhancement of the nanofluids: the suspended nanoparticles increase the thermal conductivity of the nanofluid, and the chaotic movement of ultrafine particles increases fluctuations and turbulence within host fluid that accelerate energy exchange processes.

Ding et al. (2007) experimentally investigated forced convective heat transfer performance of aqueous and ethylene glycol-based spherical TiO<sub>2</sub> nanofluids, and aqueous-based titanate nanotubes, carbon nanotubes and nano-diamond nanofluids. For aqueous-based TiO<sub>2</sub> and carbon nanotube nanofluids, the convective heat transfer coefficient enhancement exceeded, by a large margin, the extent of the thermal conduction enhancement. However, deterioration of the convective heat transfer was also observed for ethylene glycol-based spherical TiO<sub>2</sub> nanofluids at low Reynolds numbers and aqueous-based nano-diamond nanofluids. The competing effects of particle migration on the thermal boundary layer thickness and the effective thermal conductivity were suggested to be responsible for the observed controversial results.

Williams et al. (2008) experimentally investigated the turbulent convective heat transfer behavior of water-based Al<sub>2</sub>O<sub>3</sub> and ZrO<sub>2</sub> nanofluids in a flow loop with a horizontal tube test section at various flow rates ( $9000 < Re < 63,000$ ), temperatures (21–76 °C), heat fluxes (up to  $\sim 190 \text{ kW/m}^2$ ), and particle concentrations (0.9–3.6 vol. % for Al<sub>2</sub>O<sub>3</sub> and 0.2–0.9 vol. % for ZrO<sub>2</sub>) conditions. If the measured temperature- and loading-dependent thermal conductivities and viscosities of the nanofluids were used in calculating the Reynolds, Prandtl, and Nusselt numbers, the existing correlations (Dittus–Boelter, and Blasius/MacAdams) were shown to describe accurately convective heat-transfer and viscous pressure-loss behaviors in tubes. A similar conclusion was presented for their laminar flow investigations (Rea et al., 2009). Hwang et al. (2009) measured the pressure drop and convective heat transfer coefficient of Al<sub>2</sub>O<sub>3</sub>/water nanofluids flowing through a uniformly heated circular tube in the fully developed laminar flow regime. The experimental results showed that analytical predictions from the Darcy's equation for single-phase flow showed good agreement with the data for nanofluid friction factor. The convective heat transfer coefficient of the nanofluids increased by up to 8% at a concentration of 0.3 vol. % compared with that of pure water; however, this enhancement cannot be predicted by the Shah equation for single phases.

Duangthongsuk and Wongwises (2010) presented values for the heat transfer coefficient and friction factor of TiO<sub>2</sub>/water nanofluids flowing through a horizontal tube in the turbulent flow regime. The heat transfer coefficient of nanofluids at 1.0 vol. % was approximately 26% greater than that of pure water, whereas at 2.0 vol. % this was approximately 14% lower than that of the base fluid for the same conditions. The pressure drop in the nanofluids increased with increasing particle volume concentrations because of the increase in viscosity. However, nanofluids at lower particle volume concentrations only incurred a slight pressure drop. Fotukian and Esfahany (2010) experimentally investigated the turbulent convective heat transfer coefficient and pressure drop of very dilute CuO/water nanofluid (less than 0.24 vol. %) in a circular tube. The increase in heat transfer coefficient was observed to be on average 25% with 20% reduction in pressure drop. The enhanced heat transfer coefficient arose from the macro convection movement of nanoparticles, which encourages collisions of nanoparticles with the heated wall and absorption of thermal energy, lowering of the wall temperature, and remixing with the bulk of the fluid.

To compare the effective thermal conductivity of nanofluids in flow heat transfer conditions with those measured under static conditions, Na et al. (2011) measured the thermal conductivities of

Al<sub>2</sub>O<sub>3</sub>/water nanofluid under fully developed laminar flow conditions. The measured result showed that the augmentation of the effective thermal conductivity of Al<sub>2</sub>O<sub>3</sub>/water nanofluid under convective flow conditions was smaller than that under the static conditions. One can believe that the effective thermal conductivity of nanofluids under the turbulent convective flow condition is possibly different from that under static and/or laminar flow conditions. This interesting finding should be checked by more experimental evidence to find the inherent mechanism of forced heat transfer enhancement by nanofluids.

A theoretical study on the heat transfer of nanofluids in turbulent pipe flow was performed by Corcione et al. (Corcione et al., 2012), in which nanofluids were treated as pure fluids. All the convective heat transfer correlations available in the literature for single-phase flows were extendible to nanoparticle suspensions. The thermo-physical properties appearing in those correlations were effective properties of the nanofluid calculated at the reference temperature. The fundamental result obtained was the existence of an optimal particle loading for either maximum heat transfer at constant driving power or minimum cost of operation at constant heat transfer rate. This result encourages us to find optimal particle loadings for more effective use of nanofluids in practical engineering systems.

Thermal dispersion and intensified turbulence was taken for granted for the mechanism of the observed abnormal single-phase heat transfer coefficient enhancement in the analysis of experimental results. However, Buongiorno (2006) developed a two-component four-equation nonhomogeneous equilibrium model for mass, momentum, and heat transport in nanofluids. A non-dimensional analysis of the equations suggested that energy transfer by nanoparticle dispersion is negligible. Moreover, the effect of nanoparticles on turbulence intensity was also doubtful. It was proposed that the nanofluid properties may vary significantly within the boundary layer because of the effects of the temperature gradient and thermophoresis. For a heated fluid, these effects could result in a significant decrease in viscosity within the boundary layer, thus leading to heat transfer enhancement. By using Buongiorno (Buongiorno, 2006)'s models, Heyhat and Kowsary (2010) investigated the effects of particle migration due to Brownian diffusion as well as thermophoresis on heat-transfer enhancement observed in convective heat transfer of nanofluids in a laminar tube flow. They concluded that the enhancement of the convective heat transfer could not be solely attributed to the enhancement of the effective thermal conductivity, and particle migration was suggested as an important reason. Xuan and Li (2009) established Lattice–Boltzmann models to investigate flow and heat transport mechanisms inside the nanofluid at the mesoscale level. A number of external and internal forces acting on the suspended nanoparticles and interactions among nanoparticles and liquid particles have been taken into account in the models. The heat exchanges between the nanoparticles and the liquid were also considered. One should undertake more experimental evidences to validate these models.

Recently, some research groups tried to numerically simulate forced convective heat transfer in a nanofluid with uniform heat flux or temperature conditions on the wall (Namburu et al., 2009; He et al., 2009; Lotfi et al., 2010; Bianco et al., 2011), to assess the applicability of the single-phase or two-phase models, and to predict the thermal performance of different nanofluids in different flow regimes. However, the present authors believe that the numerical simulation should focus on nanoparticle behaviors such as migration or movements, distributions under shear stress, and temperature gradients, and even interactions between nanoparticles and eddies in the turbulent regime. All these behaviors are very difficult to be detected by experiment, but very important in revealing the inherent mechanisms of forced convective heat transfer enhancement. Based on these behavior studies, one can

then develop more practical models of heat transfer and flow. From these, accurately predicting heat transfer rates and pressure drops would be possible by numerical method.

Currently, experimental results on nanofluid forced heat transfer are still scattered. While experimental conditions across research groups differ, consensus on the mechanism for forced heat transfer enhancement cannot be reached. However, the following information can be obtained from the available experimental and numerical results, from which we can find the research directions for nanofluids application.

- (1) Not all nanofluids with enhanced conductivity can bring about forced heat transfer enhancement. Under suitable conditions, such as the appropriate nanoparticle material and size, the appropriate particle concentration range, and the appropriate preparation method and additives to maintain stability, a higher heat transfer coefficient of nanofluids can be achieved compared with the base fluid.
- (2) Nanofluids behave like single-phase fluids conditionally, depending largely on the base fluid, nanoparticle materials, concentration and size. More experimental evidence is needed to assess the applicability of traditional convective heat transfer correlations available in the literature for single-phase flows to estimate the nanofluids forced heat transfer performance.
- (3) Under forced convective flow condition, either in the laminar or turbulent regime, the shear stress and temperature gradient in the boundary layer may lead to the re-distribution of nanoparticles, resulting in a non-uniform thermal conductivity and viscosity distribution, changing the thermal resistance of boundary layer.
- (4) The migration or movement of nanoparticles from Brownian motion or thermophoresis should be estimated by experiment or numerical simulation to determine if the nanofluids behave like two-phase flows in which the slip velocity between the particle and base fluid plays an important role in heat transfer performance.
- (5) Many factors influence the forced heat transfer performance of nanofluids. The underlying enhancement mechanisms may not only be associated with better thermal conductivity, but also with nanoparticle behavior in the boundary layer. Numerical simulation methods such as Lattice–Boltzmann dynamic simulations may hopefully provide insight into nanoparticles motion and distribution in the boundary layer of fluids.
- (6) Understanding the fundamentals of heat transfer and wall friction is of prime importance in developing nanofluids for a wide range of heat transfer applications. We need to develop more feasible models and to obtain more experimental evidence to validate them.

### 2.3. Nanofluids boiling heat transfer and CHF enhancement

Since You et al. (2003) first reported that the CHF of Al<sub>2</sub>O<sub>3</sub>/water nanofluid pool boiling with particle concentrations ranging from 0 g/l to 0.05 g/l was increased by approximately 200% compared with that of pure water, nanofluids have been expected to be ideally suited for practical thermal systems where high heat flux removal is needed, such as in nuclear reactors. Thus, the characteristics of nanofluids boiling heat transfer, especially the characteristics of critical boiling, have become a hot research topic worldwide. The research on pool boiling and flow boiling in nanofluids will be reviewed in the following.

#### 2.3.1. Pool boiling in nanofluids

You et al. (2003) also reported that the nucleate boiling heat transfer coefficients of Al<sub>2</sub>O<sub>3</sub>/water nanofluids appeared to be

about the same as those of pure water. In contrast, a deterioration in boiling heat transfer in the same system compared with that in pure water was reported in Das et al. (2003b, 2003c), suggesting that trapped particles changed the heating surface characteristics during boiling. In a similar comparison, Bang and Chang (2005) also reported that  $\text{Al}_2\text{O}_3$ /water nanofluids had a poorer heat transfer performance in natural convection and nucleate boiling. Park et al. (2009)'s experimental results showed that the pool boiling heat transfer coefficients of the aqueous solutions with CNTs were lower than those of pure water in the entire nucleate boiling regime. Nevertheless, the CHF of aqueous solutions was enhanced greatly, showing an increase of up to 200% at a CNT concentration of 0.001 vol. %, compared to that of pure water. A deposited layer of CNTs was observed, suggesting that such deposits decreased the active nucleation sites on the surface. Kwark et al. (2009) found that higher concentration  $\text{Al}_2\text{O}_3$ /water nanofluids showed a perceptible degradation in the boiling heat transfer coefficient but have exhibited an enhanced CHF value (up to ~80%). In their experiment, an increase in nanoparticle concentration was found to increase the CHF value but no change in the boiling heat transfer coefficients until the  $\text{Al}_2\text{O}_3$  nanoparticles concentration reached about 0.025 g/l (0.0007 vol.%). Further increase in the concentration produced no further CHF enhancement. On the contrary, it degraded the boiling heat transfer.

In contrast, other literature reported pool boiling heat transfer enhancements by nanofluids (Wen and Ding, 2005; Truong, 2007; Heris, 2011; Krishna et al., 2011; Kole and Dey, 2012). In Wen and Ding's experiment (Wen and Ding, 2005), such an enhancement in  $\gamma\text{-Al}_2\text{O}_3$  (10–50 nm)/water nanofluids was reported to be about 40% at a particle loading of 1.25 wt.%. The boiling curves in nanofluid were found in Truong (2007)'s experimental results to shift to the left of that for water, corresponding to higher nucleate boiling heat transfer coefficients in the two phase regime. Heris (2011) experimentally investigated the boiling heat transfer of the CuO/ethylene glycol–water (60/40) nanofluid. The results indicated that a considerable boiling heat transfer enhancement has been achieved, specifically that the enhancement had increased with increasing nanoparticles concentration and reached 55% at a nanoparticles loading of 0.5 vol. %.

Krishna et al. (2011)'s results indicated that at comparatively low heat fluxes, there was a deterioration in Cu/water boiling heat transfer with very low Cu nanoparticle volume fraction of 0.01%. However, the nanofluid boiling heat transfer increased with increasing nanoparticle volume fraction and enhancements were observed with nanoparticle volume fractions reaching 0.1 vol. %. The maximum enhancement observed was ~50% and ~20% on smooth and rough heaters with a volume fraction of 0.1 vol. %. Kole and Dey (2012) prepared surfactant-free and fairly stable ZnO–ethylene glycol (EG) nanofluids and measured the nucleate pool boiling heat transfer characteristics of ZnO–EG nanofluids with various loading of ZnO nanoparticles at atmospheric pressure. In their experiment, a cylindrical polished copper heater was employed. The results indicated that the boiling heat transfer coefficient enhanced as ZnO concentration increased. The coefficient increase reached a maximum of 22% when ZnO volume fraction was 1.6% compared to that of base fluid. However, further loading of ZnO nanoparticles in EG decreased the heat transfer coefficient. CHF values increased appreciably as ZnO loading increased and displayed a maximum enhancement of ~117% when the ZnO volume fraction was 2.6%. The trend of the dependence on nanoparticle concentration of the boiling heat transfer coefficient was contrary to that in Krishna et al. (2011), although it should be noted that different nanofluids were used in Krishna et al. (2011) and Kole and Dey (2012). Taylor and Phelan (2009) reported some new but limited experimental data for  $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$  nanofluids that indicated that nucleate boiling

incipience occurred 2–3 °C earlier, and nucleate boiling heat transfer was enhanced by 25–40%, but sub-cooled boiling was deteriorated, compared with the pure-water baseline.

The above review shows mixed or discrepant incongruent experimental results about the characteristics of nanofluids pool boiling heat transfer. This indicates, so far, that we have not yet understood the underlying mechanisms influencing pool boiling. Many researchers have tried to explain the deterioration or enhancement of nucleate boiling heat transfer and the CHF strengthening as due to changes in heated surface characteristics from sedimentation or deposition of nanoparticles on the heated surface during the boiling process. Accordingly, this sedimentation or deposition may decrease active nucleation sites (Das et al., 2003b; Bang and Chang, 2005; Park et al., 2009), may create more active nucleation sites (Truong, 2007; Heris, 2011), and may improve the wettability of heated surfaces (Kim et al., 2007, 2010a; Wen, 2008; Wen et al., 2011). To validate this point, some research groups experimentally studied the pool boiling behavior of pure water on heated surfaces with nanoparticle coatings. These surfaces are either created during nanofluid pool boiling (Kwark et al., 2010) or pre-fabricated (Kim et al., 2010b). The significant enhancement of CHF was measured and believed to be due to wetting and wicking of the porous nanoparticle-coated surfaces. Nevertheless, Yang and Liu (2011) and Milanova and Kumar (2008)'s experimental results should be noted. Yang and Liu (2011) investigated the pool boiling heat transfer of a water-based functionalized nanofluid under sub-atmospheric conditions without nanoparticle deposition during boiling. A slight increase in the boiling heat transfer coefficient was measured comparing with that of pure water. Milanova and Kumar (2008) experimentally studied the influence of acidity on  $\text{SiO}_2$ /water-nanofluid boiling heat transfer, as the pH value of nanofluids often determines particle stability and the mutual interactions between particles and suspensions. His results showed that in the absence of deposition on the heated wire, burnout heat flux was increased by about 50%. The near uniform increase in CHF, regardless of the particle size and surface morphology, was significant. Therefore, the inherent mechanism behind CHF enhancement in nanofluids cannot be resolved just by modifications on the heated surface.

The present authors provide the following remarks in suggesting future work on the pool boiling heat transfer of nanofluids.

- (1) The pool boiling heat transfer of nanofluids is still governed by both the thermo-properties of nanofluids and the surface characteristics of the heated surface, as for pure liquid. Nanoparticles deposition is only one contribution to CHF enhancement. As we know, pool boiling includes such aspects as bubble generation, growth, and detachment from heated surfaces, motion and coalescence in the fluid, and bursting at the liquid surface. The heated surface characteristics will affect the number of generated bubbles, bubble growth rates, the size and frequency of detached bubbles. However, nanoparticles suspended in nanofluids should have comprehensive effects on the bubble growth and detachment from heated surface, motion and coalescence in fluid. These comprehensive actions result in a complete change of flow field and temperature distribution of boiling nanofluids, and of course have some effects on boiling heat transfer. This is clearly demonstrated using state-of-the-art dynamic particle image velocimetry in the latest work of Dominguez-Ontiveros et al. (2010), in which boiling point temperature and full-field velocity measurements were obtained during pure water and water-based  $\text{Al}_2\text{O}_3$  nanofluids pool boiling. A change in the hydrodynamic behavior of bubbles was observed with the introduction of nanoparticles. The measured velocity fields exhibited different

bubble and fluid behavior for the various nanofluids investigated, and which in turn highlighted the complexity of the fluid flow in pool boiling. For example, the profile developed for fluids with 0.002 vol. % of  $\text{Al}_2\text{O}_3$  nanoparticle concentration showed that in the neighborhood of nucleation zones, velocity distributions were generally less uniform and lower in magnitude for nanofluids than those for pure water. The computed vorticity fields, based on the measured full-field velocity profile, showed an increase in fluid circulation due to the presence of nanoparticles in the fluids. The wall temperature was also observed to decrease with increasing nanofluid concentration. A multi-faceted approach must be taken in the development of a more complete understanding of the mechanisms controlling nanofluid behavior in boiling. Thus, we believe that more efforts should be directed into investigating bubble dynamics together with surface tension variation by considering the presence of nanoparticles and additives (if used), to completely understand the effects of nanoparticles in boiling heat transfers and the mechanisms of CHF enhancement by nanofluids.

- (2) Nanoparticle deposition on heated surfaces is just one of the phenomena occurring in nanofluid boiling. It is understandable that nanoparticles deposition contributes to CHF enhancement in boiling heat transfer, just as other surface treatment methods do. Thus, the available experimental results of observed nanoparticle deposition just provide a new means to improve the heated-surface characteristics of boiling heat transfer systems to enhance CHF. The passive deposition of nanoparticle during boiling may result in transient characteristics in the nucleate boiling heat transfer of nanofluids. So far, there is no evidence reported on whether the generated vapor also contains nanoparticles during pool boiling. Presumably, nanofluid concentrations cannot be maintained easily using some dispersing agents, even for functionalized nanofluids, without deposition occurring during pool boiling. This implies that nanofluid pool boiling is not suitable in those thermal systems for which steady thermal management is required. However, in such systems managing for emergency core cooling (ECC) for both pressurized-water reactors (PWRs) and boiling-water reactors, in-vessel retention (IVR) of the molten core, and external vessel cooling for high-power-density light water reactors during severe accidents, high boiling heat transfer and CHF enhancement of nanofluids can increase the peak-cladding-temperature margins (in the nominal-power core) or maintain them in uprated cores for ECC in PWRs during a large-break loss-of-coolant accident. Bringing the decay heat from the molten core out more efficiently can increase the margin for vessel breach by 40% for the IVR in advanced light-water reactors during core molten accident (Buongiorno et al., 2008; Pham et al., 2012). Boiling heat transfer of nanofluids in such special applications should be studied thoroughly with consideration of the many other practical factors such as material composition and orientation of the heated surfaces, and physical conditions of the environment.

### 2.3.2. Flow boiling of nanofluids

Flow boiling heat transfer is more popular in engineering thermal systems than pool boiling. For most potential applications of nanofluids, flow boiling should still be an important research topic. Relevant research has been increasing over the past 3 years. Kim et al. (2008) presented first-of-their-kind data for flow boiling CHF in nanofluids showing that a significant CHF enhancement (up to ~30%) can be achieved. As little as 0.01% by volume concentration of alumina/water nanofluid flow boiling was tested at

atmospheric pressure, low subcooling temperatures ( $<20\text{ }^\circ\text{C}$ ), and relatively high mass flux ( $\geq 1000\text{ kg/m}^2\text{s}$ ) conditions. Peng et al. (Peng et al., 2009) experimentally investigated the influence of nanoparticles on heat transfer characteristics in CuO/R113 nanofluid flow boiling inside a horizontal smooth tube. The experimental results showed that the heat transfer coefficient of the refrigerant-based nanofluid was larger than that of pure refrigerant, and the maximum increase in the heat transfer coefficient was 29.7%. The influence of nanoparticles on flow boiling for R-134a and R-134a/polyolester mixtures was quantified by Henderson et al. (2010). The heat transfer coefficient of  $\text{SiO}_2/\text{R134a}$  had decreased as much as 55% in comparison with pure R134a. This was partly due to difficulties in obtaining a stable dispersion. However, excellent dispersion was achieved for a mixture of R134a and polyolester oil with CuO nanoparticles, and the heat transfer coefficient increased more than 100% over baseline (R134a/polyolester) results. In the range studied in these experiments, nanoparticles had an insignificant effect on the flow pressure drop with the R134a/POE/CuO nanofluid. Kim et al. (2009b) experimentally studied the CHF in flow boiling of  $\text{Al}_2\text{O}_3/\text{water}$ , ZnO/water, diamond/water nanofluids. The experimental results showed a significant CHF enhancement of up to 40–50% with respect to pure water at high mass flux (2000–2500  $\text{kg/m}^2\text{s}$ ). The enhancement appeared to be weakly dependent on nanoparticle concentration for  $\text{Al}_2\text{O}_3/\text{water}$  nanofluids, whereas it increased more pronouncedly with nanoparticle concentration for the ZnO/water and diamond/water nanofluids. In their series paper (Kim et al., 2010c), it was reported that for comparable test conditions the values of the nanofluids ( $\text{Al}_2\text{O}_3/\text{water}$ , ZnO/water, and diamond/water) and water heat transfer coefficient are similar (within  $\pm 20\%$ ). The heat transfer coefficient increased with mass flux and heat flux for water and nanofluids alike, as expected in flow boiling. Kim et al. (2010d) conducted experiments to evaluate the possibility of enhancing CHF in flow boiling using  $\text{Al}_2\text{O}_3/\text{water}$  nanofluids as working fluids vertically flowing upward in the tube under atmospheric pressure. It was verified that the dispersion stability of  $\text{Al}_2\text{O}_3$  nanofluids during the CHF experiment was sufficient when the concentration of the nanofluid was in a range 0.001–0.5 vol. %. The CHFs of  $\text{Al}_2\text{O}_3/\text{water}$  nanofluids were enhanced up to about 70%, in flow boiling for all experiment conditions. The CHFs of  $\text{Al}_2\text{O}_3$  nanofluids were increased with increasing mass flux at inlet subcooling of  $50\text{ }^\circ\text{C}$  and  $25\text{ }^\circ\text{C}$ . However, the CHF enhancement ratios of  $\text{Al}_2\text{O}_3$  nanofluids did not show a trend toward increasing mass flux at inlet subcooling of  $50\text{ }^\circ\text{C}$  and  $25\text{ }^\circ\text{C}$ . It was suggested that the effects of flow characteristics may replicate the deposition effect of nanoparticles with increased mass flux. The CHFs of the  $\text{Al}_2\text{O}_3$  nanofluids were within the margin of error virtually unchanged as  $\text{Al}_2\text{O}_3$  nanoparticle concentration increased from 0.001 to 0.1 vol. %. The effects of flow and deposition on the CHF should be investigated under higher mass flux to understand the mechanism of CHF enhancement. Ahn et al. (2010) experimentally studied the CHF enhancement during forced convective boiling of the nanofluid with 0.01 vol. %  $\text{Al}_2\text{O}_3$  nanoparticle, flowing in a horizontal rectangular channel made of transparent strengthened acrylic. A copper disk was placed on the bottom surface of the channel to bring the flow to boil. The experimental results showed that, compared to that in pure water, the nanofluid flow boiling CHF was enhanced 24% and 40% with velocity of 1 m/s and 4 m/s, respectively. The heated surface was characterized before and after boiling tests, and nanoparticles deposition was observed during boiling. Vafaei and Wen (2010) investigated subcooled flow boiling of aqueous-based  $\text{Al}_2\text{O}_3$  nanofluids in single 510- $\mu\text{m}$  microchannel with a focus on the effect of nanoparticles on CHF. The experimental results showed an increase of ~51% of CHF under very low nanoparticle concentrations (0.1 vol. %). Different burnout characteristics were

observed between water and nanofluids, as well as different pressure and temperature fluctuations and flow pattern development during stable boiling periods. Vafaei and Wen (2011) were the first to discuss the dual effects of nanoparticles in boiling heat transfer: (i) modification of the heating surface through nanoparticle deposition and (ii) modification of bubble dynamics by varying contact angles, departure bubble volume, and frequency. The second role may open a promising window for future nanofluid applications in microchannel heat transfer, avoiding the high increase in pressure drop arising from nanoparticle deposition. The local convective boiling heat transfer and pressure drop in copper–water nanofluids in narrow vertical rectangular channels with hydraulic diameter of 800  $\mu\text{m}$  were investigated by Boudouh et al. (2010). The distribution of the local heat flux, surface temperature, and local heat transfer coefficient were shown to be dependent of axial distance and nanoparticle concentration. The Cu–water nanofluid exhibited a higher local heat transfer coefficient, higher local heat flux, higher pressure drop, and lower surface temperature than its base fluid at the same mass flux. Vapor quality has been shown locally to be dependent on the Cu nanoparticles concentration in this nanofluid. Xu and Xu (2012) investigated the flow boiling heat transfer with and without  $\text{Al}_2\text{O}_3$  nanoparticles in a single microchannel with a platinum film for bottom surface heating. Particle deposition on the heating surface was not observed. The flow boiling of pure water displayed chaotic behavior due to random bubble coalescence and breakup over millisecond timescales at moderate heat fluxes. Nevertheless, the nanofluid (weight concentration of 0.2%, consisting of de-ionized water and 40 nm  $\text{Al}_2\text{O}_3$  nanoparticles) was found to mitigate significantly the flow instability without nanoparticle deposition. Flow boiling of the nanofluid was always stable or quasi-stable with significantly reduced pressure drop and enhanced heat transfer. This is an interesting finding that deserves to be studied more deeply. Kim et al. (2011) and Ahn and Kim (2012) concluded that the flow boiling CHF enhancement was caused by nanoparticles deposition on the channel inner surface.

So far, the research on nanofluids flow boiling heat transfer is still limited, in comparison with the normal flow boiling research. The available results on the effect of nanoparticles on the flow boiling heat transfer coefficients are in discrepancy, just as those on pool boiling of nanofluids. The CHF enhancement mechanism of flow boiling is not clear yet. Indeed, nanofluid flow boiling heat transfer is far more complicated than nanofluid pool boiling. In flow boiling, apart from the fluid's thermal physical properties and surface characteristics, the particular flow regime also produces differing effects on bubble generation, growth, and wall detachment, as well as motion and clustering within the fluid. Just as in nanofluid pool boiling, surface characteristics are just one of many aspects affecting bubble generation, growth, and detachment. The collective effect of nanoparticles suspended in base liquid not only influences bubble generation, growth and detachment, but also influences bubbles' motion and amalgamation in the flowing fluid. Shear stresses and temperature gradients in the fluid may result in a non-uniform distribution of nanoparticles, which will in turn influence the vapor distribution and flow pattern. Therefore, the nanofluid flow boiling heat transfer coefficient and CHF may be very different from that of base fluids because of the collective effect of suspended nanoparticles. The following remarks are to emphasize the urgent need for research on nanofluids flow boiling.

(1) The flow boiling heat transfer of nanofluids is governed by the thermo-properties of nanofluids, flow regime and inner surface characteristics of the flow channel, as for pure liquids. The present knowledge on the mechanism of flow boiling CHF enhancement is insufficient. Nanoparticle deposition is only

one aspect of boiling contributing to flow boiling CHF enhancement. We should make more efforts to investigate the mechanism from the viewpoint of bubble dynamics. The suggestion and discussion from Vafaei and Wen (2011) and Ahn and Kim (2012) could provide new directions to investigate this mechanism.

Taking these into consideration, the present authors numerically simulated single bubble growth and detachment during flow boiling with 1.0 vol. %  $\text{Al}_2\text{O}_3$ /water nanofluids and pure water at atmospheric pressure (with inlet subcooling of 0.2  $^\circ\text{C}$ , wall superheat of 5.3  $^\circ\text{C}$  and original bubble diameter of 0.4 mm) using the moving particle semi-implicit (MPS) method. The MPS method, developed by Koshizuka and Oka (1996), is suited to simulate various heat-transfer and flow problems with complex and continuous deformed boundaries. The applicability of this method to bubble dynamics had been validated by Chen et al. (Chen et al., 2010). The present numerical results, given in Fig.1, show that the numerical result for pure water coincides with Maity's experimental result (Maity, 2000) very well, validating the applicability of MPS method in this simulation. The bubble in  $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$  nanofluid grows faster, and detaches from the heated wall earlier with larger diameter compared with that in pure water case. Note that “★” indicates the critical moment when the bubble detaches from the wall. Fig. 2 shows the change in bubble size during growth indicating that the bubble in the nanofluid grows faster and detaches from the heated wall with larger diameter. That means the heat flux drawn from the wall by the departing bubble is greater compared with pure water under the same conditions. This work initially reveals the underlying mechanism of nanofluid enhanced boiling heat transfer from the viewpoint of bubble dynamics. These interesting results direct us to perform more work in this area.

(2) Stability of working fluids is required for all steady state thermal management systems. Nanoparticles deposition on the inner wall of the flow channel may cause difficulties in controlling nanofluid concentrations, resulting in transient features in thermal systems. Thus, new technology is needed to increase the stability of nanofluids so that nanofluids can be used effectively and reliably in engineering systems. This requirement seems to bring us back to the beginning of investigations into the thermo-physical properties of nanofluids and seeking suitable additives, especially for those promising nanofluids.

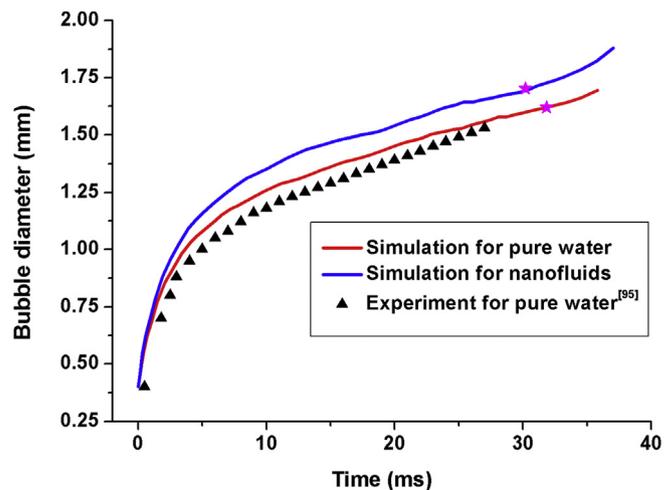


Fig. 1. Bubble growth and detachment during flow boiling for water and nanofluid.

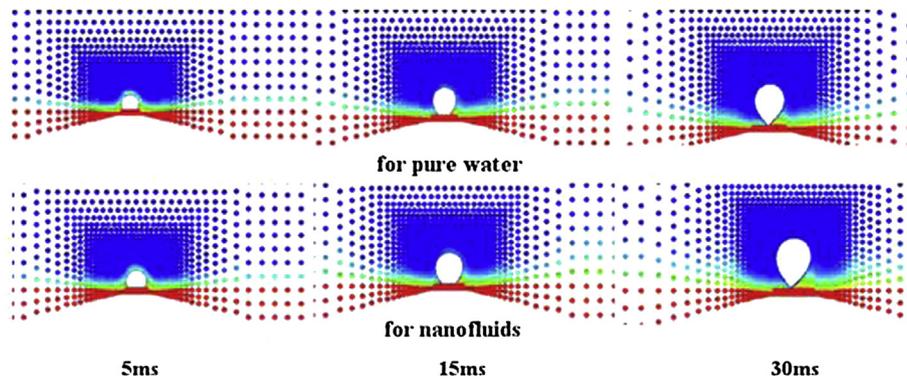


Fig. 2. Bubble size evolution during flow boiling for water and nanofluid.

(3) As for forced heat transfer in nanofluids, a higher flow boiling heat transfer coefficient can be achieved by properly selecting suitable nanoparticle materials and sizes, concentration range, appropriate preparation methods, and stabilizing additives. As there are a wide variety of nanoparticle materials to choose from, although not all are suitable, nanofluidic systems can still be adapted to application requirements. More effort is needed to find some appropriate nanofluids for the different and broad spectrum of engineering systems. From this perspective, we still have a long way to go.

### 3. The features/challenges of using nanofluids and future research

#### 3.1. The features/challenges of using nanofluids

Given the preceding review, we conclude that in the past decades nanofluid application is being turned from a novel concept into reality through some pioneering research work by scientists and engineers. However, results across different research groups are inconsistent and the underlying mechanisms leading to these unprecedented thermal transport phenomena has not as yet been determined. Practical applications in some industrial areas remain a challenge for thermal scientists and engineers. First, production of stable nanofluids with nonagglomerated nanoparticles is currently limited to laboratory-scale research. Long-term physical and chemical stability of nanofluids for high-volume production is one of the most challenging obstacles preventing nanofluid's incursion into commercial projects. Second, the reasons underscoring the "anomalously" high transport properties of nanofluids are still disputed. Surface and interface effects, nanoparticle motion, and interactions in both static and flow conditions need to be discovered. In particular, the fundamentals of nanofluid flow and heat transfer remain challenging issues for thermal scientists and engineers to resolve so that nanofluid applications can be reliably implemented.

#### 3.2. Future research

Energy-related problems are calling for more effort to turn nanofluid applications from vision to reality as soon as possible. To achieve that, urgent focus is needed on the following.

(1) Nanofluid stability under both quiescent and flow conditions should be evaluated carefully, because this property determines whether the nanofluids can be applied successfully in engineering systems in which steady thermal management is required.

(2) A nanofluid database of thermo-physical properties, including detailed characterization of nanoparticle sizes, distribution, and additives or stabilizers (if used), should be established, in a worldwide cooperation of researchers. Moreover, priority should be given to nanofluids with promising potential.

(3) More experimental and numerical studies on the interaction of suspended nanoparticles and boundary layers should be performed to uncover the mechanism behind convective heat transfer enhancement by nanofluids. Promising nanofluids that would boost the convective heat transfer increase, without much concomitant viscous pressure drop increase, need to be explored through more research.

(4) Bubble dynamics of boiling nanofluids should be investigated experimentally and numerically by considering, together with surface tension effects, the influences of the presence of nanoparticles and additives if used, to identify the exact contributions of solid surface modifications and suspended nanoparticles to CHF enhancement in boiling heat transfer.

### 4. Conclusions

The prospects of increased cooling efficiency from the use of nanofluid coolants have raised a tremendous amount of interest. However, some inconsistent or contradictory results related to – thermo-physical properties, convective heat transfer performance, boiling heat transfer performance, and CHF enhancement of nanofluids are to be found in data published in the literature. No comprehensive theory explains the energy transfer processes in nanofluids. To accelerate engineering applications of nanofluids, work that is urgently needed to be carried out has been suggested. A reliable nanofluid database of thermo-physical properties is especially needed, including details of nanoparticle composition, size, concentration, preparation method and additives (if used), beginning in particular with promising nanofluids. A thorough understanding of the interaction of nanoparticles and flow boundary layers also needs to be achieved by performing careful experimental observations and numerical simulations, to uncover mechanisms underlying convective heat transfer enhancement. Bubble dynamics in boiling nanofluids with consideration of suspended particles, additives used, and nanoparticle distributions, should be investigated experimentally and numerically to identify the exact contribution of suspended nanoparticles to boiling heat-transfer and CHF enhancement. Once we acquire such details about the above key issues, we will gain more confidence in conducting application studies of nanofluids in different engineering systems with more efficiency.

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