Chapter 14
Nanofluids as Advanced Coolants

S.M. Sohel Murshed and Carlos A. Nieto de Castro

Abstract Nanofluids have attracted great interest from the researchers all over the world due to their superior thermal transports and potential applications in numerous important fields. From extensive research, nanofluids are found to exhibit significantly higher thermal conductivity than that of base fluids. However, besides thermal conductivity, investigations on convective and boiling heat transfer are also very important in order to exploit nanofluids as advanced coolants. In this chapter, experimental investigations on these two major cooling features, i.e., convective and boiling heat transfer, of nanofluids are reported together with critical review of recent research progress in these important areas of nanofluids. Nanofluid development background along with their potential benefits and applications are also briefly discussed. Despite of controversies and scattered experimental data on all these thermal features of nanofluids, it is undisputed that nanofluids exhibit substantially enhanced thermal conductivity, convective heat transfer coefficient, and boiling critical heat flux which further increase with increasing concentration of nanoparticles, and these clearly evince that nanofluids can potentially be used as advanced coolants in the future.

14.1 Background of Nanofluids

14.1.1 Concept and Development

Cooling for maintaining desirable performance and durability of smaller features of microelectronic and more power output-based devices is one of the most important technical issues in many high-tech industries and thermal management systems.

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The conventional method to increase the cooling rate involves the use of extended heat transfer surfaces. However, this approach requires an undesirable increase in the size of the thermal management systems. In addition, the inherently poor thermal properties of traditional heat transfer fluids such as water, ethylene glycol, or engine oil greatly limit the cooling performance. Thus, existing conventional methods for increasing the heat dissipation are not suitable to meet the cooling demand of the high-tech industries. It is known that at room temperature, fluids possess orders of magnitude smaller thermal conductivity than most of the metallic or nonmetallic particles. For example, thermal conductivities of water (0.607 W/m·K) and engine oil (0.145 W/m·K) are about 5,000 and 21,000 times, respectively, smaller than that of carbon nanotubes (e.g., 3,000 W/m·K for multiwalled carbon nanotubes, MWCNT), and the thermal conductivity of water is about 700 times smaller than that of copper particle. Therefore, the thermal conductivities of fluids that contain suspended metallic or nonmetallic particles or tubes are expected to be significantly higher than those of traditional heat transfer fluids.

Although nanoparticle suspensions were used in heat transfer studies as early as 1984 by Yang and Maa [1] and then in 1993 by Masuda et al. [2], it was only in 1995 that Choi [3] at Argonne National Laboratory of USA coined the concept of "nanofluid" which has been proposed to meet the cooling challenges facing many advanced industries and devices. Apart from Yang and Maa [1] and Masuda et al. [2], Gass and coworkers [4] from Switzerland used the same term "nanofluid" to express minute volume of fluid (nanoliter) in microfluidics study in 1993. In the same year, Arnold Grimm [5], a German researcher, also won a German patent on the enhanced thermal conductivity of nano- and micro-sized particle suspensions. Aluminum particles of 80 nm to 1 μm were suspended into a fluid, and about 100% increase in the thermal conductivity of the fluid for loadings of 0.5–10 vol.% was reported in his patent.

This new class of heat transfer fluids (nanofluids) is engineered by dispersing nanometer-sized solid particles, rods, or tubes in traditional heat transfer fluids. Studies showed that nanofluids exhibit significantly higher thermophysical properties, particularly thermal conductivity and thermal diffusivity than those of base fluids [6–11]. These nanofluids have attracted great interest from the research community due to their enhanced thermal performance, potential benefits, and applications in numerous important fields such as microelectronics, microfluidics, transportation, manufacturing, medical, and so on.

14.1.2 Potential Benefits and Applications

As thermal properties, particularly thermal conductivity of fluid, play a vital role in the development of energy efficient heat transfer equipment, numerous theoretical and experimental studies on increasing thermal conductivity of liquid by suspending small particles have been conducted since the treatise by Maxwell appeared [12].

However, all the studies on thermal conductivity of suspensions were confined to millimeter- or micrometer-sized particles. The major problems of such suspensions are the rapid settling of these particles, clogging the flow channel, and increased pressure drop in the fluid. If the fluid is kept circulating rapidly enough to prevent much settling, these particles would damage the walls of the heat transfer devices (e.g., pipes and channels). Furthermore, milli- or microparticles are too large for microsystems to be used. In contrast, nanoparticles which are orders of magnitude smaller than the microsystems remain in suspension reducing erosion and clogging. Thus, with dispersion of nanoparticle, nanofluids can flow smoothly through mini- or microchannels. Another advantage is the mobility of the particles, which may bring about microconvection of fluids and hence can enhance the transports of heat. Because the nanoparticles are small, they weigh less, and chances of sedimentation are also less making nanofluids more stable.

The impact of nanofluid technology is expected to be great, considering that the heat transfer performance of heat exchangers or cooling devices is vital in numerous industries. As mentioned before, when the nanoparticles are properly dispersed, besides anomalously high thermal conductivity, nanofluids offer numerous benefits [13], which include improved heat transfer and stability, microchannel cooling without clogging, miniaturized systems, and reduction in pumping power. The better stability of nanofluids will prevent rapid settling and reduce clogging in the walls of heat transfer devices. The high thermal conductivity of nanofluids translates into higher energy efficiency, better performance, and lower operating costs. They can reduce energy consumption for pumping heat transfer fluids. Miniaturized systems require smaller inventories of fluids where nanofluids can be used. Thermal systems can be smaller and lighter. In vehicles, smaller components result in better gasoline mileage, fuel savings, lower emissions, and cleaner environment.

With the aforementioned highly desirable thermal properties and potential benefits, it is considered that nanofluids have wide range of industrial and medical applications. Nanofluids can be used to improve thermal management systems in many engineering applications including transportation, microelectromechanical systems (MEMS), electronics and instrumentations, heating–ventilating and air-conditioning, and in medical science. Details of the potential applications of nanofluids have been discussed elsewhere [10, 13] and hence will not be elaborated here.

14.1.3 Prospect as Coolants

Nanofluids are believed to be the next-generation heat transfer fluids. This is primarily from the exciting nanofluids research findings such as unusually high thermal conductivity and significantly enhanced flow and boiling heat transfer performances. However, research efforts to establish nanofluids as advanced coolant are still limited as researchers are mainly focusing on their anomalous thermal

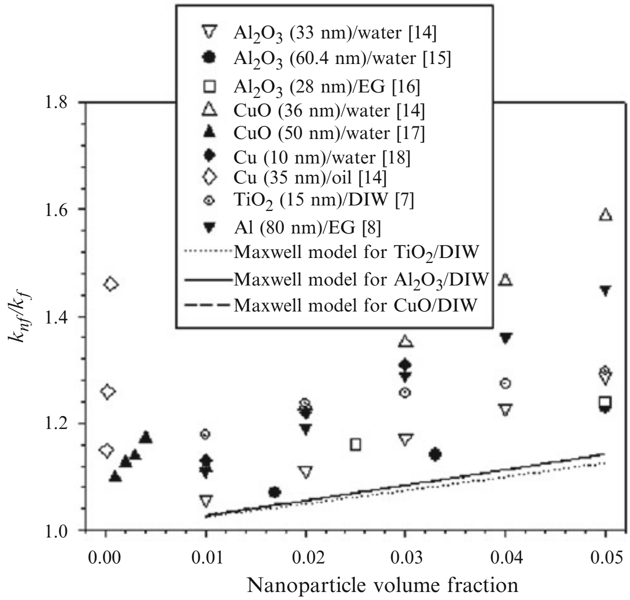

Fig. 14.1 Enhanced thermal conductivity data of various nanofluids

conductivity which is found to be significantly higher than that of base fluids [9, 10]. Some of the key results of the effective thermal conductivity of nanofluids as a function of nanoparticle volume fraction from various research groups are shown in Fig. 14.1. Although reported data are scattered and inconsistent, Fig. 14.1 clearly shows that nanofluids exhibit much higher thermal conductivities compared to their base fluids even when the concentrations of suspended nanoparticles are very low. The enhanced thermal conductivity further increases significantly with nanoparticle volume fraction. Existing classical models such as those attributed to Maxwell [12] and Hamilton and Crosser [19] were also found to be unable to predict the anomalously high thermal conductivity of nanofluids [6–8]. Studies on cooling application-based thermal properties characterization of nanofluids showed that nanofluids exhibit substantially enhanced convective heat transfer coefficient and the boiling critical heat flux which further increase with loading of nanoparticles. These highly desired thermal features of nanofluids clearly indicate that they can potentially be used as advanced coolants in the future.

Compared to research efforts made on thermal conductivity, little work has been reported on droplet spreading, convective, and boiling heat transfer characteristics of nanofluids in spite of the fact that these features are very important in order to exploit nanofluids as the next-generation coolants. It is important to evaluate the research progress on these cooling features of nanofluids and is timely to provide a state-of-the-art review on these areas of nanofluids.

14.2 Flow and Heat Transfer Characteristics of Nanofluids

Studies on convective heat transfer of nanofluids are still scarce comparing with reported works on static thermal conductivity. However, the practical applications of nanofluids as advanced heat transfer fluids are mainly in flowing systems such as mini- or microchannel heat sinks and miniaturized heat exchangers. In this section, we will critically review the reported experimental studies on convective heat transfer of nanofluids. In addition, some representative experimental results obtained from our investigation on laminar flow convective heat transfer of TiO_2 nanofluids are discussed.

14.2.1 Studies in the Literature

The experimental work of Pak and Cho [20] was the first on convective heat transfer of nanofluids (e.g., γ-Al_2O_3/water) under turbulent flow conditions. In their study, even though the Nusselt number (*Nu*) was found to increase with increasing nanoparticle volume fraction and Reynolds number, the heat transfer coefficient (*h*) actually decreased by 3–12%. The reasons for such paradoxical results might be the observed large enhancement in viscosity. On the other hand, Eastman et al. [21] later showed that with less than 1 vol.% of CuO nanoparticles, the convective heat transfer coefficient (*h*) of water increased more than 15%. The experimental results of Xuan and Li [22] also illustrated that the Nusselt number of Cu/water-based nanofluids increased significantly (about 60%) with the volumetric loading of particles. Wen and Ding [23] reported the heat transfer behavior of nanofluids at the tube entrance region under laminar flow conditions and showed that the local heat transfer coefficient varied with particle volume fraction and Reynolds number (*Re*). They also observed that the enhancement is particularly significant at the entrance region. Later, another convective heat transfer study with CuO/water- and Al_2O_3/water-based nanofluids under laminar flow conditions was conducted by Heris et al. [24]. Their results showed that heat transfer coefficient increases considerably with particle volume fraction as well as Peclet number. In their study, Al_2O_3/water-based nanofluids showed higher enhancement of heat transfer coefficient compared to CuO/water-based nanofluids.

An experimental investigation on the forced convective heat transfer and flow characteristics of aqueous TiO_2 nanofluids under turbulent flow conditions is reported by Duangthongsuk and Wongwises [25]. A horizontal double-tube counter flow heat exchanger was used, and they observed a slightly higher (6–11%) heat transfer coefficient for nanofluid compared to pure water. The heat transfer coefficient increases with increasing mass flow rate of hot water and nanofluid. They also claimed that the use of TiO_2 nanofluid has a little penalty in pressure drop.

In microchannel flow of nanofluids, Faulkner et al. [26] was the first to perform convective heat transfer experiments with aqueous carbon nanotubes (CNT) nanofluid in a microchannel with hydraulic diameter of 355 μm at Reynolds numbers

Table 14.1 Summary of forced convection heat transfer experimental studies of nanofluids

Researchers	Geometry/flow nature	Nanofluids	Findings
Pak and Cho [20]	Tube/turbulent	Al_2O_3 and TiO_2/water	At 3 vol.%, the *h* was 12% smaller than pure water for a given average fluid velocity
Xuan and Li [22]	Tube/turbulent	Cu/water	A larger enhancement of *h* with increasing particle volume fraction and Reynolds number was observed
Wen and Ding [23]	Tube/laminar	Al_2O_3/water	Increased *h* with particle volume fraction and Reynolds number was observed
Ding et al. [28]	Tube/laminar	CNT/water	At 0.5 wt.%, *h* increased by more than 350% at Reynolds number of 800
Yang et al. [29]	Tube/laminar	Graphite/automatic transmission fluid	The nanoparticles considerably increase the heat transfer coefficient of the fluid in laminar flow
Heris et al. [24]	Tube/laminar	Al_2O_3 and CuO/water	*h* increase with particle volume fraction and *Pe*. Al_2O_3 shows higher enhancement than that of CuO
Lai et al. [30]	Tube/laminar	Al_2O_3/water	*Nu* increased 8% for particle volume fraction of 0.01 and Reynolds number of 270
Jung et al. [27]	Microchannel/laminar	Al_2O_3/water	For particle volume fraction of 0.018, *h* increased up to 15%
Williams et al. [31]	Tube/turbulent	Al_2O_3 and ZrO_2/water	Heat transfer coefficient increased significantly
Hwang et al. [32]	Tube/laminar	Al_2O_3/water	At $Re=730$ and particle volume fraction of 0.003, *h* increased only up to 8%
Xie et al. [33]	Tube/laminar	Al_2O_3, ZnO, TiO_2, and MgO/water	For MgO nanofluid, *h* increased up to 252% at $Re=1{,}000$
Amrollahi et al. [34]	Tube/laminar and turbulent	MWCNT/water	At concentration of 0.25 wt.%, *h* increased up to 33–40%

between 2 and 17. They found significant increase in heat transfer coefficient of this nanofluid at CNT concentration of 4.4%. Later, Jung et al. [27] studied heat transfer performance of Al_2O_3/water-based nanofluid in a rectangular microchannel under laminar flow condition and showed that the heat transfer coefficient increased by more than 32% for 1.8 vol.% of nanoparticles. They also found that the Nusselt number (*Nu*) increases with increasing Reynolds number in the flow regime of $5>Re<300$. The published experimental works on the convective heat transfer characteristics of nanofluids are summarized in Table 14.1. A comparison of results of Nusselt number versus Reynolds number for both laminar and turbulent flow

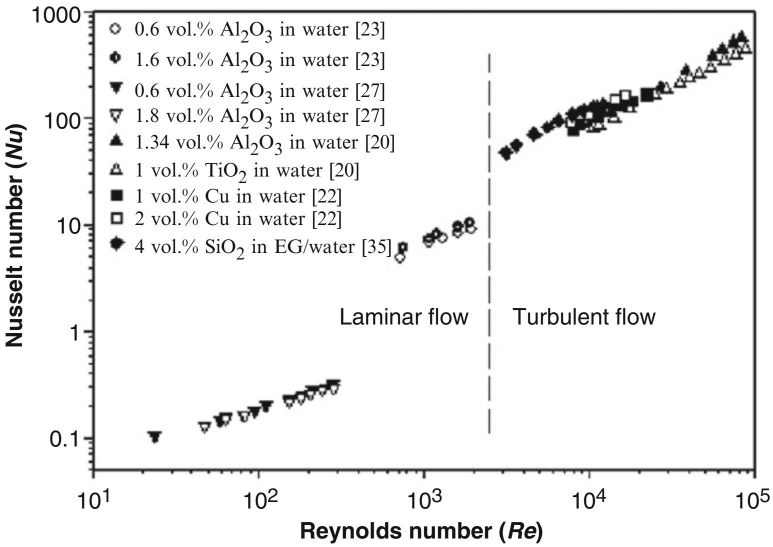

Fig. 14.2 Comparison of convective heat transfer results from various research groups

conditions from various groups is also provided in Fig. 14.2. From Table 14.1 and Fig. 14.2, it can be concluded that the results from various groups vary widely. Although some researchers [36, 37] have attempted to compile some studies on convective heat transfer with nanofluids, no critical analysis of up-to-date research findings is reported.

Several research efforts were also made to investigate the natural convection heat transfer of nanofluids. For example, Putra et al. [38] used a horizontal polyoxymethylene cylinder which was heated from one end and cooled from the other for studying natural convective heat transfer performance of aqueous CuO and Al_2O_3 nanofluids. Significant deteriorations (decrease) of convection heat transfer for these nanofluids were observed, and the deteriorations were found to increase with particle concentration particularly for CuO nanofluid. Effects of particle–fluid slip and sedimentation of nanoparticles were ascribed as the possible reasons of such deterioration. In contrast to Putra et al. [38], numerical simulation of Khanafer et al. [39] showed that in a 2-D horizontal enclosure, the natural convection heat transfer coefficient (*Nu*) of nanofluids increases with particle concentration. Wen and Ding [40] later investigated heat transfer behavior of specially formulated TiO_2/water nanofluid under the natural convection conditions. The results showed that the heat transfer coefficient decreases with increasing particle concentration. These unexpected results are in contradiction to the numerical findings of Khanafer et al. [39] but are in agreement with the observations by Putra et al. [38].

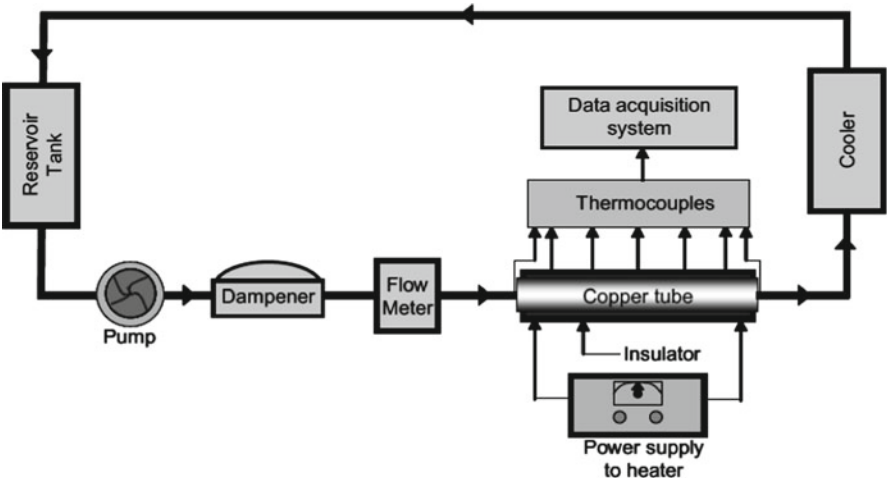

Fig. 14.3 Schematic of convective heat transfer experimental setup

14.2.2 Study by the Authors

In order to study convective heat transfer performance, sample nanofluids were prepared by dispersing different volume percentages (i.e., 0.2–0.8%) of titanium dioxide (TiO_2) nanoparticles of 15 nm diameter in deionized water (DIW) and cetyltrimethylammonium bromide (CTAB) surfactant was added as dispersant agent. To ensure proper dispersion of nanoparticles, sample nanofluids were homogenized using an ultrasonic dismembrator.

An experimental setup was established to conduct experiments on heat transfer of nanofluids at laminar flow regime in a cylindrical channel [41]. The effects of nanoparticle concentration and Reynolds number on the convective heat transfer coefficient of TiO_2/DIW-based nanofluids were studied. The schematic of experimental setup used is shown in Fig. 14.3. Details of the experimental facilities and procedures reported elsewhere [41] will not be provided here. Instead, formulations used for experimentally determination of the heat transfer coefficient (h) and the Nusselt number of nanofluids are presented.

As detailed in our previous paper [41], applying first law (energy balance) in control volume of flow channel, the following formulation for the local heat transfer coefficient is obtained:

$$h_{\text{nf}-x} = \frac{q''}{\left\{T_{\text{o,w}}(x) - \dfrac{q\left[2D_{\text{o}}^2 \ln\left(D_{\text{o}}/D_{\text{i}}\right) - \left(D_{\text{o}}^2 - D_{\text{i}}^2\right)\right]}{4\pi\left(D_{\text{o}}^2 - D_{\text{i}}^2\right)k_s x}\right\} - \left\{T_{\text{i}} + \dfrac{\left(T_{\text{o}} - T_{\text{i}}\right)}{L}x\right\}}, \quad (14.1)$$

where $T_{\text{o,w}}$ (x) is the outer wall temperature of the tube (measured using thermocouples), $q'' = \dot{m}c_{\text{p}}\left(T_{\text{o}} - T_{\text{i}}\right)/\left(\pi D_{\text{i}} L\right)$ is the heat flux of the test section (W/m^2), q is the heat supplied to the test section (W), k_s is the thermal conductivity of the copper tube (W/m·K), D_i and D_o are the inner and outer diameters of the tube, respectively, and x represents the longitudinal location of the section of interest from the entrance. L is the length of the test section, $\dot{m}$ is the mass flow rate (kg/s), and T_i and T_o are the inlet and outlet fluid temperatures, respectively.

Once the local heat transfer coefficient is determined and the thermal conductivity of the medium is known, the local Nusselt number is calculated from

$$Nu_{\mathrm{nf}-x} = \frac{h_{\mathrm{nf}-x} D_{\mathrm{i}}}{k_{\mathrm{nf}}}, \tag{14.2}$$

where k_{nf} is the effective thermal conductivity of nanofluids. The classical Hamilton–Crosser model [19], which is the same as the Maxwell model [12] for spherical particle, is used for the determination of k_{nf}, and it has the form

$$k_{\mathrm{nf}} = k_{\mathrm{f}} \left[\frac{k_{\mathrm{p}} + (n-1)k_{\mathrm{f}} - (n-1)\phi(k_{\mathrm{f}} - k_{\mathrm{p}})}{k_{\mathrm{p}} + (n-1)k_{\mathrm{f}} + \phi(k_{\mathrm{f}} - k_{\mathrm{p}})} \right], \tag{14.3}$$

where k_f and k_p are the thermal conductivities of the base liquid and the nanoparticles, respectively; ϕ is the volume fraction of nanoparticles; and n is the empirical shape factor, which has a value of 3 for spherical particle.

14.2.2.1 Axial Profiles of the Local Heat Transfer Coefficient

Figure 14.4 illustrates the local heat transfer coefficient (h) against the axial distance from the entrance of the test section at Reynolds number of $Re = 1{,}100$. Results showed that nanofluids exhibit considerably enhanced convective heat transfer coefficient which also increases with volumetric loading of TiO_2 nanoparticles. For example, at 0.8 vol.% of nanoparticles and at position $x/D_i = 25$ (where tube diameter $D_i = 4$ mm), the local heat transfer coefficient of this nanofluid is about 12% higher compared to deionized water at $Re = 1{,}100$. The observed enhancement in heat transfer coefficients of nanofluids is because of the enhanced effective thermal conductivity and the acceleration of the energy exchange process in the fluid due to the random movements of the nanoparticles. Another reason for such enhancement can be the migration of nanoparticles in base fluids due to shear action, viscosity gradient, and Brownian motion in the cross section of the tube.

14.2.2.2 Effects of Reynolds Number and Nanoparticle Concentration on Nusselt Number

The effect of Reynolds number on heat transfer coefficient (Nu) is shown in Fig. 14.5. It can be seen that the measured Nusselt number of this nanofluid in all volume concentrations is higher than that of the base fluid (water), and it increases remarkably

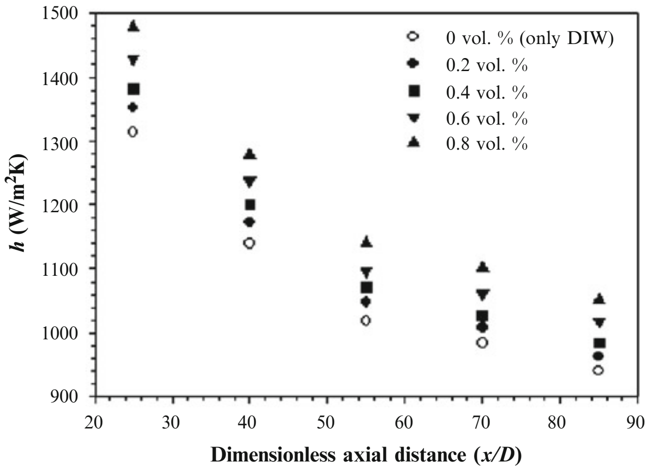

Fig. 14.4 Axial profiles of local heat transfer coefficient of nanofluid at $Re = 1{,}100$

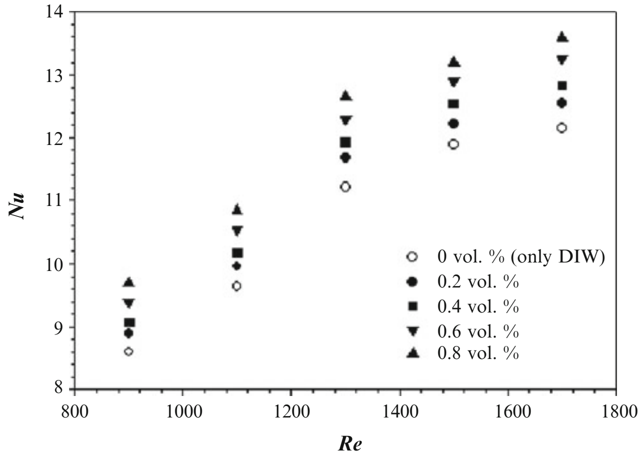

Fig. 14.5 Reynolds number versus Nusselt number at axial location of $x/D_i = 25$

with Reynolds number. The observed enhancement of the Nusselt number could be due to the suppression of the boundary layer and viscosity of nanofluids as well as dispersion of the nanoparticles. Figure 14.5 also demonstrates particle volume fraction dependence of Nusselt number. The Nusselt number of this nanofluid is found to increase almost linearly with the particle volume fraction. The nanofluid behaves more like a fluid than a conventional solid (micrometer or millimeter)–fluid mixture. The effects of several factors such as gravity, Brownian force, and friction force between the fluid and the nanoparticles may coexist in the main flow of nanofluids.

14.3 Boiling and Droplet Spreading of Nanofluids

14.3.1 Boiling Heat Transfer Studies from Literature

Although boiling is a complex and elusive process, it is a very efficient mode of heat transfer in various energy conversion and heat exchange systems as well as cooling of high-energy-density electronic components. There are two common types of boiling: pool boiling and flow or forced convective boiling. Pool boiling refers to boiling on a heated surface (heater) submerged in a pool of initially quiescent liquid, while flow boiling is boiling in a flowing stream of fluid, where the heating surface may be the channel wall confining the flow. There are numerous factors such as heater or channel surface conditions (smooth or rough), heater size, shape, material, diameter and orientation, degree of surface wetting, subcooling, inclusion of surfactants, and properties of liquid that influence heat transfer and bubble dynamics in boiling. These factors are widely studied both theoretically and experimentally and found that there are significant individual or combined effects of these factors on pool boiling heat transfer characteristics [42–44]. Heat flux in any boiling is one of the most important parameters in designing and operating the heat transfer equipment with high heat flux such as boiler, evaporator, electronic equipment, rocket engines, and so on. The critical or burnout heat flux enhancement of nanoparticle suspensions (nanofluids) depends on the particle concentration, pH of the solution, as well as on the deposition of the particles on the suspended heater surface. It is long back proven that addition of solid particle in base fluid can alter its boiling heat transfer performance. For example, Yang and Maa [1] first used nano-sized Al_2O_3 particles of as small as 50 nm in water to study the pool boiling heat transfer characteristics. They found significant increase in pool boiling performance for very small volumetric concentrations (0.1–0.5%) of nanoparticles. After nanofluids emerged, a growing number of research groups have come forward to study the boiling heat transfer characteristics of nanofluids, and it is timely to review their research findings.

An early study by You et al. [45] showed a threefold increase in critical heat flux (CHF) for Al_2O_3/water nanofluid with a flat plate heater. For Silica nanofluids, similar threefold enhancement in CHF was also later reported by Milanova and Kumar [46]. Das et al. [47] reported deterioration of boiling heat transfer of water in the presence of Al_2O_3 nanoparticles in it. Their outcome was partially attributed to the properties of the nanofluid, boiling surface, and interaction between the two. In contrast to Das et al. [47], Wen and Ding [48] showed that the enhancement of pool boiling heat transfer of the same Al_2O_3/water-based nanofluid was about 40% at 1.25 wt.% of particle loading. In another study, Witharana [49] investigated the boiling heat transfer performance of two types of Au- and SiO_2-laden aqueous nanofluids in a cylindrical vessel under atmospheric pressure. They found that the boiling heat transfer increases for Au nanofluid and decreases for SiO_2 nanofluid. These conflicting results are not well explained.

Prakash et al. [50] performed experiments to quantify the effect of heater surface roughness on pool boiling heat transfer of Al_2O_3/water-based nanofluids. They showed that while the rough heater surface increases heat transfer, smooth surface significantly deteriorates the heat transfer. For example, for rough heater surface, the heat transfer enhancement was about 70% at 0.5 wt.% concentration of alumina nanoparticles. Whereas for smooth heater, the heat flux reduction reaches up to 45% at a particle concentration of 2 wt.%. Soltani et al. [51] investigated the pool boiling heat transfer performance of Newtonian nanofluids under various heat flux densities. In their study, γ-Al_2O_3 (20–30 nm)/water- and SnO_2 (55 nm)/water-based nanofluids were used in a vertical cylindrical glass vessel. Their results showed that except for low concentrations (>0.5 wt.%) of SnO_2 nanoparticles, the boiling heat transfer coefficients of these nanofluids increase with increasing concentration of nanoparticles. These paradoxical results were attributed to the differences in thermal conductivity and size of these two nanoparticles. Recently, Truong et al. [52] conducted pool boiling experiments of diamond, ZnO, and Al_2O_3 nanoparticles–laden aqueous nanofluids with modification of sandblasted as well as bare plate heaters. They found up to 35% increase in CHF for precoated heaters compared to those of bare plate and sandblasted heaters.

Among few studies on flow boiling characteristics of nanofluids, Kim et al. [53] found about 50% enhancement in boiling critical heat flux for Al_2O_3/water nanofluids flowing through a vertical stainless steel tube. Very recently, a flow boiling experiment with two refrigerant-based nanofluids was performed by Henderson et al. [54]. In their study, SiO_2/R-134a and CuO/mixture of R-134a and polyolester oil (PO) nanofluids were used in horizontal copper tube. Results showed that while the boiling heat transfer coefficient (BHTC) of SiO_2/R-134a nanofluid decreases up to 55% compared to pure R-134a, the BHTC of CuO/(R-134a+PO) nanofluid increases more than 100% compared to its base fluid (i.e., R-134a+PO).

A summary of studies on boiling heat transfer of nanofluids is presented in Table 14.2. It can be noticed from this table that despite some inconsistent and contradictory results, most of the researchers used alumina nanofluids. However, few studies have been reported on the boiling heat transfer of CNT nanofluids which exhibit much higher thermal performance compared to those of other nanofluids [9, 10]. Thus, there is a need to conduct more investigations on boiling heat transfer of CNT nanofluids.

A comparison of heat flux versus superheat results from various groups is shown in Fig. 14.6. From these representative results (Fig. 14.6), it can clearly be seen that heat flux (also critical heat flux) data relative to superheat reported by various research groups vary widely. This is probably due to the differences in characterization of nanofluids, different size and concentration of nanoparticles used, and different types of heaters used in various research groups. Although some research groups observed deterioration of boiling heat transfer of nanofluids, the significant increase in the critical heat flux in boiling of nanofluid is still undisputed.

Table 14.2 Summary of pool boiling experiments with nanofluids

Researchers	Heater	Nanofluids	Remarks
Yang and Maa [1]	Horizontal tube heater	Al_2O_3/water	Heat flux increases considerably
Witharana [49]	Cylindrical vessels	Au and SiO_2/ water and EG	Heat transfer increases for Au nanofluids but it decreases for SiO_2
Das et al. [47]	Cylindrical cartridge	Al_2O_3/water	The heat transfer deteriorates
You et al. [45]	Cartridge	Al_2O_3/water	The CHF increases up to 200%
Vassallo et al. [55]	NiCr wire	SiO_2/water	The CHF increases significantly
Bang and Chang [56]	Square flat heater	Al_2O_3/water	Pool boiling heat transfer deteriorates but CHF increases
Wen and Ding [48]	Flat disk heater	Al_2O_3/water	The BHTC increases up to 40% at 1.2 wt.% of nanoparticle
Kim et al. [57]	NiCr wire heater	TiO_2/water	The CHF increases up to 200%
Jackson [58]	Flat copper coupon heater	Au/water	While the heat transfer decreased about 20%, the maximum CHF increase was five times over water
Prakash et al. [50]	Vertical tubular heaters	Al_2O_3/water	While rough heater surface increases heat transfer, smooth surface significantly deteriorates
Chopkar et al. [59]	Flat surface	ZrO_2/water	Enhanced boiling heat transfer is found at low particle concentration
Lv and Liu [60]	Vertical small heated tubes	CuO/water	The CHF increases only for surfactant-free nanofluids
Kathiravan et al. [61]	Horizontal tube	CNT/water	The BHTC increases up to 1.75 folds for 0.25 vol.% of CNT
Soltani et al. [51]	Vertical cylindrical glass vessel	Al_2O_3 and SnO_2/ water	Except for low concentrations (>0.5 wt.%) of SnO_2, the BHTC increases with loading of nanoparticles
Truong et al. [52]	Sandblasted and bare horizontal plate heaters	Diamond, ZnO, and Al_2O_3/ water	The CHF of the precoated heaters increased by up to 35% with respect to that of sandblasted heaters.

14.3.2 Pool Boiling Study with Carbon Nanotubes–Nanofluids

For pool boiling experiments, sample nanofluids were prepared by suspending high purity single-walled carbon nanotubes in deionized water. As a part of surface treatment, CNT bundles were refluxed with hydrochloric acid at 100°C for several hours. This acid was chosen as a reactive reagent because it removes catalytic

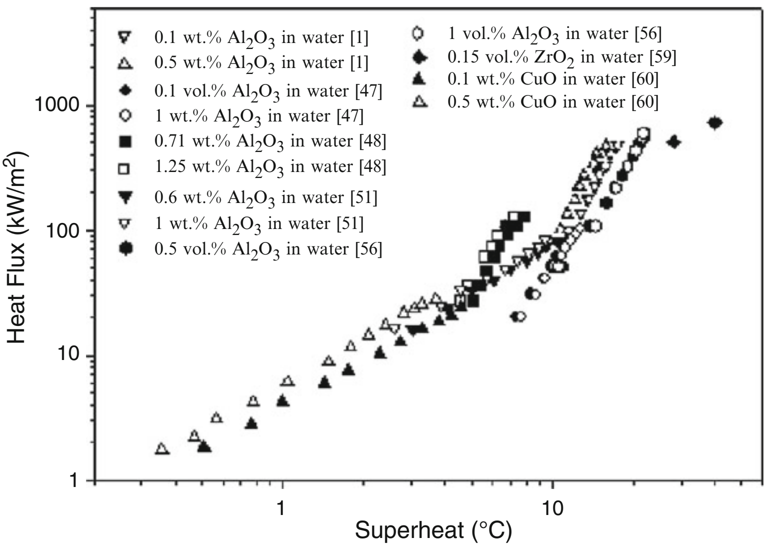

Fig. 14.6 Comparison of heat flux versus superheat results from various research groups

particles without reducing the length of the tubes or damaging the side walls. Different concentrations of sodium dodecylbenzenesulfonate (NaDBS) surfactant are used as dispersing agent for nanotubes in water. Details of the experimental facilities and procedures are reported in previous studies [62, 63].

Representative results from previous study [62] on surfactant concentration–dependent pool boiling experiments of CNT nanofluids are presented and discussed. The critical heat flux (CHF), which is the sudden jump in temperature at the same heat flux, is determined at constant 0.1% volumetric loading of CNT and for various concentrations of NaDBS surfactant. The results of boiling heat flux with respect to superheat (wire temperature minus saturation temperature of liquid, $T_w - T_s$) are presented and compared with the one for pure deionized water in Fig. 14.7. The NaDBS surfactant to CNT concentrations were varied from 1:20 to 1:1. Figure 14.7 demonstrates that the CNT nanofluid with any concentration of surfactant exhibits higher CHF value than that of base fluid. The CHF value of deionized water is 750 kW/m^2. The effect of increasing the surfactant concentration from 1:20 to 1:5 (NaDBS:CNT) results in increase of CHF value. However, if the concentration of surfactant is further increased from 1:5 to 1:1, the CHF drops drastically from 4,439 to 1,322 kW/m^2. There is, therefore, a critical concentration of surfactant for which the CHF reaches to maximum value. The highest CHF value is obtained for the concentration ratio of 1:5. The deposition of nanoparticles on the heater wire is believed to be one of the main reasons for any enhancement in CHF of this nanofluid. Kim et al. [64] also claimed that the deposition of nanoparticles on the heater wire is the main reason

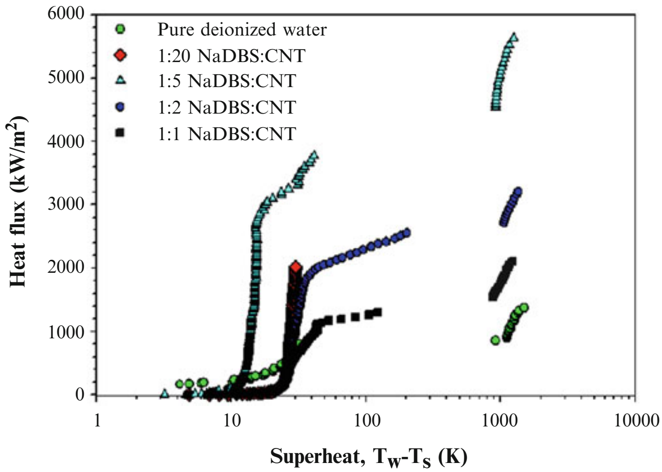

Fig. 14.7 Effect of surfactant concentration on heat flux of SWCNT nanofluid

for any enhancement in CHF of nanofluids. Nevertheless, results indicate that nanofluids boiling performance can further be enhanced by adding suitable type and concentration of surfactant in it and thus surfactant-added nanofluids show great promises as advanced coolants.

14.3.3 Studies on Droplet Spreading of Nanofluids

Besides fascinating conduction and convective heat transport properties, studies on boiling heat transfer of nanofluids indicated that nanofluids could be very promising for enhanced spray cooling systems. Very recently, authors investigated the spreading characteristics of a nanofluid droplets impinging on a metallic substrate under the influence of several key factors such as nanoparticle volume fraction, substrate temperature, and Weber number [65]. Results showed that the transient spreading diameter and height of droplet impacting onto solid surface are greatly influenced by each of these factors. Such droplet impingement study on heated substrate surface is of great importance to exploit the practical application of nanofluids as an advanced coolant in many industrial processes, particularly in spray cooling and coating. Unfortunately, scant work has been performed on droplet impingement dynamics of nanofluids on solid surfaces under various conditions. Among such studies, Wasan and Nikolov [66] were the first to investigate the effects of the particle structure formation and the structural disjoining pressure of nanoparticles on the spreading of nanofluids on solid surface. Duursma et al. [67] studied the effect of aluminum nanoparticles on droplet boil-off by allowing nanofluid drops to fall onto a copper surface at temperature higher than the liquid saturation temperature.

They demonstrated that increase in surface temperature and Weber number promotes the receding breakup scenario, while an increase in the nanoparticle concentration discourages this breakup. The influence of surface temperature on the hydrodynamic characteristics of water and nanofluid droplets impinging on a polished and nanostructured surface was investigated by Shen et al. [68]. Their results showed that SWCNT nanofluid has larger spreading diameter compared to that of deionized water, and use of a nanofluid or a nanostructured surface can reduce the total evaporation time up to 37%. Nevertheless, more studies are needed on dynamics of both nonboiling and boiling droplet impingement of nanofluids on solid surfaces as the spreading of liquid droplet plays a key role in many industrial processes like spray cooling, coating, ink-jet printing, and oily soil removal.

14.4 Conclusions

In this chapter, an exhaustive review on major cooling features such as convective and boiling heat transfers as well as droplet spreading dynamics of nanofluids together with some representative results from own experimental investigations on these areas are presented and analyzed. Reported literature review and representative results on convective heat transfer studies demonstrated that nanofluids exhibit considerably enhanced convective heat transfer coefficient compared to their base fluids, and the Nusselt number increases significantly with increasing concentration of nanoparticles as well as with the Reynolds number. Thus, nanofluids have great potential to be used as next-generation coolants.

From the review of available results on boiling heat transfer of nanofluids, it can be conferred that despite of contradictory and inconsistent data, there is undisputed substantial increase in the critical heat flux of nanofluids compared to their base fluids. However, reported data are still limited and scattered to clearly understand the underlying mechanisms as well as trend of boiling heat transfer characteristics of nanofluids. The effects of deposition of nanoparticles or tubes on heat transfer surface, surfactant concentration, and surface wettability are commonly identified as responsible for the observed boiling heat transfer results of nanofluids. Representative results of our previous investigations on pool boiling heat transfer of CNT nanofluid showed that large enhancement of boiling heat flux is possible and would depend on the concentration of the surfactants. This indicates that the boiling as well as cooling performance of nanofluids can further be enhanced by adding a suitable surfactant at proper concentration.

Studies on droplet spreading, nanofluids showed their potential for industrial processes like spray cooling, coating, and ink-jet printing. However, more extensive studies are needed on dynamics of boiling nanofluid droplets impinging on solid surfaces in order for their exploitation as advanced media for spray cooling.

Despite of controversies and scattered data on all these thermal features, nanofluids exhibit remarkably enhanced conductive, convective, and boiling heat transfer performance compared to their base fluids and thus are very useful for applications as advanced coolants. However, the progress toward fully understanding the mechanisms behind these enhanced conduction, convection, and boiling heat transfer features of nanofluids as well as their development for commercial applications as future coolant remain challenging task.

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