# Fundamental issues, technology development and challenges of boiling heat transfer, critical heat flux and two-phase flow phenomena with nanofluids

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FUNDAMENTAL ISSUES, TECHNOLOGY DEVELOPMENT AND CHALLENGES OF BOILING HEAT TRANSFER, CRITICAL HEAT FLUX AND TWO-PHASE FLOW PHENOMENA WITH NANOFLUIDS

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*Abstract*

*This paper presents a comprehensive and critical review of studies on nucleate pool boiling heat transfer, flow boiling heat transfer, critical heat flux (CHF) and two-phase flow phenomena with nanofluids. First, general analysis of the available studies on the relevant topics is presented. Then, studies of physical properties of nanofluids are discussed. Next, boiling heat transfer, CHF phenomena and the relevant physical mechanisms are explored. Finally, future research needs have been*

*identified according to the review and analysis. As the first priority, the physical properties of nanofluids have a significant effect on the boiling and CHF characteristics but the lack of the accurate knowledge of the physical properties has greatly limited the studies. Fundamentals of boiling heat transfer and CHF phenomena with Nanofluids have not yet been well understood. Flow regimes are important in understanding the boiling and CHF phenomena and should be focused on. Two phase pressure drops of nanofluids should also be studies. Furthermore, economic evaluation of the enhancement technology with nanofluid should be considered for the new heat transfer enhancement technology with nanofluids. Finally, applied research should be targeted to achieve an enabling practical heat transfer and CHF enhancement technology for engineering application with nanofluids.*

**Introduction**

Over the past decade, numerous research has been conducted on nanofluid two-phase flow and thermal physics [1-3]. Due to very complicated physical phenomena, the fundamentals and mechanisms of boiling heat transfer, two phase flow and critical heat flux (CHF) phenomena with nanofluids are not well understood so far. There are quit contradictory experimental results and mechanisms from one group to another. No agreed physical mechanisms and theory are available from the existing research and no prediction methods and models for boiling heat transfer, CHF, flow regimes and two-phase pressure drops with nanofluids are available. [1, 2, 4-6]. As a new frontier interdisciplinary research subject, there are many challenges in the fundamental knowledge, the physical mechanisms and theory of nanofluid two phase flow, boiling heat transfer and CHF [1]. Furthermore, due to the deposition of nanoparticles on the heat transfer surface reported by many researchers, there are also big challenges of the practical applications in boiling heat transfer and two-phase flow with nanofluids although some patents have been reported [7]. It is

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important to avoid fouling on the heat transfer surface when developing a new heat transfer enhancement technology. Therefore, it is essential to conduct a comprehensive review on the relevant research topics and to identify future fundamental research and technology development needs which are the objectives of this comprehensive review paper.

Nanofluids are engineered colloids made of a base fluid and nanoparticles (1-100 nm). Common base fluids include water, organic liquids (e.g. ethylene, tri-ethylene-glycols, refrigerants, etc.), oils and lubricants, bio-fluids, polymeric solutions and other common liquids [1-3]. Materials commonly used as nanoparticles include chemically stable metals (e.g. gold, copper), metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g. $Al_2O_3$, CuO), metal carbides (e.g. SiC), metal nitrides (e.g. AlN, SiN), carbon in various forms (e.g., diamond, graphite, carbon nanotubes, fullerene) and functionalized nanoparticles.

It is the first and most important thing to understand the physical properties of nanofluids which are the basis for investigating two phase flow, boiling heat transfer and CHF with nanofluids. Initially, numerous studies have mainly focused on thermal conductivities of nanofluids by taking the advantage of the very high thermal conductivities of solid nanoparticles. Table 1 presents a summary of the thermal conductivities of the nanoparticle materials and the base fluids used in nanofluids. The solid nanoparticle materials have much higher thermal conductivities than those of the base fluids, with the carbon nanotubes having the highest thermal conductivity up to 6600 W/mK. Addition of small amount of nanoparticles in the base fluids is used to enhance the thermal conductivities of the nanofluids. However, other physical properties such as viscosity, specific heat, latent heat of evaporation, surface tension and contact angle etc. have been less investigated, but they are critical in understanding the complicated two-phase flow, boiling heat transfer and CHF

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phenomena. Studies of nucleate pool boiling heat transfer, flow boiling heat transfer and CHF phenomena with nanofluids have been extensively conducted in recent years. However, without proper and accurate knowledge of the relevant physical properties, it is very difficult to obtain reliable experimental results and knowledge of the two-phase flow, boiling heat transfer and CHF phenomena and to further develop relevant reliable physical mechanisms and theory. There are big challenges in understanding the fundamentals and mechanisms of two phase flow, boiling heat transfer and CHF with nanofluids due to the lack of physical properties. Quite controversial and contradictive results and mechanisms have been obtained from different studies in the literature [1, 2, 4-6]. Without proper methods to predicting the physical properties of nanofluids, the pure numerical work of nanofluids fluid flow and heat transfer is difficult to trust although many such kind of studies have been conducted and published. Furthermore, without complete and accurate knowledge of thermal physical properties such as thermal conductivity, surface tension, specific heat, latent heat of evaporation and contact angle etc., it is difficult to obtain reliable experimental results of two phase flow, flow regimes, two phase pressure drop, boiling heat transfer and CHF with nanofluids and to develop the relevant prediction methods and models. Particularly, it is impossible to obtain complete and systematic knowledge, mechanisms and theory in this new subject. Furthermore, it is essential to put the heat transfer enhancement research with nanofluids into practical engineering application and consider the economic feasibility in technology development.

Furthermore, applying nanofluids in the frontier research in two phase flow, flow boiling heat transfer and CHF in microchannels is another interesting research subject but there are also big challenges in this aspect. In recent years, two phase flow and flow boiling

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in microchannels have become one of the most important research topics, which can achieve high heat transfer performance and be used in high heat flux cooling technology [8-13]. Enhancement of boiling and CHF is important in improving energy efficiency and operation safety in various applications [14]. One of such methods is to use nanofluids as working fluids in various engineering and industrial applications to enhance boiling heat transfer and CHF in microchannels and confined spaces [15, 16]. However, the studies of fundamentals and physical mechanisms of nanofluid two phase flow, heat transfer and CHF of nanofluids in microchannels are rare. Nanofluids have a unique feature which is quite different from those of conventional solid-liquid mixtures in which millimetre and/or micrometer-sized particles are added. Such particles settle rapidly, clog flow channels, erode pipelines and cause severe pressure drops. All these shortcomings prohibit the application of conventional solid-liquid mixtures to microchannels while nanofluids instead might be used in two phase flow and flow boiling in microchannels. In this light, nanofluids appear promising as coolants for dissipating very high heat fluxes in various applications such as cooling electronic chips through utilizing the latent heat during flow boiling in microchannels [8-13]. However, it is still necessary to assess if nanofluids can be used in microchannel or not due to the effects of the channel confinement on two phase flow and flow boiling. In the aspect of enhancement of boiling heat transfer and CHF, compared to nucleate pool boiling heat transfer enhancement with addition of small amount of surfactants, nanofluids can enhance CHF while surfactants normally do not [1, 2, 17]. It seems that nanofluids may significantly enhance CHF in both nucleate pool boiling and flow boiling processes as it might be an important method to enhance CHF and have potential applications in various industries. It is essential to understand the fundamentals and mechanisms of two phase flow, flow regimes,

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two phase pressure drop, flow boiling heat transfer and CHF and the corresponding physical mechanisms with nanofluids in microchannel.

According to the existing research regarding the physical properties and single phase and two phase heat transfer behaviours of nanofluids in the literature, the characteristics of nanofluids are summarized as follows:

a) Nanofluids have larger thermal conductivities compared to the base fluids.

b) The thermal conductivities of Nanofluids strongly depend on temperature.

c) Nanofluids enhance or reduce the specific heat.

d) Nanofluids enhance or reduce the latent heat of evaporation.

e) Nanofluids enhance or reduce single phase heat transfer.

f) Nanofluid enhance or reduce nucleate pool boiling heat transfer.

g) Nanofluids enhance or reduce nucleate pool boiling CHF.

h) Nanofluids enhance or reduce flow boiling heat transfer.

i) Nanofluids enhance or reduce flow boiling CHF.

j) Nanoparticles deposit in the heat transfer surface.

k) Nanoparticles aggregate

Furthermore, some contradictory observations and experimental results in boiling heat transfer and CHF phenomena and physical mechanisms have been found in the literature [1, 2, 16]. Therefore, studies on boiling heat transfer and CHF heat transfer phenomena and physical mechanisms, prediction methods and models and practical applications are strongly needed. According to the available studies, several challenges in the relevant research are summarized as follows:

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a) The lack of agreement between experimental results of boiling heat transfer and CHF from different research groups.

b) The lack of theoretical understanding of the underlying mechanisms with respect to nanofluid two phase flow, boiling heat transfer and CHF.

c) The lack of understanding of the effects of nanoparticle sizes, materials, shapes and concentrations on the boiling heat transfer and CHF behaviors and mechanisms.

d) The lack of understanding of channel size effects on the boiling heat transfer and CHF behaviors and mechanisms with nanofluids.

e) The lack of physical and mathematical models for predicting the boiling heat transfer coefficient and CHF due to the poor understanding of the physical mechanisms and disagreed results.

f) The lack of practical applications in thermal engineering so far although the research has been performed for many years.

g) What should we do next for the fundamental research in understanding the complicated two-phase flow, boiling heat transfer and CHF phenomena with nanofluids?

h) Where should we go with application with nanofluids and nanotechnology in thermal physics and engineering?

As a new interdisciplinary research frontier subject of nanotechnology, two-phase flow, thermal physics and engineering heat transfer, there are still big challenges of fundamental research and applications of boiling heat transfer, two phase flow and CHF with nanofluids. In this review paper, the relevant issues of fundamentals, mechanisms and technology development of boiling heat

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transfer, two phase flow and CHF are reviewed and analyzed. Furthermore, future research and technology development needs have been identified.

**Thermal physical properties of nanofluids**

Nucleate pool boiling heat transfer, flow boiling heat transfer, CHF, two-phase flow regimes and two-phase pressure drop characteristics with nanofluids strongly depend on the accurate knowledge of thermal physical properties such as thermal conductivity, specific heat, latent heat of evaporation, density, surface tension, contact angle and surface conditions such as materials and the surface roughness. Furthermore, development of relevant prediction methods and numerical simulations of complicated two-phase flow and heat transfer with nanofluids rely on proper thermal physical properties. Without proper knowledge of the thermal physical properties, the experimental and computational results are unreliable. Therefore, thermal physical properties are the first and most important in studying nanofluid two phase flow and thermal physics and engineering application.

Over the past decade, a number of studies on the thermal properties of nanofluids have mainly focused on the thermal conductivities of nanofluids. Some studies have concerned the viscosities of nanofluids while several studies have focused on the specific heat of nanofluids. Recently, limited studies have concerned the latent of heat of evaporation of nanofluids. However, many factors can affect the physical properties of nanofluids, such as material of nanoparticles, surfactants, nanoparticle size and concentration etc. Furthermore, there are no general methods and models for predicting these important physical properties. Some researchers measured the surface roughness of the heat transfer surface due to the nanoparticle deposition on the heat transfer surface. Several studies have reported the measured surfaces tension and contact angles, but there

are very limited studies and no systematic knowledge and calculation methods for these physical properties.

Although several calculation methods and models have been proposed for some physical properties such as thermal conductivities and specific heats, there are no generalized calculation methods and models which are applicable to all types of nanofluids. Even for the same type of nanofluid, there are no agreed prediction methods and models for the physical properties due to the effects of nanoparticle size, shape and concentration. Furthermore, for some physical properties such as specific heat, latent heat of evaporation, surface tension and contact angle, the available research is very limited in the literature and there are also contradictive results for the limited available research. Systematical and accurate knowledge and theory have not yet established. However, these physical properties are critical in understanding the fundamentals and mechanisms of the two-phase flow, boiling heat transfer and CHF behaviors. These important physical properties are far from understanding. Furthermore, the relevant calculation methods and models are limited. Even for the available prediction methods and models in the literature, they are not applicable to other different nanofluids. The poor understanding of the important physical properties of nanofluids prevent from achieving complete and accurate knowledge of the boiling heat transfer, two phase flow regimes, pressure drop, CHF and the physical mechanisms. It is therefore essential to review and analyze the available studies on the relevant thermal physical properties of nanofluids at first and to further identify the research needs in future.

### Research on thermal conductivities of nanofluids

Thermal conductivity is an important physical property which has been extensively investigated over the past decade. As shown in Table 1, thermal conductivities of solids are several orders of magnitude larger than those of conventional heat transfer fluids. By suspending

nanoparticles in conventional heat transfer fluids, the thermal conductivities of the nanofluids can be significantly improved. It is expected that the heat transfer performance would be significantly enhanced. The following points may be used to explain the heat transfer enhancement behavior with nanofluids:

a) The suspended nanoparticles increase the surface area and the heat capacity of the fluid

b) The suspended nanoparticles increase the effective (or apparent) thermal conductivity of the fluid.

c) The interactions and collision among particles, fluid and the flow passage surface are intensified.

d) The mixing and turbulence of the fluid are intensified.

e) The dispersion of nanoparticles enabling a more uniform temperature distribution in the fluid.

f) For boiling heat transfer and CHF, the nanoparticles possibly increase the specific heat and the latent heat of evaporation, which still needs to be investigated.

Numerous studies of enhancement of thermal conductivities of various nanofluids have been extensively conducted [18-26], just to list a few here. Substantially increased thermal conductivities of nanofluids containing a small amount of metal, like Cu, Fe, or metal oxide, like $SiO_2$, $Al_2O_3$, $WO_3$, $TiO_2$ and CuO and other nanoparticles have been reported in the literature. Eastman et al. [18] have found that a small amount (about 0.3 % by volume fraction) of copper nanoparticles of mean diameter < 10 nm in ethylene glycol increased this fluid's inherently poor thermal conductivity by 40%. Figure 1 shows their results for the effective thermal conductivity of ethylene glycol. The largest increase in thermal conductivity was obtained for a nanofluid which contained a small quantity of

thioglycolic acid to improve the stability of the metallic particles against settling. Their experimental results show that the nanofluids have substantially higher thermal conductivities compared to the base fluid. The nanofluid thermal conductivity increases with the nanoparticle volume fraction.

In general, metallic nanofluids show much more dramatic enhancements than metallic oxide nanofluids. Furthermore, nanofluid thermal conductivities are also strongly dependent on temperature [21, 26]. Particle size, shape and volume concentration also influence the thermal conductivity of nanofluids [19-21, 26]. Hong et al. [23] have concluded that thermal conductivity of a Fe nanofluid is increased nonlinearly up to 18% as the volume fraction of particle is increased to 0.55 vol. %. Comparing Fe nanofluids with Cu nanofluids, they found that the suspension of highly thermally conductive materials is not always effective.

Due the unique structure and remarkable mechanical and electrical properties of Carbon nanotubes (CNTs) [27, 28], CNTs have been extensively investigated to act nanoparticles for nanofluids. CNTs have unusually high thermal conductivity up to 6600 W/mK compared to 0.08 W/mK of a liquid refrigerant [28-31]. CNTs can thus enhance the thermal conductivity of nanofluids and heat transfer characteristics [32-37]. The first reported work on a single walled carbon nanotube (SWCNT)-polymer epoxy composite by Biercuk et al. [28] demonstrated a 70% increase in thermal conductivity at 40 K, rising to 125% at room temperature with 1 wt.% nanotube loading. They also observed that thermal conductivity increased with increasing temperature. Figure 2(a) shows the scanning electron microscope (SEM) image of carbon nanotube samples of single-walled nanotubes obtained by arc discharge [28] and Figure 2(b) shows the SEM of multiwalled carbon nanotubes obtained by chemical vapor deposition [32]. CNTs have a very high aspect ratio. CNTs from a highly entangled fiber network are not very mobile, as demonstrated by the viscosity measurements, and thus their effect on the thermal transport in fluid suspensions is expected to be similar to that of polymer composites. Hone et al. [29] reported that the thermal conductivity of SWCNTs was linear in

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temperature from 7 K to 25 K, increased in slope between 24 K and 40 K, and then rose monotionically with temperature to above room temperature. Berber et al. [30] reported an unusually high thermal conductivity of carbon nanotubes, reaching 6600 W/mK at room temperature. Kim et al. [31] reported that the thermal conductivity of individual multiwalled nanotubes reached 3000 W/mK at room temperature. Choi et al. [32] measured thermal conductivities of oil suspensions containing multiwalled carbon nanotubes up to 1 vol.% loading and found similar behavior, in this case, a 160% enhancement as shown in Fig. 3. The thermal conductivity of nanotube suspensions (solid circles) is one order of magnitude greater than predicted by the existing models (dotted lines). The measured thermal conductivity of nanotube suspensions is nonlinear with nanotube volume fraction, while theoretical predictions show a linear relationship (inset), which is thus significantly contradictive to what is expected. With increasing of concentration, the thermal conductivity is greatly increased. Xie et al. [33] found a 10-20% enhancement of effective thermal conductivities of CNT suspensions in distilled water and ethylene glycol. Several other researchers have also concluded research on the enhancement of thermal conductivity of CNT nanofluids in their studies [34-37]. The existing thermal conductivity models for conventional solid/liquid systems have been used to estimate the effective conductivities of nanofluids due to the absence of a theory for thermal conductivities of nanofluids. For example, the Hamilton and Crosser [38] model has been applied to nanofluids. However, measured thermal conductivities are substantially greater than theoretical predictions [24, 31-34]. Therefore, it is essential to develop new models for nanofluid thermal conductivities.

Physical mechanisms for the enhanced effective thermal conductivity of nanoparticle suspensions have been investigated. One of the possible mechanisms is that the Brownian motion of the nanoparticles in these suspensions contributes to the thermal conductivity enhancement [22, 24]. Several theoretical studies have been conducted to account for the higher thermal conductivity considering other various factors [22, 24, 26, 39-44]. For example, Jang and Choi [22] devised a theoretical model which accounts for the fundamental role of the dynamics of nanoparticles in

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nanofluids. The model not only captures the concentration and temperature-dependent effects, but also predicts a strong size-dependent influence.

In the aspect of the heat transfer enhancement with nanofluid, Jang and Choi [24] proposed four potential mechanisms for the anomalous increase in nanofluid heat transfer: (i) Brownian motion of nanoparticles, (ii) ballistic phonon transport inside nanoparticles, (iii) interfacial layering of liquid molecules and (iv) nanoparticle clustering. However, it is a challenge to develop a theoretical thermal conductivity model according to these mechanisms because many factors may play a role in the physical mechanisms which have not yet been well understood. According to the existing research on the physical mechanisms of thermal conductivity enhancement, it is essential to consider the physical properties of the nanoparticles and the base fluids, key factors and applied conditions which can significantly affect the thermal conductivities of the nanofluids when developing a thermal conductivity model These should include the nanoparticle material thermal conductivity, nanoparticle size, shape and volume fraction, base fluid thermal conductivity, nanoparticle thermal conductivity, temperature, surfactants used to stabilize the nanofluids and pH of the nanofluids etc. Furthermore, the contribution of the Brownian motion is directly related to other parameters of the nanofluids, such as the diffusion velocity of the base fluids and the particle agglomeration of the nanofluids.

In order to understand the controlling factors for proposing new models, Keblinski et al. [39] and Eastman et al. [40] have proposed four main mechanisms for the thermal conductivity enhancement for nanofluids: (i) Brownian motion of nanoparticles, (ii) Formation of layers at the interface between the nanoparticle and the base fluid, (iii) Particle clustering effect and (iv) The ballistic nature of the thermal transport of the nanoparticles. Of the four physical mechanisms, understanding the ballistic nature of nanoparticles is very important because of the lack of validity of the thermal diffusion hypothesis in the nanofluids. The nanoparticle size is so small that the phonon heat transfer mechanisms are assumed in the thermal diffusion change from a randomly scattered

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diffusion to a ballistic behavior. The smaller the nanoparticles of nanofluids, the higher are the ballistic phonon transport mechanisms for the nanofluids. Therefore, the validity of any macroscopic approach to the nanofluids properties is limited by this restriction and such studies are very limited in the literature. Furthermore, other physical mechanisms have also been investigated to account for the nanofluid thermal conductivity enhancement, such as the variation of the pH of the fluid and the transient conduction which may be responsible for the thermal conductivity enhancement [41-43].

Although extensive studies on thermal conductivity enhancement of nanofluids have been conducted, the fundamental knowledge and the physical mechanisms of thermal conductivity enhancement with nanofluids have not yet well been understood. No concrete conclusions have been reached that prove which is/are the controlling mechanisms. Further research is needed to develop a suitable model to predict the thermal conductivity of nanofluids and should take account of the important molecular and nano-mechanisms that are responsible for enhancing the thermal conductivity of nanofluids. In fact, fundamental studies should be performed to provide improved insight into the mechanisms of the thermal conductivity of nanofluids. Furthermore, since nanoparticles can form nano or microstructures, the thermal conductivity of such a nanofluid under static conditions could be quite different under flow conditions. It is also important to set up large database of thermal conductivities with nanofluids in order to achieve a generalized prediction model which might be applicable to all nanofluids, if not all, to most nanofluids at least. Apparently, it is still a long way to go to achieve such a model due to the complicated and variety of nanofluids and many controlling factors involved.

### *Research on the viscosities of nanofluids*

Viscosity is another important physical property in investigating the two-phase flow, flow regime, two phase pressure drop, boiling heat transfer and CHF phenomena with nanofluids. Nanofluids may show Newtonian and/or Non-Newtonian behaviour depending on the nanoparticle

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material, size and shape, the volume percentage of particles, temperature, surfactants and the methods used to disperse and stabilize the nanoparticle suspension. Several studies have reported the measured viscosities of nanofluids which show quite different behaviors. The viscosities of nanofluids are normally much higher than that of their base fluids. Viscosity is a strong function of temperature and the volumetric concentration of nanoparticles while the particle-size effect seems to be important only for sufficiently high particle fractions.

Kilkarni et al. [45] measured the rheological behavior of copper oxide nanoparticles dispersed in a 60:40 propylene glycol and water mixture, with particle volumetric concentrations from 0 to 6% at temperatures from -35 to 50°C. The nanofluids exhibited a Newtonian fluid behavior. However, quite different rheological behavior was found with different types of nanofluids in another study from the same research group. Kulkarni et al. [46] measured the rheological behavior of CuO-water nanofluids with volumetric concentrations of 5 to 15% at temperatures from 278 to 323 K. These nanofluids showed time-independent, shear thinning, pseudo-plastic non-Newtonian fluid characteristics. They proposed a correlation to predict the viscosity of these nanofluids as a function of temperature and the volumetric concentration based on their own data. It seems the proposed correlation work well for their own experimental viscosity data. However, the model may not be applicable to other nanofluids and conditions due to different behaviors of various nanofluids.

Nguyen et al. [47] investigated the effects of temperature and particle volume concentration on the dynamic viscosity of water-$Al_2O_3$ nanofluids at temperatures from 22 to 75°C. They found a hysteresis phenomenon of the measured viscosities as shown in Fig. 4. For a given particle volume concentration, there is a critical temperature beyond which nanofluid viscous behavior becomes drastically altered. If a fluid sample is heated beyond such a critical temperature, a striking increase of viscosity occurs. If it is cooled after being heated beyond this critical temperature, then a hysteresis phenomenon occurs. Such an intriguing hysteresis phenomenon and mechanisms are poorly understood. Furthermore, the critical temperature was found to be strongly dependent on both

particle fraction and size. It is unknown if this phenomenon exists for all other nanofluids as no such phenomenon was reported by other research groups. With limited nanofluids, it is difficult to reach a general conclusion with respect to viscosity hysteresis. In the practical application, both heating and cooling may occur. This raises a question: how could the viscosity be modeled for the practical calculation? It is thus essential to understand the physical mechanisms of such a hysteresis and to identify if it exists for other nanofluids.

Ding et al. [37] measured the viscosity of water based CNT nanofluids. They found that the viscosity of CNT nanofluids increased with increasing the CNT concentration and decreasing temperature. Figure 5 shows their viscosity measurements for CNT nanofluids at pH = 6. The CNT nanofluid exhibits non-Newtonian characteristics with a shear thinning behavior. A non-linear relationship occurs at high shear rates.

With respect to the theoretical model for viscosity of solid-fluid mixtures, the effective viscosity of a fluid containing a dilute suspension of small particles is given by the classic Einstein equation [48]:

$$\mu_{mix} = \mu_f \left( 1 + \frac{5}{2} \phi \right)$$

(1)

where $\mu_{mix}$ is the viscosity of the mixed fluid, $\mu_f$ is the viscosity of ambient fluid and $\phi$ is the volume fraction of spheres in the suspension. However, the experimentally measured nanofluids viscosities deviate from the classical model because these models relate viscosity as a function of volume concentration only. There is no consideration of temperature dependence and particle aggregation in this model. Therefore, it is important to understand the controlling factors and parameters which may affect the viscosities of nanofluids through systematic measurement of various nanofluids. Such a systematic knowledge is still not available. Furthermore, the physical mechanisms of the different viscosity behaviours of nanofluids have not yet well understood. These can limit the development of reliable models and prediction methods for nanofluids.

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Although several models and prediction methods have been developed for the viscosities of nanofluids, there are big discrepancies of the measured viscosities and the calculated values for other nanofluids. This is mainly due to the controlling factors which may significantly affect the fluid behaviours, such as nano-particle materials, nanoparticle size and shape, the concentration, pH and temperatures etc. Particularly, these models and methods were only developed according to their own measured viscosity data and test conditions. In general, they are unable to be extrapolated to other nanofluids and conditions. Furthermore, quite different non-Newtonian behaviours of nanofluids may occurs for some nanofluids while Newtonian behaviour may occur for other nanofluids. Therefore, it is quite difficult to propose a generalized model for all nanofluids, but effect should be made to achieve a unified model for some nanofluids with similar behaviours such as Newtonian fluids and the same type of non-Newtonian fluids.

In general, no systematic theory and a generalized model are available for the viscosities of nanofluids. There are many factors which may significantly affect the viscosity of nanofluids such as the nanoparticle shapes and sizes, materials and concentration etc. Furthermore, when preparing a nanofluid, surfactants are normally used as stable agent for the nanofluid. In this case, it is much more complicated to propose a generalized model or prediction method for the viscosities for all nanofluids. Furthermore, for different pH and temperature, viscosity can be significantly affected but no systematic studies on the parameters are available in the literature. Further experimental research is needed to expand the viscosity database for nanofluids while fundamental investigations on fluid/particle surface interactions should be conducted as a prerequisite to developing theoretical models. Both Newtonian and non-Newtonian models should be developed for different nanofluid behaviors according to large amount of experiment data under a wide range of conditions.

### *Research on the specific heats of nanofluids*

Specific heat is an important physical property in investigating the boiling heat transfer and CHF behaviours of nanofluids. Without a proper calculation method for the specific heat of a

nanofluid, it is difficult to obtain accurate heat transfer and CHF results and mechanisms with the nanofluid. However, the research of specific heat is rare in the literature. No systematic knowledge and agreed prediction methods and models are available so far. Instead, there are several studies on the specific heats of nanofluids only in recent years. Several studies have reported that the specific heat can be enhanced using nanoparticles [49-54], which is of significance for boiling heat transfer and CHF phenomena if this is the case. It is also important for understanding the relevant physical mechanisms of boiling and CHF phenomena with the knowledge of the specific heat enhancement.

The specific heat of a nanofluid depends on the specific heat of the base fluid and the nanoparticles, the volume concentration of nanoparticles, and temperature. From the available studies, it is concluded that the specific heat of a nanofluid decreases with increasing the volume concentration of the nanoparticles and increases with increasing the temperature. Nelson and Banerjee [53] used differential scanning calorimeter for measurement of specific heat capacity of exfoliated graphite nanoparticle fibers suspended in polyalphaolefin at mass concentrations of 0.6% and 0.3%. They found an increase in the specific heat with increase in the temperature. The specific heat capacity of the nanofluid was found to be enhanced by 50% compared with PAO at 0.6% concentration by weight. This is significant for heat transfer enhancement with nanofluids and for understanding the heat transfer mechanisms as well. However, further research is needed to confirm the specific heat enhancement for other nanofluids as apparently only few studies show this enhancement phenomenon. Furthermore, the physical mechanisms of the specific heat enhancement are also urgently needed to explain the experimental results.

Vajjha and Das [54] measured the specific heat of three nanofluids containing $Al_2O_3$, $SiO_2$ and ZnO nanoparticles. The first two were dispersed in a base fluid of 60:40 by mass of ethylene glycol and water and the last one in deionized water. They developed a general specific heat correlation. However, the validation of this model for other nanofluids is questionable as it is only based on their own measured data.

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It is essential to develop reliable models for predicting the specific heat of nanofluids. Several models have been developed for the specific heat of nanofluids so far. When nanoparticles are added to a fluid, the observed thermal properties of the resultant solution will vary between that of the dispersed and fluid phases. Two simple analytical models, both based on the classical mixing theory, have been proposed for calculating the specific heat of nanofluids. The first model implying a linear relationship as:

$$c_{pnf} = \phi c_{pnp} + (1 - \phi) c_{pbf} \tag{2}$$

where $c$ is the specific heat and subscripts $nf$, $np$ and $bf$ refer to the nanofluid, the nanoparticle and the base fluid respectively, and $\phi$ is the volume fraction of the nanoparticles. Although this model has been used to evaluate the specific heat of nanofluids in may studies on the heat transfer behaviour with nanofluids, this model has been found to be inadequate in predicting the specific heat of nanofluids. As such, the relevant heat transfer results are unreliable.

Assuming local thermal equilibrium between the nanoparticles and the base fluids, Xuan and Roetzel [55] used the below equation for evaluation of the specific heat of nanofluids:

$$\left(\rho c_p\right)_{nf} = \phi \left(\rho c_p\right)_{np} + (1 - \phi)\left(\rho c_p\right)_{bf} \tag{3}$$

where the density of nanofluids is calculated according to the ideal mixture rule

$$\rho_{nf} = \phi \rho_{np} + (1 - \phi) \rho_{bf} \tag{4}$$

Although this model has been used for investigations of thermal conductivity, diffusivity and heat transfer of nanofluids, it has not yet been validated as many key factors may affect the specific heat of nanofluids.

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An improved model for calculating the specific heat of nanofluids was proposed by Buongiorno [56]. This model assumes thermal equilibrium between the particles and the fluid, which is expressed as:

$$c_{pnf} = \frac{\phi\left(\rho_{np}c_{pnp}\right) + (1-\phi)\left(\rho_{bf}c_{pbf}\right)}{\phi c_{pnp} + (1-\phi)c_{pbf}} \qquad (5)$$

Although this model has been widely used in investigating specific heat, diffusivity and heat transfer of nanofluids, it is not always effective. Higher specific heat capacities for nanoparticles themselves are possible when the size of particles is decreased. As already mentioned, without proper and accurate calculation methods of the specific heat of a nanofluid, the relevant heat transfer and CHF enhancement results are not reliable. It is not clear how the specific heats of nanofluids is evaluated in many studies of heat transfer and CHF phenomena as such information is generally not mentioned in the available studies. It is obvious that the experimental data of the specific heats are very limited. No generalized methods and models are available for calculating the specific heat. For a specific nanofluid, the specific heat should be measured before the heat transfer and CHF experiments.

According to the analysis of the available studies, systematic experiments on the specific heats of nanofluids should be conducted to uncover the mechanisms of the specific heat enhancement. Furthermore, a well-developed model for the specific heats of nanofluids is not available although various models are used for evaluation of the specific heats in many studies. In the long run, effort should be made to achieve a generalized model for predicting the specific heats of nanofluids, which are based on a well-documented database covering most nanofluids and a wide range of conditions.

***Research on other thermal physical properties of nanofluids***

Boiling heat transfer, two phase flow regimes, two-phase pressure drop and CHF characteristics strongly depend on thermal physical properties. Besides thermal conductivity, viscosity and specific heat, other thermal physical properties such as surface tension, contact angle and latent heat of evaporation etc. are critical in understanding the nanofluid two-phase flow, boiling heat transfer and CHF behaviors, mechanisms and models. However, these physical properties of nanofluids are much less investigated so far. Systematic and accurate knowledge and physical mechanisms of these physical properties have not yet been established Therefore, it is essential to conduct systematic experimental research to obtain the complete and accurate knowledge and mechanisms of these important physical properties for nanofluids and to further develop the relevant prediction methods and models.

Surface tension is extremely important in understanding the boiling and CHF phenomena and mechanisms. However, studies of surface tension are rare in the literature. Xue et al. [57] measured surface tension data for a carbon nanotube nanofluid. With addition of CNTs into water, the surface tension increases by about 14% compared to pure water at the same temperature. This is contrary to the effect arising from the surface tension reduction with the addition of a surfactant in water by Cheng et al. [17] as shown in Fig. 6. The higher surface tension of CNT suspensions could modify the mechanisms controlling nucleate boiling, flow boiling, CHF and flow pattern transitions, which might be characterized by the formation of larger-sized bubbles with diminished departure frequencies and an increased tendency to coalesce. Furthermore, two-phase patterns and pressure drops may be affected as well. It should be realized that surfactants are normally used as stable agent in preparing stable nanofluids. It is unclear how the combined function of surfactants and nanoparticles would be for the surface tension of nanofluids. Therefore, more measured surface tension data are needed to build a database for surface tensions of nanofluids and relevant physical mechanisms should be completely understood in order to develop the relevant prediction methods and models.

Tanvir and Qian [58] measured the surface tension of deionized (DI) water, ethanol and n-decane based nanofluids with addition of multi-walled carbon nanotubes (MWCNTs), B, Al, and $Al_2O_3$ nanoparticles. As show in Figs. 7 and 8 respectively, at high particle concentrations, the surface tension of the nanofluids increases with increasing particle concentration as compared to that of the base fluids. This is likely due to the increasing Van der Waals force between the accumulated particles at the at the liquid-gas interface, which increases the surface free energy and cause the surface tension to increase. However, at low particle concentrations (below 3-4 wt.%), additional of particles generally has little influence on the surface tension because the distance between the particles is large enough even at the liquid/gas interface. An exception is for the nanofluids containing MWCNTs or when a surfactant is added to the nanofluids. In such cases, the surface tension decreases at low particle concentrations, compared to the pure base fluid. This is because of the electro static repulsive force between particles, which is present due to the existence of a surfactant layer or the polymer groups attached to MWCNTs, reduces the surface free energy and thus causes a reduction in surface tension. Their experimental results show that surface tension decreases with increasing surfactant concentration, and increases with increasing particle size.

The existing experimental research has inferred that the surface tension of nanofluids changes with the base fluid and with the influence of concentration, nanoparticle types and their sizes. The surface tension of the nanofluids increases compared to that of the base fluid in all cases. According to the limited available studies on the surface tensions of nanofluids, three main conclusions may be summarized as:

a)    The surface tension of the nanofluids increases with increasing the concentration of nanoparticles,

b)    The Surface tension value of $Al_2O_3$, $TiO_2$ and $SiO_2$ nanofluids differs with each other due to the variation of nanoparticles bulk density;

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c) Larger nanoparticles exhibit a higher surface tension than that of smaller nanoparticles.

However, studies of nanofluid surface tensions are limited in the literature. More experimental investigations are needed to verify if these points are applicable to different nanofluids. Furthermore, mechanisms of specific heat enhancement of nanofluids should be studies to understand the physical phenomena. In the long run, effort should be made to find the suitable replicas or correlations for the prediction of the enhancement of surface tension considering all the effective parameters.

Contact angle is another important parameter in understanding and modelling two-phase flow, boiling heat transfer and CHF of nanofluids but is less concerned so far. Some researchers measured the contact angle of nanofluids which may be changed after the boiling processes due to the nanoparticle depositions on the boiling heat transfer surfaces. Kamatchil et al. [59] measured the contact angles of nanofluids on a Ni-Cr wire after the boiling process. The static contact angles of Ni–Cr wire after boiling with DI water and different concentrations of rGO/water nanofluids were measured using a contact angle meter as shown in Fig. 9. They have found that the contact angle on the rGO deposited thin Ni–Cr wire increases with concentrations except for DI water boiled surface as shown in Fig. 9(a). This might be due to the hydrophobic nature of rGO. Though a rGO layer exhibits hydrophobic behaviour, there is water absorption in the rGO layer which means a reduction in contact angle after 1 min as shown in Fig. 9(b). Hence, the favourable water absorption on the deposited surface is attributed to the wickability of rGO layer which further aids in the enhancement of CHF.

Xia et al. [15] measured the static contact angles using DI water on a smooth coper surface and the MWCNT nanoparticle deposition surface after boiling respectively. Their results are contradictory to those obtained by Kamatchil et al. [59]. Figure 10 shows their measured contact angles. They have found that the nanoparticles deposited surface decreased 16 degrees compared to the original copper surface. The variation of contact angle has a great influence on the solid-liquid-

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vapor interface. The deposited surface could reduce the contact angle to enhance boiling heat transfer. The MWCNTs deposition is conductive to wet the surface, and thus make it easier for bubbles to depart from the boiling surface and increase the boiling heat transfer coefficient. The main reason of enhanced boiling heat transfer is due to the deposition of agglomerate nanoparticles, which may increase the number of nucleate sites and bubble departure frequency.

So far, systematic knowledge of the contact angle of nanofluids is not available due to the very complicated phenomena and affecting factors but need to be extensively investigated and to further propose theoretical models for predicting the contact angles for nanofluids. Furthermore, the dynamic contact angles during boiling process are different from the static contact angles and there is no such information for nanofluids. Therefore, experimental studies are needed to achieve such knowledge and models as well.

Furthermore, the latent heat of evaporation for nanofluids is critical in investigating boiling heat transfer and CHF phenomena and models, However, the relevant research is rare in the literature. More recently, several researchers measured the latent heat of evaporation of nanofluids [60, 61]. Both the latent heat of evaporation can be enhanced and decreased with nanofluids. Naturally, understanding of how the nanoparticles would affect the latent heat of nanofluids is very important to explaining the various boiling heat transfer and CHF phenomena. However, systematic knowledge and mechanisms of latent heat enhancement or decrease with nanofluids have not yet established. It is impossible to reach a general conclusion at this stage due to the limited research. However, it is important to understand how the nanoparticles affect the latent heat of evaporation of nanofluids because they may be able to explain some of the contradictive results of boiling heat transfer and CHF phenomena and mechanisms with nanofluids observed by different research groups.

**Nucleate boiling heat transfer and CHF in pool boiling with nanofluids**

Studies on the fundamentals, theory and mechanisms of nucleate boiling heat transfer and CHF phenomena in pool boiling with nanofluids have been extensively investigated over the past decade. However, there are contradictory results regarding the nucleate boiling heat transfer and CHF in pool boiling. In general, some studies show a decrease or no change in nucleate boiling heat transfer with nanofluids while others show an increase in the heat transfer. Furthermore, quite different heat transfer mechanisms are proposed to explain the phenomena and experimental results. However, unified physical mechanisms have not yet been achieved. Regarding the CHF phenomena in pool boiling, most studies showed CHF enhancement results at pool boiling of nanofluids while few studies showed decrease in CHF. In explaining the CHF enhancement phenomena, an enhanced boiling surface typically increases heat transfer coefficients significantly and the deposition of nanoparticles on the heat transfer surfaces reported in many researchers may be another factor but not yet well understood. If this is case, nanoparticle coatings the heat transfer surfaces may be made to enhance the CHF rather than using deposited nanoparticles on the heat transfer surface caused in the boiling process of nanofluids. In general, such deposited nanoparticles are unstable and easily removed by the fluid and bubble circulation in the boiling process. For a new technology of heat transfer and CHF enhancement using nanofluids, fouling caused due to the deposition of nanoparticles should be avoided. Otherwise, it is difficult to apply such an enhancement technology in practical engineering application.

In order to prepare stable and uniformly dispersed nanofluids, surfactants are generally used as a stable agent in preparing nanofluids. The effects of surfactants on the nucleate boiling heat transfer and CHF phenomena, behaviors and mechanisms should be systematically investigated because addition of a surfactant may either enhance or deteriorate nucleate boiling heat transfer and CHF behaviors as in the comprehensive review by Cheng et al. [17]. The nanoparticle types,

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concentrations and sizes may also play a key role the nucleate boiling heat transfer and CHF but systematic knowledge and relevant theory are still lacking. Whether the heat transfer enhancement or decrease is caused by the surfactants or the nanoparticles or both. It is better to clearly identify the mechanisms. Therefore, all the affecting parameters should be considered in understanding the heat transfer and CHF mechanisms and developing relevant prediction methods and models.

The existing experimental and mechanistic investigations on the nucleate boiling heat transfer and CHF phenomena in pool boiling are summarized and analyzed here. It is helpful to put the available results in proper perspective. For instance, nucleate pool boiling data are often measured with about ±20-30% errors and the experimental data from independent studies on the same pure fluid often disagree by 30-50% or more. The traditional prediction methods and models are sometimes used/modified to predict the nanofluids boiling heat transfer coefficients and CHF. However, they are still limited due to many controlling factors such as inaccurate physical properties, the poor understanding of the physical mechanisms and the lack of systematic and accurate experimental data and so on. Therefore, it is essential to present a comprehensive and deep analysis of the available studies of the important topics. These studies are also the basis to understand more complicated flow boiling heat transfer and CHF with nanofluids which are also discussed in this review. Furthermore, as mentioned in the physical properties of nanofluid, nucleate boiling and CHF phenomena are strongly related to the relevant physical properties. Without proper knowledge of the physical properties, it is difficult to obtain accurate knowledge and reasonable physical mechanisms with nanofluids. In fact, this is the case for most of the available studies in the literature because how to evaluate the relevant physical properties in the reduction of the experimental data is not clearly given in these studies.

### *Research on nucleate pool boiling heat transfer and mechanisms with nanofluids*

Studies on the nucleate pool boiling heat transfer and the corresponding physical mechanisms with nanofluids. have been extensively conducted over the past decade. Table 2 list

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some selected studies on nucleate pool boiling heat transfer with nanofluids. There are quite contradictory results in these studies. Some studies have also shown heat transfer enhancement in nucleate pool boiling with nanofluids while others have shown no heat transfer enhancement or decrease in nucleate pool boiling.

Yang and Maa [62] conducted pool boiling heat transfer experiments using $Al_2O_3$ nanofluids in 1984, which might be the first research in this field. According to their experimental results, low concentrations of $Al_2O_3$ nanofluids with 50 nm diameter can enhance the nucleate pool boiling heat transfer. Tu et al. [63] conducted experimental study of nucleate boiling heat transfer with $Al_2O_3$ nanofluids as well. Significant heat transfer enhancement in nucleate pool boiling with an $Al_2O_3$-water nanofluid, up to 64% for a small fraction of nanoparticles was obtained in their study. Wen and Ding [64] conducted experimental investigation on the nucleate pool boiling heat transfer with $\gamma$-$Al_2O_3$-water nanofluids. They found that the presence of alumina in the nanofluid enhanced heat transfer significantly, by up to 40% for a 1.25 wt% concentration of the nanoparticles. Wen et al. [65] conducted experimental study on nucleate pool boiling heat transfer of $TiO_2$-water nanofluids. Their results showed that heat transfer increased by up to 50% at a concentration of 0.7 vol.%. Ghopkar et al. [66] reported that $ZrO_2$-water could enhance nucleate pool boiling heat transfer at low particle volumetric concentrations but the boiling heat transfer decreases with further increasing in the nanoparticle concentration in the nanofluid. They mentioned that addition of a surfactant to the nanofluids drastically decreased heat transfer whereas surfactants often increase nucleate boiling heat transfer. This may depend on the types of surfactants as pointed out by Cheng et al. [17]. Surfactants are usually used as a stable agent for preparing the nanofluids. However, whether a surfactant is used or not is not mentioned in many available studies. Furthermore, the combined function of

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surfactants and nanoparticles should be systematically investigated to understand the phenomena and mechanisms.

Furthermore, it is important to report weather the experimental results are repeatable or not. Such information is generally missing in most studies. Without a stable agent, deposition of nanoparticles may occur after some time in most case. In this case, the reported experimental results cannot be repeated due to the deposition of nanoparticles. In practice, it is essential to produce stable nanofluids which may be used as heat transfer fluids for engineering application. In fact, such information is also missing in most studies. Simple reporting boiling heat transfer enhancement with nanofluids is not enough. Furthermore, complete understanding of the effects of surfactants on the nucleate pool boiling with a nanofluid is not yet well established. Cheng et al. [17] have presented a comprehensive review on boiling and CHF with surfactants, which may be referred for the details of the relevant research. Particularly, combined function of nanoparticles and a surfactant is not well explored and should be thoroughly investigated to understand the physical mechanisms and to further develop relevant heat transfer enhancement technology in practical engineering application.

Some researchers have found contradictory results to the heat transfer enhancement using nanofluids. Witharana [67] conducted experiments on nucleate boiling heat transfer of Au (unspecified size)-water, $SiO_2$ (30nm)-water and $SiO_2$-ethylene glycol nanofluids. Their experimental results for Au-water nanofluid boiling heat transfer showed the nanofluid heat transfer coefficients were higher than those of pure water and increased with increasing gold particle concentration. The enhancement of heat transfer was only about 11% at the intermediate heat fluxes (3 W/cm$^2$) and 21% at a higher heat flux (4 W/cm$^2$). These are with

the boiling heat transfer coefficient measurement uncertainty range of 20 to 30%. Therefore, the measurement uncertainty is generally bigger than 11% heat transfer enhancement in their experiments of nucleate boiling heat transfer with nanofluids. Therefore, the heat transfer enhancement of only 11% is not really convinced. Furthermore, the economic benefit should be considered when developing a new heat transfer enhancement technology. Such a low heat transfer enhancement is possible not economic if considering the cost of producing the nanofluids and thus may be insignificant. On the contrary to the observed heat transfer enhancement, their $SiO_2$-water and $SiO_2$-ethylene glycol nanofluids showed a decrease in their heat transfer coefficients. These contradictory behaviours were not explained in their study. It is essential to investigate the corresponding physical mechanisms to explain the experimental results.

Yang and Liu [68] conducted experiments on nucleate pool boiling heat transfer of refrigerant R-141b with and without nano-sized Au particles on a horizontal plain tube. Three concentrations of 0.09 vol.%, 0.45 vol.% and 1 vol.% were used in their experiments. For R-141b with 0.09 vol.% nanoparticles, there is no significant effect on pool boiling heat transfer and the experimental heat transfer coefficients for pure R141b agreed very well with those predicted by the Cooper [69] correlation. However, the nucleate boiling heat transfer increased with increasing the nano-particles concentration. At the particles concentration of 1.0 vol. %, the heat transfer coefficients are more than twice higher than those of the base fluid. Their results agree with those by Wen and Ding [65] but are in contradiction to those of Das et al. [70] and Bang and Chang [71] who observed decrease in nucleate boiling heat transfer coefficients due to the presence of nano-particles. Furthermore, they repeated their measurements of heat transfer coefficients for four times with the intervals of every 5 day.

They found that the measured nucleate boiling heat transfer coefficients decreased for each test and finally close to those of the base fluid. They attribute to the trapped particles on surface and reduced the number of activation nucleation sites. They also measured the surface roughness of the heat transfer surface before and after boiling. The surface roughness of the heat transfer surface decreased from 0.317 µm before boiling test to 0.162 µm after tests. Further investigation by a transmission electron microscopy and Dynamic Light Scattering particle analyzer showed that the nano-particles aggregated from the size of 3 nm before the experiments to 110 nm after experiments. According to their study, they have concluded that the nano-sized Au particles are able to significantly increase nucleate pool boiling heat transfer of refrigerant R-141b on the plain tube surface. However, the tube surface roughness and particle size changed after the boiling experiments. The effects of both parameters can significantly degrade the nucleate boiling heat transfer coefficients. In developing a heat transfer enhancement technology, it is important to produce a stable and uniformly dispersed nanofluids which may be used in long term practical engineering application. The deposition and aggregation which may significantly affect the nucleate boiling heat transfer should be avoided. Therefore, a reliable technology is needed with nanofluids for heat transfer application.

Some studies have shown that nanoparticles do not enhance nucleate pool boiling heat transfer or decrease it. Li et al. [72] conducted experimental study on nucleate pool boiling heat transfer with a CuO/water nanofluid. They found that heat transfer deteriorated with addition of the nanoparticles. They attributed this to the decrease in active nucleation sites caused by nanoparticle sedimentation on the boiling surface based on observations. Das et al. [70, 73] conducted an experimental investigation on nucleate pool boiling heat transfer characteristics of $Al_2O_3$-water nanofluids under atmospheric conditions. Figure 11

shows their experimental results on a smooth heater and a rough heater [70]. Addition of nanoparticles in the base fluid degraded the nucleate boiling performance as illustrated in Fig. 11. They speculated that the deterioration in boiling heat transfer was not due to a change in the fluid property but due to the change in the surface wettability due to the entrapment of nanoparticles in the surface cavities which reduced the boiling nucleates. You et al. [74] also reported deterioration in nucleate pool boiling heat transfer with $Al_2O_3$-water nanofluids. Kim et al. [75] found that heat transfer coefficients of $Al_2O_3$-water nanofluids remained unchanged compared to those of water. Vassallo et al. [76] conducted experimental investigation of nucleate boiling heat transfer with silica nano-solutions and silica micro-solutions on a 0.4 mm NiCr wire submerged in each solution at atmospheric pressure. Their results showed no appreciable differences in nucleate boiling heat transfer coefficients with the nanofluids and those of the base fluid. A thick (0.15–0.2 mm) silica coating was observed to form on their wire heater. They speculated that the roughness of the solid substrate might be responsible for the observed results. The additional thermal resistance of the silica could also have played a role in the nucleate boiling heat transfer. Prakash Narayan et al. [77] studied the effect of heat transfer surface orientation on the nucleate pool boiling heat transfer with $Al_2O_3$–water nanofluids. They found that the nucleate boiling heat transfer deteriorated for all tests of their study. A significant effect of the surface orientation on the nucleate boiling heat transfer was found, where a horizontal orientation gave the best boiling heat transfer performance and the heater surface at an inclination of 45° gave the worst boiling heat transfer performance. This may be relevant the bubble departure speed due to the surface orientation effect.

Both heat transfer enhancement and deterioration have been observed for nanofluid nucleate boiling in the available studies. It is essential to clarify the heat transfer

mechanisms. Nearly all reported deterioration in nucleate boiling heat transfer is due to the deposition or aggregation of nanoparticles. The question is how the deposition or aggregation of nanoparticles could be avoided because a table nanofluids are needed in the practical engineering application. Furthermore, if a nanofluid does not enhance heat transfer, it is naturally no use in engineering application. However, if a nanofluid can enhance heat transfer, stability and durability of the nanofluid must be maintained for practical engineering application. In this case, economic feasibility should be investigated. Therefore, evaluation of heat transfer enhancement with nanofluids should be done but such information is missing in nearly all the available studies.

Surfactants are generally used as stable agents in preparing nanofluids in some stuides. It is important to understand how surfactants affect the nucleate boiling heat transfer behaviours and the physical mechanisms because surfactants may enhance or deteriorate the heat transfer behaviours [17]. Furthermore, the heat transfer surface conditions may change due to the deposition of nanoparticles and the nanoparticles may aggregate to larger particles in the boiling process, which may have a significant effect on the nucleate boiling heat transfer behaviour and the physical mechanisms. Therefore, it is essential to consider the effects of surfactants used in the nanofluids and understand the combined heat transfer behaviour and the physical mechanisms due to both nanoparticles and surfactants, and the nanoparticle aggregation.

Many researchers have tried to understand the nucleate boiling heat transfer mechanisms from various aspects. Tang et al. [78] investigated the nucleate boiling heat transfer of $\delta$-Al$_2$O$_3$-R141b nanofluids considering the surfactant effect. They have found that high concentration of nanofluids may deteriorate the nucleate boiling heat transfer without

surfactant due to the deposition of nanoparticles. However, the nucleate boiling heat transfer may be enhanced with the addition of the surfactant because the surfactant reduced the thermal resistance of the nanoparticle deposition. He et al. [79] investigated the heat transfer characteristics of nucleate boiling with ZnO-ethylene glycol/water nanofluids in a cylindrical vessel. Their experimental results have showed that the low concentration of nanofluids can enhance the nucleate boiling heat transfer. However, the nucleate boiling heat transfer coefficient decreases with increasing the nanoparticle concentration because the deposition of the nanoparticle on the heat transfer surface may reduce the surface roughness and as such the nucleate boiling heat transfer decreases. Shoghl et al. [80] conducted experimental study on the nucleate pool boiling heat transfer of nanofluids with ZnO, $\alpha$-Al$_2$O$_3$ and MWCNTs particles. They have found that the effects of the heat transfer surface and the properties of nanofluids may both significantly affect the nucleate boiling heat transfer performance. Furthermore, their experimental results with different nanofluids have showed quite different heat transfer behaviours and mechanisms. The carbon nanotube-water nanofluids could enhance the nucleate boiling heat transfer while the ZnO and Al$_2$O$_3$-water nanofluids deteriorated the nucleate boiling heat transfer. This may be due to the change of the properties of the nanofluids and the boiling heat transfer surface conditions such as surface roughness.

Shahmoradi et al. [81] conducted experiments of nucleate pool boiling heat transfer with Al$_2$O$_3$-water nanofluids on a flat heater at concentrations lower than 0.1 vol.%. Their experimental results have showed that the nucleate boiling heat transfer coefficient decreases with increasing the concentration of nanoparticles. Sarafraz and Hormozi [82] conducted experimental investigation of nucleate pool boiling heat transfer with Al$_2$O$_3$-

ethylene glycol nanofluids on a stainless steel cylindrical surface. They have found that the number of nucleation sites are constantly reduced and thus the nucleate boiling heat transfer coefficient decreases with increasing the concentration of nanofluids due to the deposition of nanoparticles on the heat transfer surface and thus reduced the boiling active nucleation sites. They also conducted experiments of nucleate pool boiling heat transfer with MWCNTs nanofluids on a plain surface and five different micro-finned surfaces to further explore the corresponding physical mechanisms according to the nucleate boiling heat transfer behaviours [83]. Their results have showed that the nucleate boiling of the nanofluids lead to the nanoparticle deposition on the plain surface which may reduce boiling nucleation sites and thus decreases the boiling heat transfer coefficient. However, the micro-finned surfaces can break the deposition of nanoparticles to increase the boiling nucleation sites and therefore enhance the nucleate boiling heat transfer. Sarafraz and Hormozi [84] conducted experimental investigation of nucleate pool boiling of CuO/water nanofluids at a concentration of 0.1-0.4 wt%, with or without surfactant (SDS, SDBS or Triton X-100). They found a significant heat transfer deterioration of nanofluids without the surfactants but heat transfer enhancement with the addition of the surfactants. They observed rectilinear changes with time of nanoparticle deposition on the heater surface in both regions with natural convection and nucleate boiling regimes. They have speculated that the nucleate boiling heat transfer deterioration might be caused due to the nanoparticle deposition on the heat transfer surface which reduced the number of nucleation sites. The formed a thick layer of nanoparticles on the heat transfer surface increased the thermal resistance as a fouling resistance. In the presence of surfactants, the surface tension of the fluid was reduced and thus the bubble formation and detachment were significantly intensified. Therefore, the nucleate boiling heat transfer was enhanced while it was decreased without

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the surfactants. According to this study, nanoparticles cannot enhance the boiling heat transfer and the observed heat transfer enhancement is due to the surfactants. In this case, using surfactant solutions alone would be suggested for the heat transfer enhancement rather than nanofluids.

Diao et al. [85] conducted experimental study on nucleate pool boiling heat transfer with Cu/R141b nano-refrigerant with addition of surfactant SDBS on a flat surface at atmospheric pressure. Three nanoparticle concentrations of 0.008, 0.015 and 0.05 vol.% were used. They found that nucleate boiling heat transfer was enhanced. The enhancement ratio increases with increasing the nanoparticle concentration. They attributed the nucleate boiling heat transfer enhancement to two main physical mechanisms:

a)  The surfactant decreased the surface tension of the nanofluids and therefore increased the bubble departure frequency and decreased of the bubble departure diameter.

b)  The nanoparticles were continuously deposited on the boiling heat transfer surface and modified the heated surface conditions, therefore increased the active nucleation sites which in turn enhanced the nucleate boiling heat transfer.

However, the nanoparticle deposition increases the thermal resistance in the meantime, which might reduce/diminish the nucleate boiling heat transfer enhancement performance. Their observations and explanations of the nucleate boiling heat transfer mechanisms are quite similar to those by Sarafraz and Hormozi [84]. If the proposed mechanisms could dominate the boiling heat transfer enhancement phenomena, it would be better to use a

coated surface to enhance the nucleate boiling heat transfer rather than using a nanofluid. The deposition of nanoparticle on the heat transfer surface makes it is impossible to put the nanofluids into practical engineering application because the deposited nanoparticles may foul the surface and reduce the concentration of the nanoparticles in the boiling process.

It is essential to produce a stable nanofluids which do not deposit the nanoparticles in the boiling heat transfer process. Some studies have showed that the nucleate boiling heat transfer is enhanced with the nanoparticles and no deposition of the nanoparticles is observed the heat transfer surface. Park and Jung [86] studied the effect of CNTs on nucleate pool boiling heat transfer of two halocarbon refrigerants (R123 and R134a). The refrigerant based nanofluids have 1 vol.% of CNTs. Their results showed that CNTs nano-particles increased the nucleate pool boiling heat transfer coefficients for both refrigerants. Figure 12 shows their measured nucleate boiling heat transfer coefficients of R134a with and without CNTs. Enhancements up to 36.6% were observed at low heat fluxes. With increasing heat flux, however, the enhancement diminished due to more vigorous bubble generation according to the visual observations of the boiling process. In addition, no deposition of the particles on the heat transfer surface was observed in their study.

Xia et al. [15] recently conducted systematic experimental investigation on nucleate pool boiling heat transfer of MWCNTs water-based nanofluids in a confined space. The effects of various surfactants and the change of boiling heat transfer surface conditions due to the nanoparticle deposition have been investigated in their study. First, the MWCNTs nanofluids with different volume concentrations from 0.005% to 0.2% were prepared using a two-step method. In addition, the effects of four different surfactants on the stability of the nanofluids were investigated and the suitable surfactant gum acacia (GA) was selected as the stable agent for the nanofluids for the boiling experiments. Furthermore, GA with four different mass fractions of 0.1%, 0.3%, 0.5% and 0.7% was

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respectively dissolved in the base fluids to investigate the effect of the surfactant concentration on the stability of the nanofluids. Then, experiments of nucleate pool boiling heat with the nanofluids having various mass fractions of the MWCNTs were conducted at a sub-atmospheric pressure of $1 \times 10^{-3}$ Pa. The test heat fluxes are from 100 to 740 kW/m$^2$. They have found that the MWCNTs nanofluids enhanced the nucleate boiling heat transfer. This is mainly caused by the nanoparticle deposition on the boiling heat transfer surface which increased the surface roughness and thus increased the boiling nucleate sites. However, addition of surfactant GA can inhibit the deposition of the nanoparticles and thus may reduce the boiling heat transfer coefficient of the nanofluids. They explained that the mechanisms of the boiling heat transfer enhancement of the nanofluids at lower heat fluxes are different from those at higher heat fluxes. At lower heat fluxes, the nanoparticle deposition layer increases the frequency of bubble formation and thus the boiling heat transfer is enhanced while at the high heat fluxes, the boiling heat transfer processes may facilitate the nanoparticle deposition and the disturbance of the MWCNTs may increase the enhancement ratio of heat transfer coefficient with increasing the heat flux. Figure 13 shows the comparison of the boiling heat transfer coefficient with the MWCNTs volume concentration at a lower heat flux of 100 kW/m$^2$ and a higher heat flux of 740 kW/m$^2$. The heat transfer coefficients at the higher heat flux are around four times higher than those at the lower heat flux. It should be noted that there is a fast-increase in the nucleate boiling heat transfer coefficients occurred at lower concentrations of the nanofluids. However, this variation of the boiling heat transfer coefficients becomes flat at higher concentrations. It indicates that this is a critical concentration of the nanofluids at which the boiling heat transfer enhancement remains unchanged beyond this critical concentration. According to their study, the effects of the nanofluids concentration on the nucleate boiling heat transfer enhancement may be attributed to the variation of the surface roughness due to the nanoparticles deposition. However, there is no significant change with further increasing the concentration of the nanofluids beyond the critical concentration and thus the enhancement of the boiling heat transfer remains unchanged. They explained the heat transfer enhancement performance according the observed bubble

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dynamics. Initially, a bubble emerges on the boiling surface and kept growing. Shortly afterwards, it departures from the surface slowly which may deteriorate the heat transfer from the boiling surface to the fluid. At last, the liquid back to initial state without phase-change. With respect to the physical mechanisms for the heat transfer enhancement, the deposition of the nanoparticles on the boiling heat transfer surface evidently improves the number of nucleation sites which can increase the bubble formation rate and reduce the region of no phase-change. The slower generation and departure of bubble, the more obvious enhancement of heat transfer of deposition. With increasing the heat flux, the boiling pattern is transformed from an isolated bubble to continuous bubbles and bubbles departs very quickly.

Numerous studies have also tried to explore the mechanisms of deterioration or enhancement of nucleate pool boiling heat transfer with nanofluids according to the corresponding experimental results and observations. In general, the nucleate boiling heat transfer mechanisms mainly include the decreasing of active nucleation sites from nanoparticle sedimentation on the boiling surface, the change of wettability of the surface and nanoparticle coatings on the surface. Furthermore, bubble dynamics including bubble growth, bubble size and departure frequency were studied via visualization using a high-speed camera. Tu et al. [63] reported that there were smaller bubbles with no obvious changes of bubble departure frequency compared to pure water. The different observed bubble behaviours thus apparently account for the deterioration or enhancement of nucleate boiling heat transfer. You et al. [74] observed that the average size of departing bubbles increased significantly and the bubble frequency decreased significantly in nanofluids compared to those in pure water. Bang et al. [87] conducted visualization on nucleate pool boiling and the liquid film separating a vapour bubble from a heated surface, which was used to explain the deterioration of nucleate boiling heat transfer. However, the

various contradictory results make it difficult to explain the phenomena utilizing methods for pure fluids.

Xia et al. [15] explained the heat transfer enhancement mechanisms by measuring the contact angles on a smooth surface and a deposited surface after boiling as shown in Fig. 10. They also observed the deposition of nanoparticles on the heat transfer surface. Figure 14 shows the macroscopic and microscopic photographs which clearly indicate the structures of the deposited nanoparticles. Furthermore, they observed the bubble behaviours using a high-speed video camera, which are used to explain the heat transfer enhancement mechanisms [15]. Figure 15(a) shows the condition of the prepared nanofluids in all concentrations of GA. The nanofluid is black and the multiwalled carbon nanotube particles are well mixed in the base fluid after ultrasonic oscillation. Fig. 15(b) and (c) shows the condition of the MWCNTs nanofluid after boiling without and with surfactant GA, respectively. The MWCNTs in nanofluid without GA agglomerated and deposited at the bottom of nanofluid after boiling while the nanofluid with surfactant GA still keep good dispersion after boiling process. With increasing heat flux, the activity of nanoparticles is more severe in the liquid, which is helpful to the dispersion of nanoparticles by surfactant. However, the main reason for the enhancement of heat transfer by nanofluid is the aggregation layer of the nanoparticles on the boiling surface. According to this observation, the surfactant can make particles uniformly dispersed in the base fluid and inhibit the deposition generated on the boiling surface, reduce the roughness of boiling surface and weaken the active nucleation sites

Chon et al. [88] reported evaporation and dryout of nanofluid droplets on a heated surface to understand the evaporation mechanisms of liquid droplets. They experimentally studied the thermal characteristics of evaporating nanofluid droplets using a microheater array of 32 line elements that

are 100 μm wide, 0.5 μm thick, and 1.5 cm long under a constant-voltage mode. Four different nanofluids have been tested, containing 2-nm Au, 30-nm CuO, 11-nm $Al_2O_3$, and 47-nm $Al_2O_3$ nanoparticles, each as 5 μL droplets with 0.5 vol.% in water. Figure 16 shows the evolution of the $Al_2O_3$ nanofluid droplet evaporation and dryout with sequential photographs and the schematic sketch of the processes. Just after placement on the microheater substrate, the droplet is pinned at the edge (a). During the liquid-dominant evaporation (b), the strong pinning of nanoparticles acts to congregate them to the rim. The droplet thickness and contact angle decrease while the wet diameter remains constant. With further evaporation of liquid, the contact angle exceeds the critical angle, and the thin core liquid region begins to break away from the rim, i.e., depinning (c). The depinned core liquid then shrinks toward the center as the evaporation and dryout further progresses (d). Finally, the resulting ring-shaped nanoparticle stain is formed along the rim, and the evaporation is completed (e). Strongly pinned nanofluid droplets are considered for a sequential evaporation process of (1) pinning, (2) liquid dominant evaporation, (3) depinning, (4) dryout and (5) formation of a nanoparticle stain. Upon completion of the evaporation process, ring-shaped nanoparticle stains are left, the pattern of which strongly depends upon the nanoparticle sizes. Smaller nanoparticles result in relatively wider edge accumulation and more uniform central deposition, whereas larger nanoparticles make narrower and more distinctive stains at the edge with less central deposition. According to their results, nanofluid evaporation consists of three periods. first, Liquid Dominant Evaporation (I) occurs with steady thermal properties that are nearly identical to those of pure water with little effect of suspended nanoparticles on the overall heat and mass transfer. Next, the Dryout Progress (II) characterizes the later part of evaporation, when the nanoparticle effect dominates, water level recedes. This period shows a discontinuous surge of temperature and heat flux due to the high thermal conductivity of nanoparticles, which in turn rapidly recovers to the dry heater condition while the recovery process for a pure water droplet is gradual and continual. Finally, the formation of Nanoparticle Stain (III) period occurs, which strongly depends on nanoparticle size. Their research focused on evaporation of droplets of nanofluids but

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provides some understanding of the evaporation mechanisms which may help to explain their effect on the boiling process and two-phase phenomena of nanofluids.

Quite different mechanisms have also been explored to explain the nanofluid nucleate boiling phenomena. Sefiane [89] presented a review to theoretically explore the influence of the disjoining pressure on the nucleate boiling heat transfer. The disjoining pressure could push the liquid-vapor meniscus towards the vapor phase and increase the volume of the microlayer, which is equivalent to an increased wettability effect. Such an effect was hypothesized to increase the nucleate boiling heat transfer. However, validation of the proposed mechanisms with more experimental data is needed.

According to the afore-going review and analysis of the selected studies of the nucleate pool boiling heat transfer phenomena and mechanisms, quite different results of nucleate pool boiling heat transfer with different nanofluids have been reported in the literature. Both enhancement and deterioration were reported, depending on many factors and their mutual interactions. One of the most commonly explanations for the boiling heat transfer enhancement and almost all explanations for the deterioration were the nanoparticle deposition on the heat transfer surface. However, the explanations for the mechanisms are diverse and even contradictory. For the nucleate boiling heat transfer enhancement due to the nanoparticle deposition, the physical mechanisms include:

a) It decreases the surface contact angle and thus modifies the surface wettability.

b) It changes the surface roughness and increases the available nucleation sites.

c) It enhances the lateral wicking of liquid into the microlayer regions of the evaporating meniscus, causing a slower rise in local wall temperature

d) It induces faster rewetting in nanofluids than in pure water, resulting in an earlier collapse of vapor film on the surface.

For the nucleate boiling heat transfer deterioration due to the nanoparticle deposition on the heat transfer surface, the mechanisms include:

a) It changes the surface properties and wettability.

b) It reduces the roughness, cavities and active nucleation sites of the surface.

c) It increases surface fouling resistance because of the deposited layer.

During the pool boiling process of nanofluids, nanoparticles continuously deposit on the heated surface. At low concentrations, the deposited nanoparticle layer causes an enhancement in heat transfer coefficient because the effect of thermal conductivity of nanofluids is more dominant than the effect of the nanoparticle layer. At high concentrations, however, the reduction in the number of active nucleation sites and the formation of an extra thermal resistance caused by the deposited nanoparticle layer become more dominant than the effect of the thermal conductivity of nanofluids, resulting in the deterioration of the heat transfer coefficient. The enhancement or deterioration of pool boiling transfer is also dependent on the surface particle interaction. It increases by multiplying the active nucleate sites and creating the active cavities while decreases due to the blocked nucleation cavities.

Furthermore, addition of surfactants in nanofluids may have a significant effect on the nucleate boiling heat transfer. Surfactants may increase or decrease the nucleate boiling heat transfer. However, systematic knowledge and understanding of the combined effects of both surfactant and nanoparticles on the nucleate boiling heat transfer with nanofluids have not yet fully achieved. Furthermore, observations with and without nanoparticle depositions on the heat transfer surfaces have been found in different studies. In explanation of the nucleate boiling heat transfer enhancement mechanisms, it seems that the surface condition changes due to the deposition of nanoparticles and thus an increase of active boiling

nucleation sites are generally adopted. However, in the meantime, the thermal resistance is increased due to the deposited layer of nanoparticles the heat transfer which may diminish the heat transfer enhancement or decrease the heat transfer. In practice, the deposition is not wanted. If this is the case, possibly the best method is to develop nanoparticle coating for heat transfer enhancement. The question is if there are any other different mechanisms which may be used to explain the nucleate boiling heat transfer enhancement with nanofluids.

In general, complete and systematic knowledge and fully understanding of the fundamentals and physical mechanisms of nucleate boiling heat transfer with nanofluids have not yet achieved. There are still big challenges in this important subject. Therefore, it is essential to explore and understand the various physical mechanisms governing the heat transfer processes with nanofluids through systematic and careful experimental and theoretical research. In the long run, effort should be made to develop reasonable prediction methods and models for nanofluid nucleate pool boiling heat transfer with incorporating the proper thermal physical properties. Furthermore, technology development of nanofluids is another important aspect. Putting the heat transfer enhancement technology with nanofluids into practical engineering application is another big challenge and needs to be considered urgently by the heat transfer community.

*Research on CHF phenomena and physical mechanisms in pool boiling with nanofluids*

Unlike quite different and contradictory results of nucleate pool boiling heat transfer with nanofluids in various studies, most of the available studies have shown the CHF in pool boiling can be enhanced with nanoparticles while few studies have shown a decrease of CHF in pool boiling with

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nanofluids. Table 3 lists the elected studies on CHF in nucleate pool boiling heat transfer with nanofluids. Numerous studies seem to clearly conclude that the primary mechanism of the CHF enhancement in pool boiling with nanofluids is the change of the surface microstructure of the boiling heat transfer surface due to a nanoparticle layer coating formed on the surface during pool boiling process of nanofluids [74, 75, 89-97]. If this is the case, it would be easier to use an enhanced surface with a porous coating from a practical application viewpoint.

Some studies have shown significant enhancement of the CHF in nucleate pool boiling with nanofluids. You et al. [74] found drastic CHF enhancement for the pool boiling with $Al_2O_3$-water nanofluids. Figure 17 shows their experimental results for the CHF in pool boiling, where up to three times enhancement was achieved as compared to that of the base fluid. They also performed a visualization of the boiling process and found that the average size of departing bubbles increased but the frequency of departing bubble decreased. Figure 18 shows their observed bubble images. They concluded that the unusual CHF enhancement of nanofluids could not be explained by any existing CHF model, i.e. no pool boiling CHF model includes thermal conductivity or liquid viscosity and hence cannot explain this phenomenon, and the enhancement on liquid-to-vapor phase change was not related to the creased thermal conductivity. They also reported the enhancement in CHF for both horizontal and vertical surface orientations with the nanofluids. Noting a change of the roughness of the heater surface before and after their experiments, they hypothesized that the reason for the increase in the CHF might be due to a surface coating formed on the heater with nanoparticles. Furthermore, they also studied the effect of nanoparticle concentration on the CHF enhancement in pool boiling. Figure 19(a) shows the variation of CHF enhancement ratio versus the nanoparticle concentration for $Al_2O_3$-water nanofluid boiling on a flat copper plate. The CHF enhancement ratio increases with increasing the nanoparticle concentration in general. However, there is a critical concentration beyond which the CHF enhancement ration remain constant at the maximum enhancement value. Kim and Kim [94] obtained similar results for various nanofluid boiling on NiCr wire as shown in Fig, 19(b).

Kim et al. [75] conducted investigation on the effect of nanoparticles on the CHF enhancement in pool boiling of $Al_2O_3$-water. They found that the CHF was improved by up to 200% at a concentration of 0.01 g/l. They found that the size of departing bubbles increased and the bubble frequency decreased significantly in nanofluids compared to those in pure water through visualization. The orientation of the heater surface had a great effect on the CHF. Kim at al. [90, 91] also reported a significant enhancement in CHF was achieved for $Al_2O_3$-water, $ZrO_2$-water and $SiO_2$-water nanofluids at concentrations less than 0.1 vol. %. They noted that a porous layer of nanoparticles formed on the heat transfer surface. This porous layer significantly improved the surface wettability, which may explain a plausible mechanism of the CHF enhancement obtained in their experiments. Kim et al. [92], Kim et al. [93] and Kim and Kim [94] found that the CHF enhancement was achieved for $Al_2O_3$-water and $TiO_2$-water nanofluids at concentrations from 0.005 to 0.1 vol. % with a maximum increase of about 100%. They also found that nanoparticles coated their heat transfer surfaces and thus apparently enhanced the surface wettability. Hence, if the augmentation is the results of the coating, one would conclude that it is more effective to directly coat the surface rather than use nano-particles in the fluid to enhance the CHF.

Tu et al. [63] also found that the CHF enhancement was achieved for the pool boiling of $Al_2O_3$-water nanofluids. Vassallo et al. [76] reported a significant increase in the CHF for the pool boiling of $SiO_2$-water nanoparticles with a maximum value of three times compared to that of the pure water. Milanova and Kumar [95] found that the CHF of ionic solutions with $SiO_2$ nanoparticles was enhanced up to three times compared to that of conventional fluids. Nanofluids in a strong electrolyte, i.e. in a high ionic concentration, yielded higher CHF than buffer solutions. Xue et al. [96] conducted experiments on pool boiling with CNTs-water nanofluids. They found that the CHF, the transition boiling and the minimum heat flux in the film boiling were significantly enhanced.

Park et al. [97] conducted experiments of nucleate boiling heat transfer up to CHF using CNTs. They found that CHFs of all aqueous solutions increased at all CNT concentrations as compared

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to that of pure water. For multi-walled CNTs with the polyvinylpyrrolidone polymer dispersant used in their study, the optimum CNT concentration was 0.001% and the CHF increased 200% as compared to that of pure water at that concentration. They also observed deposition of CNTs on the heat transfer surface during bubble formation and departure. The surface images taken by SEM after CHF experiments showed that as the CNT concentration increased, the CNT deposition on the surface also increased. But beyond the optimum CNT concentration of 0.001%, CNTs were conglomerated and the CHF began to decrease. As the nucleate boiling progressed, CNTs were deposited to form a thin film on the surface and the contact angle decreased. Because of this deposition, the probability of forming a large vapor blanket by bubbles at high heat flux decreased and consequently, the CHF increased. The surface deposition, however, acts as a thermal resistance to reduce the bubble generation and in turn the reduction in boiling heat transfer coefficient occurs in the entire nucleate boiling range.

Gilbert Moreno et al. [98] examined the size dependence of alumina-water nanofluid CHF using gravimetrically separated nanofluids with average particle diameters of 69, 139, 224, and 346 nm. They found that the magnitude of CHF enhancement was nearly identical for each nanofluid sample under saturated pool-boiling conditions at a concentration of 0.025 g/l in their study. Jo et al. [99] investigated the size effect using silver nanoparticles with mean particle diameters ranging from 3 to 250 nm. In contrast to the results of Gilbert Moreno et al. [98], the highest increase of about 31% in CHF occurred for the nanofluid with 3-nm particles, and the enhancement decreased with increasing particle size as shown in Fig. 20. It is obvious that the quite different results are obtained by different researchers. At present, the research studies on this aspect are still rare. Therefore, it is impossible to obtain agreed conclusions on the effects of nanoparticle material and size from analysis of the existing data. More systematic studies must be carried out to clarify the effects of nanoparticle material and size on CHF enhancement with nanofluids.

However, few studies show the deterioration of CHF in pool boiling with nanofluids. Diao et al. [85] conducted experiments of the CHF in pool boiling with Cu/R141b nano-refrigerant with a

surfactant Sodium Dodecyl Benzene Sulphonate (SDBS) on a flat surface at atmospheric pressure. They found that the CHF was deteriorated with addition of the nanoparticle. They explained that addition of the surfactant in the nanofluid increased bubble number and departure frequency, therefore facilitating the bubble coalescence which prevented the liquid from accessing the heat transfer surface and thus decreased CHF. They also conducted experiments of the nucleate pool boiling of pure R141b on the nanoparticle deposited surface and found that the CHF of pure R141b on the deposited surface was higher than that of on the bare boiling heat transfer surface without the nanoparticle deposition. It seems that it is difficult to explain their results for both increase and decrease of CHF in their pool boiling experiments. The relevant mechanisms were not provided in their study.

Sakashita [100] conducted experiments of the CHF in nucleate pool boiling with $TiO_2$/water nanofluid on a 7 mm diameter vertical copper surface at pressures from 100 to 800 kPa. They found that the nanofluid enhanced the CHF about two times at atmospheric pressure. With increasing the pressure, however, the CHF enhancement with the nanofluid decreased and almost disappeared at 800 kPa. They speculated that the CHF enhancement was caused by the improvement in the surface wettability due to the deposition of nanoparticles on the heated surface. However, they could not explain why the CHF enhancement diminished at higher pressures. However, the physical mechanisms for such a phenomenon are not explained.

Kamatchi et al. [59] conducted experiments on the CHF of nucleate pool boiling with reduced graphene oxide (rGO)/water nanofluids at different concentrations on a thin electrically heated Ni–Cr wire at atmospheric pressure. They found that addition of rGO nanoparticles in water enhanced the CHF ranging from 145% to 245 % as compared to that of the base fluid. It was identified that the rGO formed a porous layer on the surface and the thickness of the layer increased with increasing the nanofluid concentrations. The rGO deposited layer increased pore volumes to hold the liquid, and a capillary flow was induced towards the dry area below the bubbles growing on the heater surface,

which delayed the occurrence of local dryout. They analyzed mechanisms of the CHF enhancement based on surface wettability, surface roughness, and porous layer thickness and indicated that the liquid macrolayer dryout theory model is sufficient to explain the mechanism of CHF enhancement of the thin wire with rGO deposition in pool boiling of the nanofluid.

Sarafraz et al. [101] conducted experimental investigation of nucleate pool boiling heat transfer and CHF with synthesized zirconia/water–ethylene glycol nanofluids ($ZrO_2$/WEG50). WEG50 means 50/50 water/ethylene glycol mixture. The nanoparticle concentration is 0.025–0.1 vol.%. Their experimental results demonstrated that $ZrO_2$/WEG50 nanofluids could enhance the boiling heat transfer by 4.1%, 7.2%, 10.4%, and 12.1%. As already mentioned in the foregoing, such heat transfer enhancement is within the measurement uncertainty of nucleate boiling. It would be insignificant for such small increases in heat transfer. A very slight particle deposition was also observed on the heated surface after boiling experiments, which had no impact on the heat transfer coefficients but enhanced the CHF up to 29%. They speculated that the $ZrO_2$ nanoparticle deposition on the surface created a porous layer, which intensified the capillary wicking action and thus resulted in the CHF enhancement because more liquid was absorbed by the porous layer and transferred to the hotspot regions underneath the growing bubbles due to the decrease in the static contact angle. Sarafraz et al. [102] also conducted experimental investigations on nucleate pool boiling heat transfer and CHF behaviors of functionalized carbon nanotube (FCNT) and non-functionalized carbon nanotube (CNT) water based nanofluids. They found that that the FCNT nanofluids had stronger enhancements of the CHF and heat transfer coefficient than the CNT nanofluids. The fouling behaviors of FCNT and CNT nanofluids on the heat transfer surface are very different. The fouling is rectilinear for the FCNT nanofluids and it is asymptotic for the CNT nanofluids. They found that fouling formation of nanoparticles on the heat transfer surface weakened the capillary wicking action on the heater and therefore decreased the nucleate boiling heat transfer due to the fouling thermal resistance but slightly enhanced the CHF. Compared to the CNT nanofluid, the FCNT nanofluid considerably enhanced both the heat transfer coefficient and CHF because it did not change the roughness of the

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heat transfer surface significantly and had very good wettability. They found that the lower contact angle between the liquid droplet and the heat transfer surface kept more liquid to be absorbed by the porous fouling layer and thus greatly enhanced the CHF in nucleate pool boiling. This was mainly due to its lower fouling formation and its regular porous deposition on the surface.

Kwark et al. [103] optically observed a single circular nanoparticle coating formed on a boiling surface, where a single active bubble nucleation site was allowed to undergo several boiling cycles, as shown in Fig. 21. Accordingly, nanofluid boiling itself, and specifically microlayer evaporation, is responsible for producing the nanoparticle layer on the surface.

Kim et al. [90, 91] investigated the surface effect on CHF enhancement of water-based nanofluids containing alumina, zirconia, and silica nanoparticles. In their research, the deposition of nanoparticles on the heater surface significantly improved the wettability, as measured by the reduction of the static contact angle as shown in Fig. 22. Note that no appreciable differences were found between pure water and nanofluids. They inferred that the build-up of a porous layer with oxide nanoparticles increases the adhesion tension and the roughness factor (the ratio of the effective contact area to the smooth contact area), and both effects lead to a pronounced reduction of the contact angle in accordance with the modified Young-Laplace equation.

Ujereh et al. [104] investigated the effects of coating silicon and copper substrates with nanotubes on nucleate pool boiling heat transfer. Different CNT array densities and area coverage were tested with FC-72. They found that fully coating the substrate surface with CNTs was highly effective in reducing the incipience superheat and greatly enhancing both nucleate boiling heat transfer coefficients and CHF.

Ahn et al. [105] investigated pool boiling of refrigerant PF-5060 on two silicon wafer substrates coated with vertically aligned multiwalled carbon nanotubes (MWCNT) "forests" of 9 $\mu$m (type-A) and 25 $\mu$m (type-B) height. The MWCNT forests enhanced CHF by 25-28% compared to that

of bare silicon (without MWCNT coating). However, enhancement of nucleate boiling heat transfer was not found to be sensitive to the height of the MWCNT forests. In contrast, for the film boiling regime, Type-B MWCNT yielded 57% higher heat transfer at the Leidenfrost point compared to that of bare silicon. However, for the type-A MWCNT, the film boiling heat transfer values were nearly identical to the values obtained on bare silicon. SEM images with a top view of the MWCNT structures obtained before and after the experiments did not show any change of the inherent morphology of the MWCNT structures. But further studies are still needed to clarify the nucleate boiling heat transfer enhancement and the CHF enhancement mechanisms

From the afore-going review and analysis of the selected studies on CHF in pool boiling, it seems that the CHF enhancement in the nucleate pool boiling with nanofluids is mainly caused due to the deposited porous coating on the boiling heat transfer surface and change of the surface conditions. The thin nanoparticle porous layer deposited on the heat transfer surface during nucleate boiling of nanofluids and thus the CHF can be enhanced due to the improved wettability of the heating surface as the liquid can be absorbed into the heating surface through the capillary function the micro-pores in the nanoparticle porous layer. However, completely and systematic definite theory and physical mechanisms linking the improved wettability and the CHF enhancement on the nanoparticle layer have not yet been developed due to the very complicated physical phenomena of nucleate pool boiling and CHF with nanofluids. The available explanations of the CHF enhancement mechanisms using the traditional CHF theory and mechanisms are only qualitative from the observed phenomena.

Characteristics and mechanisms of the CHF enhancement with nanofluids have been identified from the review and analysis in terms of the effects of primary parameters such as nanoparticle concentration, nanoparticle material and size, heater size, system pressure, existence of additives and experimental conditions. Further research work is needed to incorporate the impact of microscale deposition of nanoparticles with nanoscale pores and the information of bubble dynamics

in the microscale boiling and two-phase flow underneath the bubble generation, departure and coalesce. In fact, there lack such complete and systematic knowledge and fully understanding of the nucleate boiling and CHF phenomena with nanofluids. It is difficult to uncover the underlying mechanisms leading to the CHF mechanisms and models only from the current large-scale conventional nucleate boiling experiments on the nucleate pool boiling and CHF with nanofluids, which only yield time-averaged and space-averaged information of the very complex phenomena of nucleate pool boiling and CHF. Therefore, it is essential to understand the fundamental mechanisms of the CHF enhancement in nanofluids through careful designed experiments and adopting state-of-the-art measurement techniques including flow visualization, local and instantaneous measurements (for example, direct measurement of the time-dependent temperature and liquid-vapor phase distributions on the heater surface in high heat-flux nucleate boiling) and systematic experiments covering a wide range of test parameters because the CHF is strongly dependent on the test pressures, heat transfer surface geometry and orientation.

Furthermore, the primary reason for the CHF enhancement is the change of the microstructure and topography of the heat transfer surface due to the nanoparticle deposition on the surface during the boiling process, not because of the nanofluid itself. The deposited nanoparticle layer improves the characteristics of the heated surface, such as the surface wettability, roughness, and capillary wicking performance, resulting in significant CHF enhancement. The interaction between the nanofluids and the heat transfer surface should be well understood in order to understand the CHF enhancement phenomena and mechanisms. Furthermore, there is no comprehensive theory explained the mechanisms of the CHF enhancement over a wide range of nanoparticle sizes and concentrations. In particular, the occurrence of CHF was inconsistent among different research groups. Furthermore, the surfactants used in the nanofluids may increase or decrease the CHF. The combined function and mechanism of surfactants and nanoparticles should be systematically investigated. Therefore, effort should be made to achieve a comprehensive theory of CHF with nanofluids and quantitative prediction methods and models for the CHF with nanofluids

should also be targeted through integrating the proper physical properties. Furthermore, development of CHF enhancement technology is urgently needed and the economic feasibility of using nanofluids should also be evaluated.

**Flow boiling heat transfer and CHF with nanofluids in macroscale channels**

Flow boiling and CHF phenomena are much more complicated compared to those in pool boiling. Many studies of flow boiling heat transfer and CHF with nanofluids have been conducted in recent years. The available studies include the thermal performance of thermosyphons, evaporation heat transfer in heat pipes, spray cooling of nanofluids and flow boiling of nanofluids in macroscale channels and microchannels etc. However, both flow boiling heat transfer and CHF enhancement and deterioration have been reported. The maximum enhancement was up to 400% while the maximum deterioration was 55%. Furthermore, various mechanisms have been proposed to explain the experimental results of the heat transfer and CHF phenomena in flow boiling. However, due to the very complicated phenomena involved in flow boiling in different channels with the effects of several parameters such as types of nanoparticles, concentration, nanoparticle size, operation pressure and different channels etc., there are still big challenges in obtaining the knowledge and theory of flow boiling. Especially various relevant thermal physical properties have not been well understood. Physical properties such as thermal conductivity, the specific heat, latent heat of evaporation, surface tension and contact angle are critical in understanding the flow boiling heat transfer and CHF mechanisms and further developing prediction methods and models. Without proper these important physical properties, it is difficult to obtain reliable results and to understand the mechanisms. Furthermore, it is essential to develop reliable heat transfer enhancement technology in engineering application. However, poor understanding of the fundamentals and mechanisms may not be able to achieve it at present.

***Research on flow boiling heat transfer and mechanisms with nanofluids in macroscale channels***

Compared to the nucleate pool boiling research, studies on flow boiling with nanofluids are very limited. Furthermore, quite contradictory experimental results exist in these studies. Table 4 lists several selected studies on flow boiling heat transfer with nanofluids in macroscale channels. Some researchers found that the flow boiling heat transfer performance was deteriorated with addition of nanoparticles while others reported the heat transfer was enhanced. Furthermore, the relevant physical mechanisms have been investigated to explain the observed flow boiling heat transfer performance but not yet well understood so far.

Khandekar et al. [106] investigated the overall thermal resistance of a closed two-phase thermosiphon using water and various water based nanofluids ($Al_2O_3$, CuO and laponite clay) as working fluids. All these nanofluids showed inferior thermal performance relative to pure water. However, Henderson et al. [107] investigated flow boiling of R134a based nanofluids in a horizontal tube and have found flow boiling could be enhanced. Some reported noticeable decrease in the heat transfer coefficient was observed and a liquid film of high particle concentration may be formed on the tube surface. No agreement on the heat transfer mechanisms have been reached so far.

Xue et al. [57] studied the thermal performance of a CNTs-water nanofluid in a closed two-phase thermosyphon and found that the nanofluid deteriorated the heat transfer performance. Liu et al. [108] reported that boiling heat transfer in their thermosphon was greatly enhanced using a Cu-water nanofluid in a miniature thermosyphon as shown in Fig. 23.

Ma et al. [109] reported that the heat transport capacity of an oscillating heat pipe was significantly increased using a diamond nanoparticles-water nanofluid. Liu et al. [110] studied in a flat heat pipe evaporator and found that the heat transfer coefficient and the

CHFs of CuO-water nanofluids were enhanced by about 25% and 50%, respectively, at atmospheric pressure whereas about 100% and 150%, respectively, at a pressure of 7.4 kPa. They also found that there was an optimum mass concentration for attaining a maximum heat transfer enhancement. Furthermore, Liu and Qiu [111] studied boiling heat transfer and CHF of jet impingement with CuO-water nanofluids on a large flat surface and found that boiling heat transfer was deteriorated while the CHF was enhanced compared to that of pure water.

Park et al. [112] studied flow boiling of nanofluids in a horizontal plain tube having an inside diameter of 8 mm. A noticeable decrease in the heat transfer coefficient was observed in their study. A liquid film of high particle concentration may be formed on the tube surface. Akhavan-Behabadi et. al. [113] investigated the effect of CuO nanoparticles on flow boiling heat transfer of R600a-Polyester mixture (99/1) inside a horizontal smooth tube having an inner diameter of 8.26 mm. The nanoparticle concentrations of 0.5–1.5 wt.%. They found that the nano particles enhanced the flow boiling heat transfer. A maximum heat transfer enhancement up to 63% was achieved at the highest concentration of 1.5 wt%. Setoodeh et al. [114] conducted experiments on the subcooled flow boiling with $Al_2O_3$/water nanofluid at a concentration of 0.25 vol% in a horizontal channel with a hot spot. They found that the heat transfer was enhanced. The heat transfer coefficient increased with increasing the surface roughness and the mass flux.

Nikkhah et al. [115] conducted experiments of flow boiling with CuO/water nanofluids in an upward conventional heat exchanger. They analyzed the surface images taken with the digital microscopic imaging system and found that the thickness of deposited layer and roughness of surface significantly increased with increasing time, which could affect the wettability of surfaces and the contact angle of bubbles. The higher fouling resistances were measured with increasing

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concentration and mass flux of nanofluids. However, the fouling resistances were significantly reduced with increasing the wall temperature at higher heat flux when the heat transfer was changed from the convection dominated heat transfer to the nucleate boiling dominated heat transfer. It should ne mentioned that fouling should be avoided in practical application. If the heat transfer enhancement is caused due to the fouling of nanoparticles on the tube surface. It would use a coating to enhance the flow boiling heat transfer rather than using a nanofluid.

Sarafraz et al. [116] conducted experimental study and visualization of subcooled flow boiling with CuO/water nanofluids at concentrations of 0.1–0.3 wt% in an upward flow in an annular channel. The measured boiling heat transfer coefficient decreased with increasing the nanoparticle concentration. The observed bubbles were larger with decreasing the mass flux and increasing the heat flux. The bubble behaviors may be used to explain the heat transfer mechanisms with the nanofluids. However, further deep analysis of the bubble dynamics is needed in understanding the physical mechanisms.

Paul et al. [117] investigated the rewetting phenomenon in a vertical tube with bottom flooded by $Al_2O_3$/water nanofluids, with emphasis on estimating the apparent rewetting temperature and the construction of boiling curve from the temperature–time responses recorded during the rewetting phenomenon. They found that the rewetting of the nanofluids took place faster than in pure water and therefore the heat transfer and CHF were enhanced due to the rewetting. They conjectured that the deposition of nanoparticles resulted in the formation of micro-cavities and in turn altered the surface wettability and roughness, which thereby led to the heat transfer and CHF enhancements and an earlier collapse of vapor film.

Sarafraz and Hormozi [118] conducted experimental study on the flow boiling heat transfer of MWCNT, CuO, and $Al_2O_3$ water based nanofluids in an upward annulus heat exchanger. They found that MWCNT-water nanofluids had higher heat transfer performance and lower thermal fouling resistance than those of the other two nanofluids. Their results showed that the heat transfer

coefficient of the MWCNT-water nanofluid increased with increasing the nanoparticle concentration. They also fund that $Al_2O_3$-water nanofluid had higher heat transfer coefficients than those of the CuO-water nanofluids. They observed fouling of nanoparticles on the heat transfer surface. As shown in Fig. 24, the fouling resistance of MWCNT/water decreased with increasing nanoparticle concentration while those of $Al_2O_3$/water and CuO/water nanofluids increased with increasing nanoparticle concentration and all increased with increasing time. The flow boiling heat transfer deteriorated with time for all three nanofluids. The main reason was due to the deposition of nanoparticles on the heat transfer surface, which could reduce the surface roughness and nucleation sites and consequently deteriorated the heat transfer. As already mentioned, fouling should be avoided when using a nanofluid in practical application. In this case, using nanofluids for flow boiling heat transfer is not recommended. Furthermore, the heat transfer behaviors are changing in the boiling processes, which makes it difficult to predict the heat transfer coefficients. As already mentioned, fouling should be avoided when developing a new heat transfer enhancement technology for practical engineering application. If the heat transfer enhancement would be caused due to the coating of nanoparticles, it would be better to use a coating technology rather than using nanofluids.

Wang and Su [119] experimentally investigated the characteristics of saturated flow boiling heat transfer of $\gamma$-$Al_2O_3$/$H_2O$ nanofluids with 20 nm diameter and 0.1%, 0.5% volume concentration in a vertical tube. The effects of surface heat flux (50-300 kW/m$^2$), pressure (0.2–0.8 MPa) and mass flux (350-1100 kg/ m$^2$s) on the flow boiling heat transfer were investigated. The most enhancement was about 86% for $\gamma$-$Al_2O_3$/$H_2O$ nanofluid saturated flow boiling heat transfer compared to those of deionized water. The average Nusselt number was increased by 23% and 45% respectively for 0.1 vol.% and 0.5 vol.%. The Nusselt number increases when increasing the surface heat flux, the volume concentration of nanoparticle and the test pressure. Furthermore, they reported the nanoparticles deposited on the heating surface by SEM observation and nanoparticles did not change obviously after the boiling. They attributed this to the continuous operation of an ultrasonic oscillation. In

addition, the mass flux has insignificant effect on the heat transfer enhancement. It should be mentioned that unique variables of nanofluid saturated flow boiling need to be ensured as far as possible and the changes of nanoparticles should be avoided when investigating the heat transfer enhancement mechanisms. The density of nanofluid was regularly measured to monitor the change of nanofluids. Fig. 25 shows the nanoparticles deposit on the heating surface, which is due to the water evaporation process and the nanoparticles stay in the recess of the heating surface. Compared to the deionized water, the Nusselt number was increased for the nanofluids, and the mean enhancement rates were about 19% and 47% respectively for the volume concentrations of 0.1% and 0.5% under the condition of 600 ± 50 kg/ $m^2$s of mass flux and 0.4 MPa of pressure as shown in Fig. 26.

In summary, the heat transfer enhancement in flow boiling with nanofluids are mainly attributed to the following key mechanisms:

a)      The nanoparticle deposition on the heated surface,

b)      The reduction of the boundary layer height due to the disturbance of nanoparticles and the formation of molecular adsorption layer on the surface of nanoparticles,

c)      The inhibition of the dry patch development by the structural disjoining pressure and the enlarged percentage of liquid film evaporation heat transfer region with the nanoparticles,

d)      Higher thermal conductivity or high viscosity of nanofluid due to the nanoparticle addition and

e)      Improved bubble dynamics and flow patterns due to nanoparticle suspension.

However, understanding of the heat transfer mechanisms of flow boiling with nanofluids is far from sufficient due to the very complicated phenomena and mechanisms. Furthermore, there are

quite contradictory results from different studies. The modification of the surface wettability due to the nanoparticle deposition on the heat transfer surface is one of the main explanations for the flow boiling heat transfer enhancement by some researchers while it is also one of the most commonly explanations for the heat transfer deterioration by others. This must be clarified. Otherwise, it is impossible to develop a practical heat transfer enhancement technology for engineering application due to the contradictory mechanisms.

### *Research on CHF and physical mechanisms in flow boiling with nanofluids in macroscale channels*

A number of studies of CHF with nanofluids have been conducted to understand the phenomena and mechanisms. Table 5 lists several elected studies on CHF in flow boiling with nanofluids in macroscale channels. For the CHF in nanofluid flow boiling, most of the available studies have reported the CHF enhancement. The maximum enhancement could reach100%.

Kim et al. [120, 121] conducted internal flow boiling CHF experiments of flow boiling with dilute alumina, zinc oxide, and diamond water-based nanofluids inside tube. They varied the concentration of the nanofluids from 0.001 vol. % to 0.1 vol. %, and the mass flux from 1000 kg/m$^2$s to 2500 kg/m$^2$s. They found that the nanofluids exhibited a significant CHF enhancement with respect to pure water at high mass fluxes of 2000-2500 kg/m$^2$s. However, there was no enhancement at a lower mass flux of 1000 to 1500 kg/m$^2$s. They suggested that some nanoparticles were deposited on the boiling surface during the experiments. Such particle deposition increased the wettability of the boiling surface.

Ahn et al. [122] investigated CHF in flow boiling with 0.01-vol. % alumina–water nanofluids in a copper tube. They used the flow velocity from 0 m/s (pool boiling) to 4 m/s in their experimental study. Nano/microstructures were formed on the heat transfer surface during flow boiling of the nanofluids, significantly changing the surface morphology. However, the surface roughness change

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alone was not enough to explain the observed CHF enhancement in flow boiling. The surface wettability change due to the nanoparticle deposition was identified as a key parameter accounting for the CHF enhancement. Furthermore, ad hoc tests were performed to assess the effect of nanoparticle deposition on the heat transfer surface. The CHF on the nanoparticle-coated heat transfer surface at a given flow velocity in pure water increased more than that of a bare surface in pure water as shown in Fig. 27. It is clearly shown in Fig. 27 that both the CHFs of the nanofluid and on the nanoparticle-coated surface are higher than those of pure water and the predicted CHF by the Katto and Kurata correlation [123]. Furthermore, in order to understand the CHF enhancement mechanisms, Ahn et al. [124, 125] conducted visualization of CHF phenomena in flow boiling with pure water on a nanoparticle-coated heater to interpret the effect of the nanoparticles on the CHF enhancement. They postulated that the enhanced surface wettability of the nanoparticle-coated heater influenced the flow boiling regime entirely, and delayed the CHF, based on classical models. Fig. 28 shows their observed CHF occurrence processes on the bare and nanoparticle coated specimens. The difference between the CHF phenomena of a bare heater and nanoparticles-coated heater can be explained by the behaviours of the vapour mushroom on the surface. According to the bubble crowding model, the CHF is generally triggered by turbulent fluctuations on the heat transfer surface. However, for nanofluid CHF phenomena in their study, the mechanism that the CHF was triggered by the vapour mushroom covering on the heat transfer surface can be used to explain the observed results from visualization. There were clearly large vapour mushrooms when the CHF occurring on both bare and nanoparticles-coated heaters. However, the near CHF phenomena were quite different from each other because the flow regimes on the nanoparticles-coated surface fast developed at higher heat flux than on the bare surface and therefore, the wetting zone of nanoparticle-coated surface was larger than that of the bare surface at the same heat flux. From the point of view at the near CHF, the former had the sharp liquid-vapour interface which was deemed as the non-nucleate boiling due to a large mushroom and the later had the non-sharp liquid-vapour interface which was still deemed as nucleate boiling under large mushroom as shown in Fig. 29. In

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addition, the liquid over the nanoparticle-coated surface moved fast to the heated surface and tended to maintain the nucleate boiling, not to transit into film boiling.

Kim et al. [126, 127] reported nanoparticle deposition on the heater surface after nanofluid flow boiling and considered this to be the main cause behind the observed CHF enhancement. They found CHF enhancement of up to 70%, with a nanoparticle content of less than 0.01% by volume of alumina in water. This again shows that only a small nanoparticle concentration is required to obtain dramatic CHF enhancements during nanofluid flow boiling. Several studies on CHF with various nanofluids under different test conditions have been conducted in various channels. These covers the low pressure and low flow conditions [128, 129], the effect of micro/nanoscale structures on CHF [130], flow boiling in downward-facing channels [131], CHF with magnetic nanofluids [132] and magnetic field effect on CHF with ferrofluid in annulus [133]. In general, CHF enhancement has been achieved but understanding the mechanisms is quite different and this needs to be further investigated.

From selected studies on the CHF enhancement in flow boiling with nanofluids, most available studies have attributed the CHF enhancement to the nanoparticle deposition on the heat transfer surface because it decreases the surface contact angle and thus modified the surface wettability. Other explanations on the CHF enhancement include the following key mechanisms:

a) It enhances lateral wicking of liquid into the microlayer regions of the evaporating meniscus, causing a slower rise in local wall temperature.

b) It increases available active nucleation sites.

c) It yields faster rewetting which results in an earlier collapse of vapor film on the heat transfer surface.

However, the research in this aspect is far from understanding. Quite different mechanisms have been proposed by different researchers. Particularly, the nanoparticle deposition may also cause CHF

deterioration as reported by some researchers. The nanoparticle deposition on the heat transfer surface would be one of the main reasons for the CHF enhancement, and other mechanisms need to be further understood through systematic investigation. Already mentioned in nanofluid pool boiling, this nanoparticle deposition is also a reason for the CHF deterioration by some researchers. Besides, the nanoparticle suspension in nanofluids might also be a reason that cannot be ignored. Therefore, investigations into the physical mechanisms of CHF in nanofluid flow boiling should seek both the nanoparticle deposition on the surfaces and nanoparticle suspension in the nanofluids. Other mechanisms might also be explored to explain the complication CHF phenomena in flow boiling with nanofluids, e.g. the physical properties such as latent heat of evaporation, specific heat, surface tension and contact angle etc. Apparently, poor knowledge of these critical thermal physical properties prevents from understanding the CHF mechanisms from different aspects.

Understanding of mechanisms of heat transfer and CHF enhancement of nanofluid flow boiling is insufficient so far. Further effort should be made to understand the mechanisms and possibly lead to achieving well developed theory and models. Especially, no relevant research on the influence of two phase flow patterns on flow boiling heat transfer and CHF is available in the literature because flow patterns are intrinsically correlated to the flow boiling heat transfer and CHF phenomena. Furthermore, the effects of the nanoparticle size, material, shape and concentration on flow boiling and CHF are not well understood and should be systematically investigated. The corresponding mechanisms and theoretical modeling are not available either. Therefore, more experiments should be conducted to achieve a complete understanding of the phenomena with nanofluids. New mechanisms and theoretical study are needed as well to explain and predict the results. Particularly, fouling is not allowed in practical engineering application. If the flow boiling heat transfer and CHF enhancements are mainly caused by the fouling of nanoparticle deposition on the heat transfer surfaces, it is better to develop relevant practical enhancement technology using surface coatings rather than using nanofluids. Furthermore, economic feasibility should be evaluated for the heat transfer and CHF enhancement technology with nanofluids or nano-coatings.

**Flow boiling heat transfer and CHF with nanofluids in microchannels**

Flow boiling compared to pool boiling could potentially enhance the cooling performance of a microchannel heat sink by increasing the heat transfer coefficient. Furthermore, since flow boiling relies to a great degree on latent heat transfer, better temperature axial uniformity is realized both in the coolant and the wall compared to a single-phase heat sink. In recent years, flow boiling and CHF phenomena with nanofluids in microchannels have been extensively investigated, but understanding of the fundamentals and mechanisms is still poor. There are still big challenges when using nanofluids in microchannels. The question posed here is whether nanoparticles could further enhance an already superior performance in microscale channels. Furthermore, what is the obstacle to put flow boiling of nanofluids in microchannels into practical application?

In recent years, several studies were conducted to investigate the flow boiling heat transfer and CHF behaviors with nanofluids in mini- and micro-channels [134-142]. However, such research is very limited. Table 6 list the selected studies on flow boiling heat transfer and CHF with nanofluids in microscale channels. Systematic knowledge. mechanisms and theory on the topics have not yet established. Use of nanofluids appears promising in several aspects of flow boiling heat transfer and two-phase flow in microchannels, but still faces several challenges: (i) the lack of agreement between experimental results from different research groups and (ii) the lack of theoretical understanding of the underlying mechanisms with respect to nanoparticles.

Lee and Mudawar [135] conducted flow boiling experiments in a micro-channel heat sink using pure water and a 1% $Al_2O_3$ nanofluid solution as shown in Fig. 29. But they suggested that nanofluids should not be used in microchannels due to the deposition of the nanoparticles. No measured flow boiling heat transfer coefficients were presented in their study.

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Chehade *et al*. [136] conducted an experimental study on nanofluid convective boiling heat transfer in parallel rectangular minichannels of 800 μm hydraulic diameter. Their experiments were conducted with pure water and silver nanoparticles suspended in a water base fluid. The experimental results showed that the local heat transfer coefficient, local heat flux, and local wall temperature were affected by silver nanoparticle concentration in a water base fluid. They compared the average heat transfer coefficients of pure water, 25 mg/L and 50 mg/L silver concentration nanofluid. At the same mass flux, the average heat transfer coefficients of nanofluids are larger than those of pure water. According to the observation, the heat transfer coefficient increases with increasing the nanoparticle concentration. The maximum enhancement of the average heat transfer coefficient is about 132% for 25 mg/L and 162% for 50 mg/L. In addition, the boiling local heat transfer enhancement by adding silver nanoparticles in base fluid is not uniform along the channel flow. Better performances and the highest effect of nanoparticle concentration on the heat transfer were obtained at the mini-channel's entrance.

Few studies on flow boiling and CHF of nanofluids in microscale channels and surface coating effects and showed enhanced heat transfer and CHF behaviors with nanofluids. Duursma et al. [137] conducted experiments of subcooled flow boiling with $Al_2O_3$/ethanol nanofluids in horizontal, rectangular, high-aspect-ratio microchannels. The results showed that nanoparticles enhanced the boiling heat transfer significantly, with a peak at the concentration of 0.05%. The two-phase visualizations observed bubble confinement and deformation. The study of heat and mass transfer near the three-phase contact line revealed the important role played by this zone in two-phase flow boiling in microchannels.

Khanikar et al. [138] performed flow boiling experiments in a carbon nanotube (CNT)- coated copper microchannel. They used just water as the working fluid. Appreciable differences in the influence of the CNT coating were observed at high rather than low mass velocities. The CHF was repeatable at low mass velocities, but degraded following repeated tests at high mass velocities,

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demonstrating that high flow velocities caused appreciable changes in the morphology of the CNT-coated surface. While the CHF was enhanced by the increased heat transfer area associated with the CNT coating, the enhancement decreased following repeated tests because the CNT fin effect was compromised by the bending. This result also supported the relationship between flow boiling CHF enhancement and the nanoparticle-deposited surface. Flow boiling CHF enhancement in nanofluids is strongly related to the surface wettability, which is similar to the pool boiling CHF enhancement. Further experimental data need to be collected on the flow boiling of nanofluids to obtain a more substantial database and a better understanding of nanofluid flow boiling mechanisms. In contrast with pool boiling, the flow boiling CHF in nanofluids is still being investigated and strongly needed.

Vafaei and Wen [139, 140] investigated flow boiling heat transfer of aqueous alumina nanofluids in single microchannels with particular focuses on the CHF and the potential dual roles played by nanoparticles, i.e., (i) modification of the heating surface through particle deposition and (ii) modification of bubble dynamics through particles suspended in the liquid phase. Their flow boiling experiments reveal a modest increase in CHF by nanofluids, being higher at higher nanoparticle concentrations and higher inlet subcoolings. The bubble formation experiments show that suspended nanoparticles in the liquid phase alone can significantly affect bubble dynamics. Figure 30 shows their measured CHF Data of alumina nanofluids with two concentrations (0.011 vol.% and 0.1 vol.%) at a subcooling of 45°C. It shows that the CHF increases with increasing concentration in their study.

However, the very limited studies are not sufficient to understand the fundamentals and mechanisms of flow boiling heat transfer and CHF phenomena in microchannels. Understanding the mechanisms of flow boiling with nanofluids in microscale channels is necessary but not yet investigated so far. It is essential to conduct systematic experiments in the relevant topics. Furthermore, new theoretical study is needed as well to explain and predict the results. Especially, one could also note that some nanofluids coat the heat transfer surfaces, and hence this may

significantly influence the results. The surface effects need to be clearly separated from the fluidic effects in order to deduce the actual trends in the nanofluid data and thus build new models. Especially for microscale channels, this has often not been done in previous studies, but should be investigated. Therefore, future research should be aimed at developing new fabrication technology for stable nanofluids at first, characterizing the nanofluids, modelling their physical properties and conducting experimental and theoretical investigation on flow boiling and CHF of nanofluids in single and multi-microchannels with various nanoparticle sizes. Surface coat effect should also be considered in the modelling aspect. Particularly, development of a practical heat transfer and CHF enhancement technology using nanofluids or nano-coatings in microchannels should be explored and economic feasibility should be evaluated as well.

**Analysis and Discussion**

Numerous studies have been conducted to investigate complicated phenomena and mechanisms of nucleate pool boiling and flow boiling with nanofluids. So far, no prediction methods and models have been developed for flow boiling heat transfer and CHF with nanofluids. It is very helpful to understand the phenomena and mechanisms through analysing the existing correlations and models for boiling heat transfer and CHF by incorporating and considering the relevant nanofluid physical properties.

Examining widely quoted correlations for nucleate pool boiling heat transfer, it is not evident as to how a nanofluid will have an influence. For example, the Cooper [69] correlation Eq. (6) is based on the reduced pressure $p_r$ but nothing is known about the effect of nanofluids on the critical pressure or vapor pressure curve.

$$h_{nb} = 55 p_r^{0.12 - 0.2\log_{10} R_p} \left( -\log_{10} p_r \right)^{-0.55} M^{-0.5} q^{0.67} C \qquad (6)$$

where $h_{nb}$ is nucleate boiling heat transfer coefficient, $R_p$ is surface roughness ($\mu m$), $M$ is molecular weight, $q$ is heat flux and $C$ is a constant which is 1 for horizontal plane surfaces and 1.7 for horizontal copper tubes according to Cooper's original paper. However, comparison with experimental data suggests that better agreement is achieved if a value of 1 is used also for horizontal tubes. Note that the heat transfer coefficient is a fairly weak function of the surface roughness parameter $R_p$, which is seldom well known. A value of $R_p =$ 1 is suggested for technically smooth surfaces. Thus, a nano-coating may have an effect but would be very small.

Taking the Forster and Zuber [143] correlation:

$$h_{nb} = 0.00122 \left[ \frac{k_L^{0.79} c_{pL}^{0.45} \rho_L^{0.49}}{\sigma^{0.5} \mu_L^{0.29} h_{LV}^{0.24} \rho_V^{0.24}} \right] \Delta T_{sat}^{0.24} \Delta p_{sat}^{0.75} \tag{7}$$

it would predict an increase in heat transfer coefficients through the increase in liquid thermal conductivity and a decrease in heat transfer coefficients by the increase in liquid viscosity and surface tension. In Eq. (7), $k_L$ is liquid thermal conductivity, $c_{pL}$ is liquid specific heat, $\rho_L$ and $\rho_V$ are liquid and vapor density, $\sigma$ is surface tension, $\mu_L$ is liquid dynamic viscosity, $h_{LV}$ is latent heat, $\Delta T_{sat}$ and $\Delta p_{sat}$ are the superheated temperature difference between the wall temperature and the saturated fluid temperature and pressure difference between the saturated pressure at wall temperature and the saturated fluid pressure respectively.

Taking the Stephan and Abdelsalam [144] correlation for water derived by multiple regression:

$$h_{nb} = 0.0546 \left[ \left( \frac{\rho_V}{\rho_L} \right)^{1/2} \left( \frac{q D_{bub}}{k_L T_{sat}} \right) \right]^{0.67} \left( \frac{h_{LV} D_{bub}^2}{a_L^2} \right)^{0.248} \left( 1 - \frac{\rho_V}{\rho_L} \right)^{-4.33} \frac{k_L}{D_{bub}} \tag{8}$$

$$D_{bub} = 0.0146\beta \left[ \frac{2\sigma}{g(\rho_L - \rho_V)} \right]^{1/2} \tag{9}$$

Here $D_{bub}$ is bubble departure diameter, the contact angle $\beta$ is assigned a fixed value of 35° irrespective of the fluid, $T_{sat}$ is the saturation temperature of the fluid in $K$, $a_L$ is the liquid thermal diffusivity and $g$ is gravity constant. It can be summarized that the dependency of heat transfer on the liquid thermal conductivity, density and viscosity are as follows:

- $h_{nb} \propto k_L^{-0.166}$

- $h_{nb} \propto \sigma^{0.083}$

Thus, it would predict a decrease in heat transfer coefficients through the increase in liquid thermal conductivity and an increase in heat transfer coefficients by the increase in surface tension while no liquid viscosity effect is concerned.

On the other hand, neither liquid thermal conductivity nor liquid viscosity is found in the critical heat flux model of Lienhard and Dhir [145] for pool boiling:

$$q_{crit} = 0.149 h_{LV} \rho_V \left[ \frac{\sigma g(\rho_L - \rho_V)}{\rho_V^2} \right]^{1/4} \tag{10}$$

where $q_{crit}$ is critical heat flux (CHF). According to this correlation, CHF increases with increasing surface tension and liquid density. On the other hand, $q_{crit}$ is only proportional to $\sigma^{1/4}$, so its effect is rather weak.

With respect to flow boiling heat transfer models, the nanofluid effect on the nucleate boiling contribution would be the same as in the previous section, utilizing the convective heat transfer correlation for annular flow of Kattan et al. [146]:

$$h_{cb} = 0.0133 \mathrm{Re}_L^{0.69} \mathrm{Pr}_L^{0.4} \frac{k_L}{\delta} \tag{11}$$

$$\mathrm{Re}_L = \frac{4\rho_L u_L \delta}{\mu_L} \qquad (12)$$

$$\mathrm{Pr}_L = \frac{c_{pL}\mu_L}{k_L} \qquad (13)$$

where, $h_{cb}$ is convective heat transfer coefficient, $Re_L$ is liquid film Reynolds number, $Pr_L$ is liquid Prandtl number and $\delta$ is liquid film thickness. It can be summarized that the dependency of heat transfer on the liquid thermal conductivity, density and viscosity are as follows:

- $h_{cb} \propto k_L^{0.6}$

- $h_{cb} \propto \mu_L^{-0.29}$

Thus, this predicts an increase in heat transfer coefficient through the increase in the liquid thermal conductivity but a decrease in heat transfer coefficient by the increase in liquid viscosity, while no surface tension effect is concerned.

Regarding the critical heat flux in saturated flow boiling in microchannels, the recent empirical correlation of Wojtan et al. [147]:

$$q_{crit} = 0.437\left(\frac{\rho_V}{\rho_L}\right)^{0.073} We_L^{-0.24}\left(\frac{L_H}{D}\right)^{-0.72} Gh_{LV} \qquad (14)$$

$$We_L = \frac{G^2 L_H}{\rho_L \sigma} \qquad (15)$$

can be used for the analysis here, where $We_L$ is Weber number based on heated length, $D$ is tube diameter, $L_H$ is heated length and $G$ is mass flux. Similar to the critical heat flux model of Lienhard and Dhir [145] for pool boiling, neither liquid thermal conductivity nor liquid viscosity is found in this expression. However, critical heat flux increases with increasing surface tension and liquid density according to this expression.

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From the above analysis, it is clearly shown that the physical properties such as surface tension, liquid density and viscosity have a significant effect on nucleate pool boiling heat transfer, convective flow boiling and CHF in both pool and flow boiling processes. So far, the lack of knowledge of these physical properties of nanofluids greatly limits an evaluation of the possible effect. This also poses a serious question: which physical properties should we use to reduce experimental data for nanofluids? The data reduction methods used might be one of the reasons why the available experimental are contradictory.

Furthermore, nucleation density site, bubble dynamics, thin film evaporation, dryout, liquid-vapour interfacial force and boiling surface structures are the main factors which affect nucleate boiling heat transfer and CHF [9-12, 15-17, 148, 149]. For nanofluids, the size and type of nanoparticles are important, but it is still unclear how they would affect the underlying mechanisms. Considering the controversies in the available studies, the aggregation of nanofluids could be an important factor affecting boiling performance, which needs to be clarified quantitatively. Furthermore, the mechanisms that explain the substantial increase in boiling heat transfer and CHF still need to be verified.

In the long run, as one very important research topic, it is also essential to be targeted to develop flow patterned based prediction methods for flow boiling heat transfer, critical heat flux and two phase pressure drop with nanofluids because boiling heat transfer, CHF and two phase pressure drop mechanisms are intrinsically related to the bubble dynamics and flow patterns [12, 148-150]. Such mechanistic prediction methods based on the flow patterns may predict the heat transfer, CHF and two phase pressure drops more accurately. Therefore, it is essential to develop the relevant research in future.

**Conclusions and future research needs**

There are still many unresolved problems with respect to our knowledge of boiling heat transfer, CHF, two-phase flow, flow regimes and pressure drop with nanofluids. Many controversies exist with numerous conflicting experimental results and trends of nanofluid two phase flow, boiling heat transfer and CHF phenomena. In general, nanofluids have been found to increase, decrease or have no effect on boiling heat transfer and CHF. Furthermore, putting the boiling heat transfer and CHF enhancement technology in to practical engineering application is essential when conducting relevant research but there are still big challenges. The following conclusions have been obtained and future research needs have been identified according to the deep analysis of the selected studies in this comprehensive review:

1) Physical properties such as thermal conductivity, viscosity, surface tension, specific heat, latent heat of evaporation and contact angles have a significant effect on nucleate pool boiling, flow boiling and CHF phenomena and mechanisms. To properly present the experimental results and to understand the physical mechanisms related to the two-phase, boiling heat transfer and CHF phenomena, the nanofluid physical properties should be systematically investigated to set up a consistent database of physical properties and to further develop generalized prediction methods and models for the physical properties.

2) Nucleate pool boiling heat transfer and its mechanisms should be further investigated. The inconsistencies between different studies should be clarified. Furthermore, the effects of nanoparticle size and type on heat transfer should be studied. The boiling heat transfer mechanisms responsible for these trends should be identified and be able to explain why nucleate heat transfer may be enhanced, no

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change or decreased. Experimental data should also be segregated by fluids which deposit on the boiling heat transfer surface and those that do not, in order to prove if the fluid alone can enhance performance.

3) CHF phenomena in pool boiling process should be systematically investigated and the physical mechanisms responsible for its delay to higher heat fluxes should be definitively identified. Furthermore, a new model for CHF should be developed according to the experimental nanofluid data and the CHF mechanisms.

4) More experiments on nanofluid two-phase flow, flow boiling heat transfer and CHF should be conducted in both macroscale channels to evaluate the potential benefits of nanofluids. These should also include heat transfer performance, CHF, two-phase flow patterns and pressure drop in various types of channels. Especially, the two-phase flow, flow boiling heat transfer and CHF characteristics should be related to the corresponding flow patterns. So far, no systematic knowledge and theory have yet been established.

5) Nanofluid two-phase flow, flow boiling heat transfer and CHF phenomena in microchannels should be understood through systematic experimental and theoretical studies. It is essential to evaluate if nanofluids could achieve significant flow boiling heat transfer and CHF enhancement in microchannels.

6) The sediment or coating of nanoparticles on the boiling heat transfer surface is a big question that needs to be resolved. For example, if such a coating is beneficial, then it could be applied more easily using a coating process rather than nanofluid deposition. If such a nanoparticle layer has adverse effects, then ways to prevent it are needed or

the correct nanofluids should be found. When investigating new heat transfer enhancement technology with nanofluids, it is essential to avoid fouling on the heat transfer surface and to further develop an enabling practical technology in engineering application.

7) In general, the nanoparticle types, sizes and shapes may have a significant effect on two phase flow, boiling heat transfer and CHF behaviors. However, no systematic knowledge in this aspect has yet been achieved so far. Therefore, effort should be made to understand the phenomena, mechanisms and to further develop relevant models with these effects.

8) In general, the nanoparticle concentration has remarkable influence on the boiling heat transfer and CHF with nanofluids and there is an optimum value of nanoparticle concentrations. It therefore necessary to obtain such an optimum value for either heat transfer or CHF when conducting relevant experimental studies.

9) Two phase flow regimes are critical in understanding relevant boiling heat transfer and CHF phenomena. However, little research has been conducted in this respect. Furthermore, no prediction methods and models for boiling heat transfer and CHF are available so far. Therefore, models and prediction methods that include the nano-particle effects on the flow regimes should be developed based on accurate measurements and observations of two phase flow, boiling heat transfer and CHF with nanofluids.

10) From a practical point of view, considering application of nanofluids to actual thermal-flow systems, good stability of nanoparticles is one of the critical necessary conditions. Surfactants are generally used to improve dispersion stability of nanoparticles. However, surfactants may

enhance or deteriorate the boiling heat transfer and CHF. It is essential to clarify the effects of surfactants on the experimental results. The combined function of surfactants and nanoparticles should be systematically investigated to understand the physical mechanisms. Furthermore, the economic evaluation of the heat transfer and CHF enhancement with nanofluids should be performed. If the technology is not economic, it is not necessary to develop such a technology. Otherwise, new feasible application of nanofluids should be explored.

**Acknowledgements**

**Nomenclature**

$C$        constant in Eq. (6)

$c_{pL}$        liquid specific heat, J/kgK

$c_{pbf}$        base fluid specific heat, J/kgK

$c_{pnf}$        nano fluid specific heat, J/kgK

$c_{pnp}$        nano particle specific heat, J/kgK

$CA$        contact angle

$CHF$        critical heat flux

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*CNT*    carbon nanotube

*D*    tube diameter, m

$D_{bub}$    bubble departure diameter, m

*DI*    deionized

*FCNT*    functionalized carbon nanotube

*G*    mass flux, $kg/m^2s$

*GA*    gum acacia

*g*    gravity constant, 9.81 $m/s^2$

$h_{cb}$    convective heat transfer coefficient, $W/m^2K$

$h_{LV}$    latent heat of evaporation, J/kg

$h_{nb}$    nucleate boiling heat transfer coefficient, $W/m^2K$

$k_L$    liquid thermal conductivity, W/mK

$L_H$    heated length, m

*M*    molecular weight

*MWCNT*    multiwalled carbon nanotube

*Nu*    Nusselt number

$Pr_L$    liquid Prandtl number, defined by Eq. (13)

$P_{out}$    outlet pressure, Pa

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$p_r$       reduced pressure

$q$       heat flux, $W/m^2$

$q''$       heat flux, $W/m^2$

$q_{crit}$       critical heat flux (CHF), $W/m^2$

$Ra$       surface roughness, $\mu m$

$R_p$       surface roughness, $\mu m$

$Re_{Dh}$       Reynolds number based on hydraulic diameter

$Re_L$       liquid film Reynolds number, defined by Eq. (12)

$SDBS$       Sodium Dodecyl Benzene Sulphonate

$SEM$       scanning electron microscopy

$SWCNT$ single walled carbon nano tube

$T_{in}$       temperature of the fluid at inlte, K

$T_{sat}$       saturation temperature of the fluid, K

$T_s$       saturation temperature of the fluid, K

$T_{tc4}$       wall temperature at location 4, K

$T_W$       wall temperature, K

$u_l$       liquid film velocity, m/s

$We_L$       Weber number based on heated length, defined by Eq. (15)

### Greek symbols

$a_L$      liquid thermal diffusivity, $m^2/s$

$\beta$      contact angle, °

$\Delta p_{sat}$      superheated pressure difference between the pressure at wall temperature and saturated fluid pressure, Pa

$\Delta T_{sat}$      superheated temperature difference between the wall temperature and saturated fluid temperature, K

$\delta$      liquid film thickness, m

$\phi$      volume fraction of spheres in the suspension

$\mu_f$      viscosity of ambient fluid, $N/m^2s$

$\mu_L$      liquid dynamic viscosity, $N/m^2s$

$\mu_{mix}$      viscosity of the mixed fluid, $N/m^2s$

$\theta$      contact angle, °

$\rho_{bf}$      base fluid density, $kg/m^3$

$\rho_L$      liquid density, $kg/m^3$

$\rho_{nf}$      nanofluid density, $kg/m^3$

$\rho_{np}$      nano particle density, $kg/m^3$

$\rho_v$     vapor density, kg/m$^3$

$\sigma$     surface tension, N/m

$\tau$     time, second

**Subscripts**

*bf*     base fluid

*bub*     bubble

*cb*     convective boiling

*crit*     critical

*f*     fluid

*H*     heated

*in*     *inlet*

*L*     liquid

*l V*     liquid-vapor

*mix*     mixture

*nb*     nucleate boiling

*nf*     nanofluid

*np*     nano particle

*out*    outlet

*p*    constant pressure

*sat*    saturation

*s*    saturation

*tc*    thermocouple

*V*    vapor

*W*    wall

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**128.**    S. W. Lee, S. D. Park, S. Kang, S. M. Kim, H. Seo, D. W. Lee, and I. C. Bang, "Critical heat flux enhancement in flow boiling of $Al_2O_3$ and SiC nanofluids under low pressure and low flow conditions," *Nucl. Eng. Technol.*, vol. 44, no. 4, pp. 429-436, 2012.

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**130.**    H. S. Ahn, and M. H. Kim, "The effect of micro/nanoscale structures on CHF enhancement," *Nucl. Eng. Technol.*, vol. 43, no. 3, pp. 205-216, 2011.

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**Table 1. Thermal Conductivities of Various Solids and Liquids at Room Temperature.**

| Material | Form | Thermal Conductivity (W/mK) |
|---|---|---|
| Carbon | Nanotubes | 1800-6600 |
| | Diamond | 2300 |
| | Graphite | 110-190 |
| | Fullerenes film | 0.4 |
| Metallic solids (pure) | Silver | 429 |
| | Copper | 401 |
| | Nickel | 237 |
| Non-metallic solids | Silicon | 148 |
| Metallic liquids | Aluminum | 40 |
| | Sodium at 644 K | 72.3 |
| Others | Water | 0.613 |
| | Ethylene Glycol | 0.253 |
| | Engine Oil | 0.145 |
| | R134a | 0.0811 |

**Table 2 Selected studies on nucleate pool boiling heat transfer with nanofluids.**

| Literature | Nanofluids | Main research contents | Main conclusions |
|---|---|---|---|
| Yang and Maa [62] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was enhanced. |
| Tu et al. [63] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was enhanced. |
| Wen and Ding [64] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was enhanced. |
| Wen et al. [65] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was enhanced. |
| Ghopkar et al. [66] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was enhanced. |
| Witharana [67] | Au-water, $SiO_2$-water and $SiO_2$-ethylene glycol | Nucleate pool boiling heat transfer | Both heat transfer enhancement and deterioration were observed |
| Yang and Liu [68] | Au-R-141b | Nucleate pool boiling heat transfer | Heat transfer was enhanced. |
| Das et al. [70, 73] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was deteriorated. |
| Bang and Chang [71] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was deteriorated. |
| Li et al. [72] | CuO-water | Nucleate pool boiling heat transfer | Heat transfer was deteriorated. |
| You et al. [74] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer was deteriorated. |
| Kim et al. [75] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer | Heat transfer remained unchanged. |
| Vassallo et al. [76] | $SiO_2$-water | Nucleate pool boiling heat transfer | No appreciable heat transfer change |
| Prakash Narayan et al. [77] | $SiO_2$-water | Nucleate pool boiling heat transfer | Heat transfer was deteriorated. |
| Tang et al. [78] | $\delta$- $Al_2O_3$ -R141b | The surfactant effect of the boiling heat transfer | Heat transfer was deteriorated without surfactant while was enhanced with surfactant. |
| He et al. [79] | ZnO-ethylene glycol/water | Nucleate pool boiling heat transfer and mechanisms | Heat transfer was enhanced. Nanoparticle deposition was observed. |
| Shoghl et al. [80] | ZnO-water, $\alpha$- $Al_2O_3$ -water and MWCNs-water | Nucleate pool boiling heat transfer and mechanisms | Both the surface and the properties of the nanofluids have a significant effect on the heat transfer characteristics |
| Shamoradi et al. [81] | $Al_2O_3$ -water | Nucleate pool boiling heat transfer and mechanisms | Heat transfer decreases with increasing the nanofluid |

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| | | | |
|---|---|---|---|
| Sarafraz and Hormozi [82] | Al$_2$O$_3$-ethylene glycol/water | Nucleate pool boiling heat transfer and mechanisms | Heat transfer decreases with increasing the nanofluid concentration and deposition was observed |
| Sarafraz and Hormozi [83] | MWCNTs-water | Nucleate pool boiling heat transfer and mechanisms | Heat transfer decrease and increase mechanisms were analyzed. |
| Sarafraz and Hormozi [84] | CuO-water | Nucleate boiling heat transfer with and without surfactants | Heat transfer was deteriorated without surfactants while it was enhanced with surfactants |
| Diao et al. [85] | Cu/R141b | Nucleate pool boiling heat transfer and mechanisms | Heat transfer was enhanced. The enhancement ratio increases with increasing the concentration. |
| Park and Jung [86] | CNTs-R123 and CHTs-R134a | Nucleate pool boiling heat transfer and mechanisms | Heat transfer was enhanced at lower heat flux while no heat transfer enhancement was observed at high heat flux. |
| Bang et al. [87] | | Nucleate boiling heat transfer and visualization | Heat transfer mechanisms |
| Xia et al. [15] | MWCNTs-water | Nucleate pool boiling heat transfer, visualization and mechanisms | Heat transfer was enhanced. The mechanisms were analyzed according to the bubble patterns. |

**Table 3 Selected studies on CHF in nucleate pool boiling heat transfer with nanofluids.**

| Literature | Nanofluids | Main research contents | Main conclusions |
|---|---|---|---|
| Tu et al. [63] | $Al_2O_3$ -water | CHF in nucleate pool boiling | CHF was enhanced. |
| You et al. [74] | $Al_2O_3$ -water | CHF in nucleate pool boiling | CHF was enhanced. |
| Kim et al. [75] | $Al_2O_3$ -water | CHF in nucleate pool boiling | CHF was enhanced. |
| Vassallo et al. [76] | $SiO_2$-water | CHF in nucleate pool boiling | CHF was enhanced. |
| Diao et al. [85] | Cu/R141b | CHF in nucleate pool boiling | CHF was enhanced. |
| Kim et al. [90], and [91] | $Al_2O_3$-water, ZrO2-water and $SiO_2$-water | CHF and mechanisms in nucleate pool boiling | CHF enhancement. A porous layer of nanoparticles formed. |
| Kim et al. [93] and Kim and Kim [92] and [94] | $Al_2O_3$-water and $SiO_2$-water | CHF in nucleate pool boiling | CHF was enhanced. |
| Milanova and Kumar [95] | $SiO_2$-water | CHF and mechanisms in nucleate pool boiling | CHF was enhanced. |
| Xue et al. [96] | CNTs-water | CHF in nucleate pool boiling | CHF was enhanced. |
| Park et al. [97] | CNTs-water | CHF in nucleate pool boiling | CHF was enhanced. |
| Skashita [100] | $TiO_2$-water | CHF in nucleate pool boiling | CHF was enhanced. |
| Kamatchi et al. [59] | rGO-water | CHF in nucleate pool boiling | CHF was enhanced. |
| Sarafraz et al. [101] | $ZrO_2$-water-ethylene glycol | CHF in nucleate pool boiling | CHF was enhanced. |
| Sarafraz et al. [102] | FCNT-water and CNT-water | CHF in nucleate pool boiling | CHF was enhanced. |

**Table 4 Selected studies on flow boiling heat transfer with nanofluids in macroscale channels.**

| Literature | Nanofluids | Main research contents | Main conclusions |
|---|---|---|---|
| Khandekar et al. [106] | $Al_2O_3$, CUO and laponite clay-water | Overall thermal resistance of a closed two-phase thermosiphon | Heat transfer was deteriorated. |
| Henderson et al. [107] | R134a-based nanofluids | Flow boiling in a horizontal rube | Heat transfer was enhanced. |
| Xue et al. [57] | CNTs-water | Thermal performance in a closed two phase thermosyphon | Heat transfer was deteriorated. |
| Liu et al. [108] | Cu-water | Flow boiling heat transfer in a miniature thermosyphon | Heat transfer was enhanced. |
| Ma et al. [109] | Diamond-water | Flow boiling heat transfer in an oscillating heat pipe | Heat transfer was enhanced. |
| Liu al. [110] | CuO-water | Flow boiling heat transfer in a flat heat pipe evaporator | Heat transfer was enhanced. |
| Liu and Qiu [111] | CuO-water | Boiling heat transfer of jet impingement | Heat transfer was enhanced. |
| Park et al. [112] | Refrigerant based nanofluids | Flow boiling heat transfer in a horizontal tube | Heat transfer was deteriorated. |
| Behabadi et al. [113] | CuO-R600a-Polyester | Flow boiling heat transfer in a horizonatl tube | Heat transfer was enhanced. |
| Setoodeh et al. [114] | $Al_2O_3$ -water | Subcooled flow boiling heat transfer in a horizontal tube | Heat transfer was enhanced. |
| Nikkhah et al. [115] | CuO-water | Flow boiling heat transfer in a upward conventional heat exchanger | Heat transfer was deteriorated. |
| Sarafraz et al. [116] | CuO-water | Subcooled flow boiling heat transfer. in an upward annular channels | Heat transfer was deteriorated. |
| Paul et al. [117] | $Al_2O_3$ -water | Flow boiling heat transfer in a vertical tube | Heat transfer was enhanced. |
| Sarafraz and Hormozi [118] | MWCNT-water, CuO-water and $Al_2O_3$ -water | Flow boiling heat transfer in an upward annulus heat exchanger | Heat transfer was deteriorated. |
| Wang and Su [119] | $\gamma$-$Al_2O_3$ -water | Flow boiling heat transfer in a vertical tube | Heat transfer was enhanced. |

**Table 5 Selected studies on CHF in flow boiling with nanofluids in macroscale channels.**

| Literature | Nanofluids | Main research contents | Main conclusions |
| --- | --- | --- | --- |
| Kim et al. [120, 121] | $Al_2O_3$ -water, ZnO-water and Diamond-water | CHF in flow boiling and mechanisms | CHF was enhanced at higher mass flux while no CHF enhancement was observed for lower mass flux |
| Ahn et al. [122] | $Al_2O_3$ -water | CHF in flow boiling and mechanisms | CHF was enhanced due to the change of surface wettability. |
| Ahn et al. [124, 125] | $Al_2O_3$ -water | CHF visualization in flow boiling and mechanisms | The nanoparticle coated heater to change surface wettability. |
| Kim et al. [126, 127] | $Al_2O_3$ -water | CHF in flow boiling and mechanisms | CHF was enhanced due to the surface wettability change. |

**Table 6 Selected studies on flow boiling heat transfer and CHF with nanofluids in microscale channels.**

| Literature | Nanofluids | Main research contents | Main conclusions |
|---|---|---|---|
| Li and Mudawar [135] | $Al_2O_3$-water | Flow boiling experiments in microchannel heat sink | No heat transfer results. Deposition of nanoparticles was observed. |
| Chehade et al. [136] | Silver-water | Flow boiling in parallel rectangular microchannel | Heat transfer was enhanced. |
| Duursma et al. [137] | $Al_2O_3$-ethanol | Subcooled flow boiling in horizontal rectangular high asp[ect ration microchannels | Heat transfer was enhanced. |
| Khanikar et al. [138] | Water in CNT coating in microchannel | Flow boiling in the nanoparticle CNT coating in microchannel | CHF was enhancement on the nanoparticle-deposited surface |
| Vafaei and Wen [139, 140] | $Al_2O_3$-water | Flow boiling in a single microchannel | CHF was enhanced. |

**List of Figure Captions**

Fig. 1. The effective thermal conductivity of ethylene glycol is improved by up to 40% through the dispersion of 0.3 vol. % Cu nanoparticles [18].

Fig. 2. Scanning electron micrographs of carbon nanotube samples: (a) single-walled nanotubes obtained by arc discharge [28]; (b) multiwalled carbon nanotubes obtained by chemical vapor deposition [32].
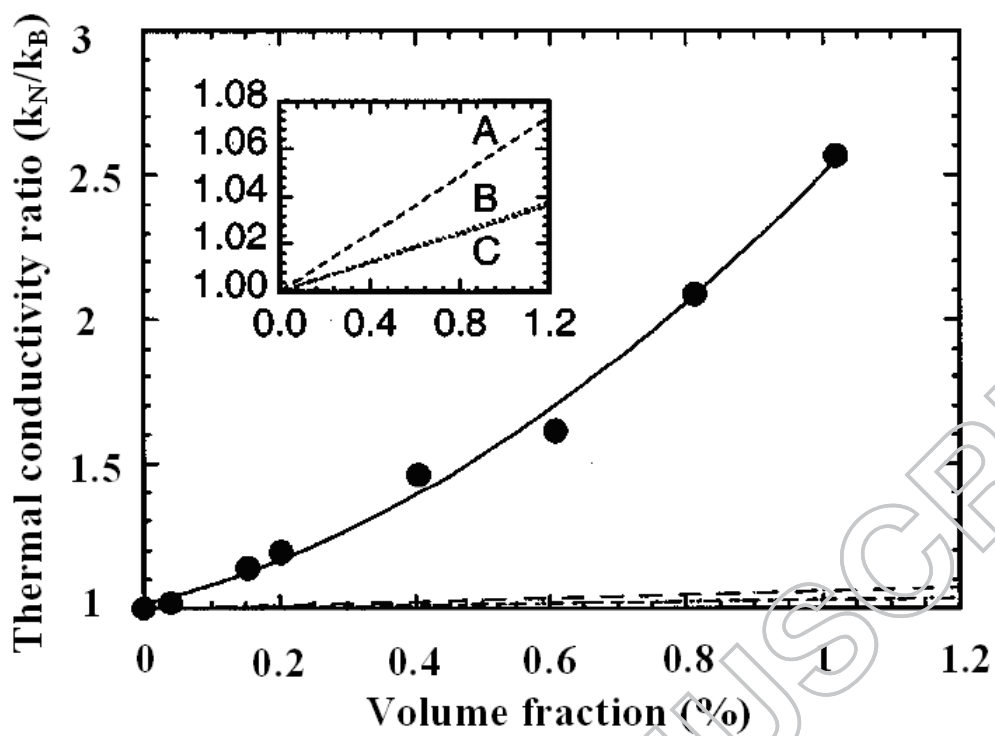
Fig. 3. Effective thermal conductivity of CNT suspensions with respect to the pure fluid as a function of nanotube volume ratio, and the prediction of (A) Hamilton-Crosser equation; (B) the Boonecaze and Brady equation; and (C) Maxwell's equation [32].

Fig. 4. Hysteresis observed for water–$Al_2O_3$-47 nm, 7% particle volume fraction [47].
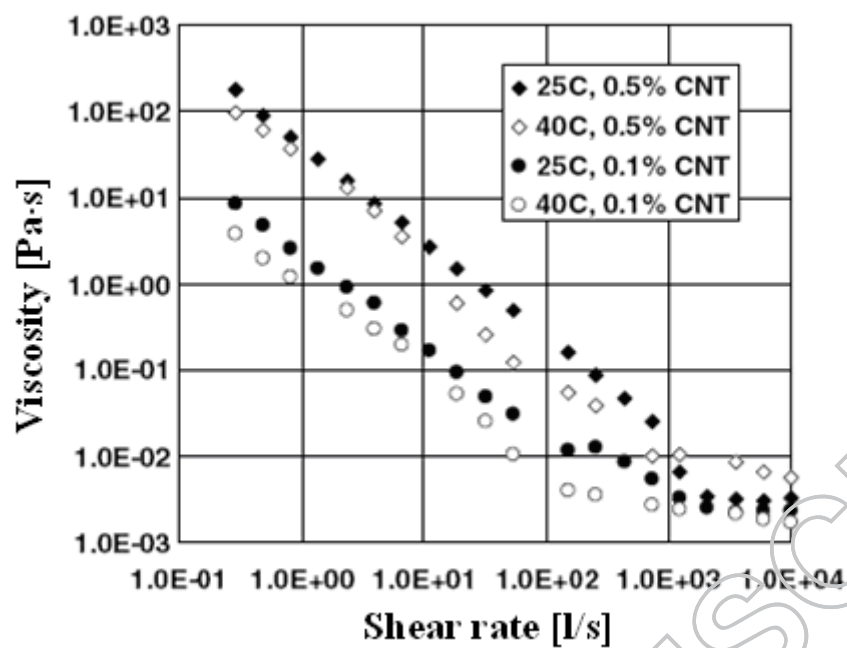
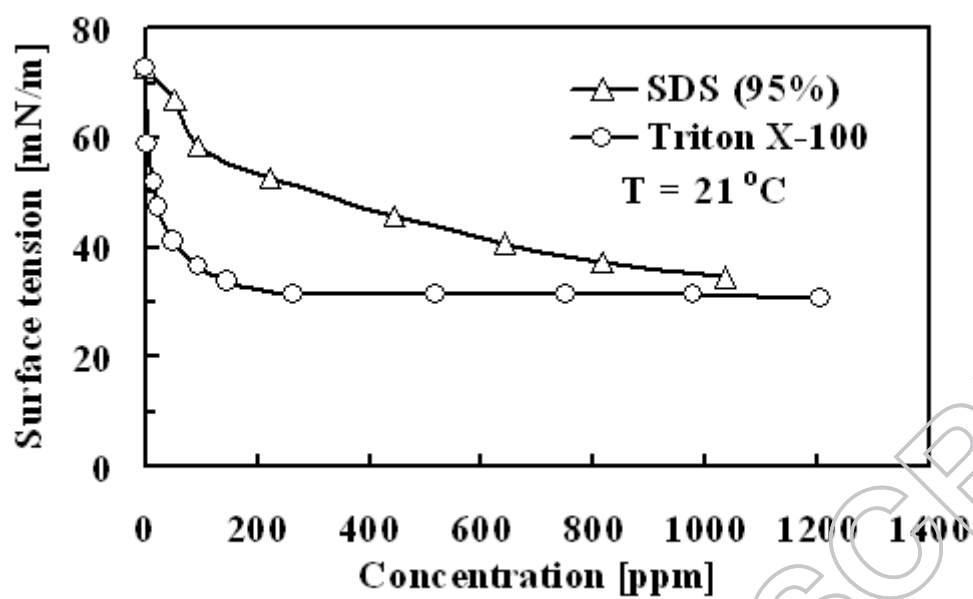Fig. 5. Viscosity of CNT nanofluids (pH = 6) [37].

Fig. 6. Variation of the measured equilibrium surface tension versus surfactant concentration [17].
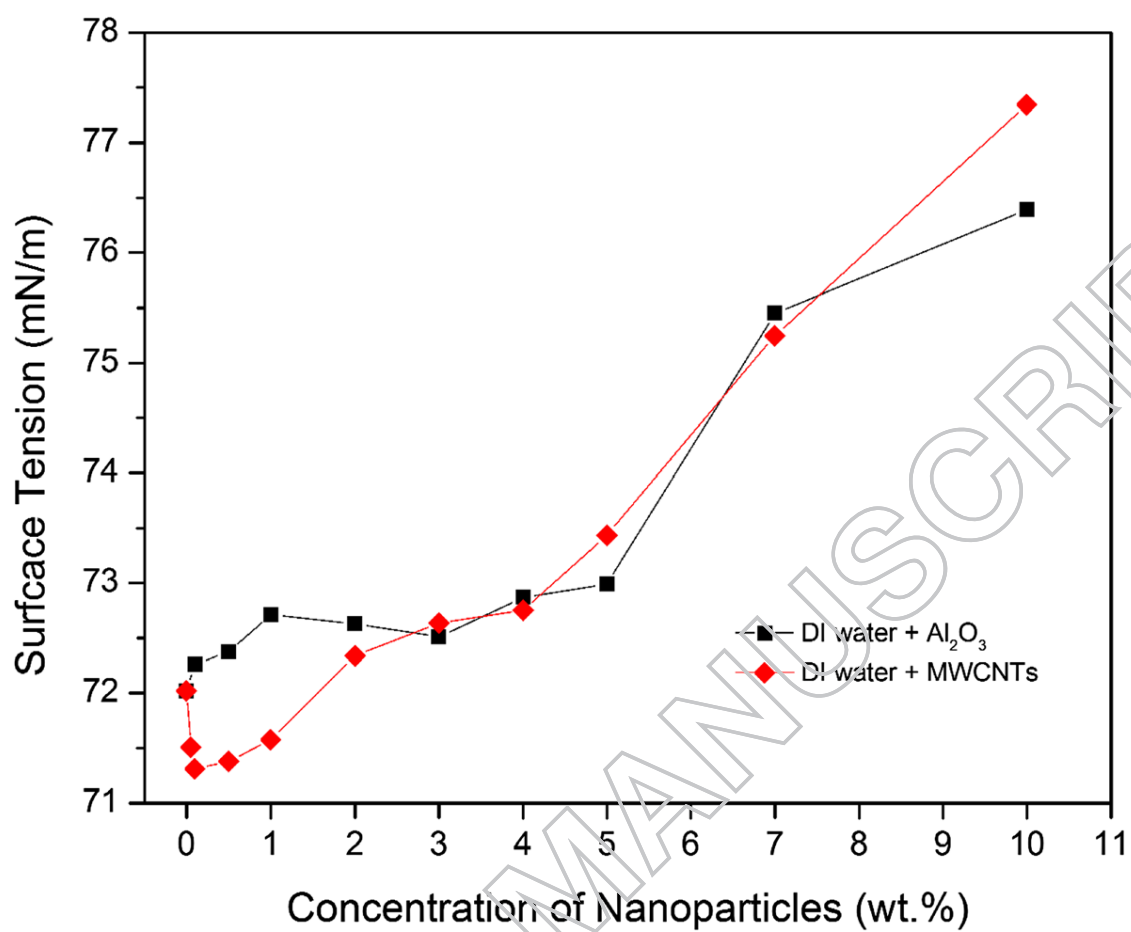
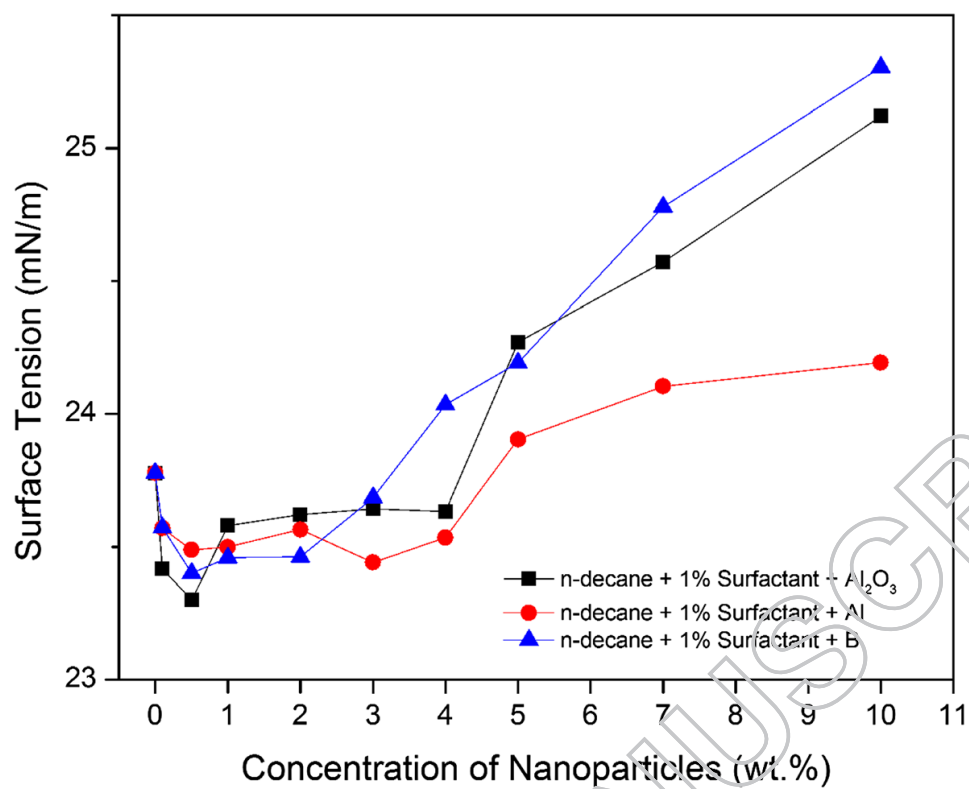Fig. 7. Surface tension variation with nanoparticle concentration for DI water based nanofluids [58].

Fig. 8. Surface tension variation with nanoparticle concentration for n-decane based nanofluids [58].
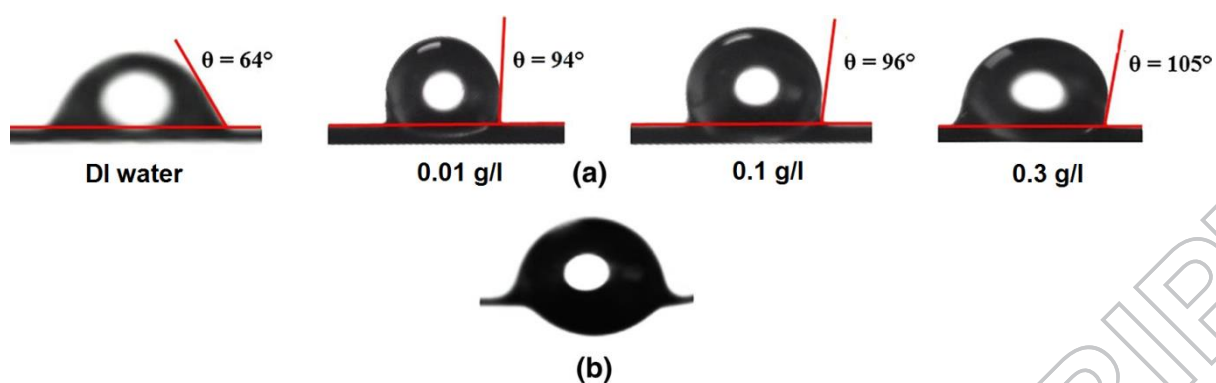
Fig. 9. Contact angle on the Ni–Cr wire heater surface a after boiling with DI water and rGO/water nanofluids b water absorption phenomena of rGO layer after 1 min for 0.3 g/l concentration [59].
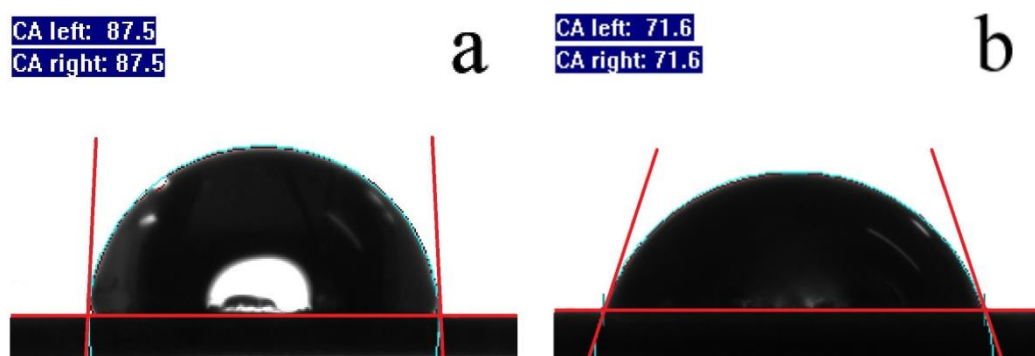
Fig. 10. Static contact angle of (a) a smooth copper surface and (b) a nanoparticles deposition surface [15].
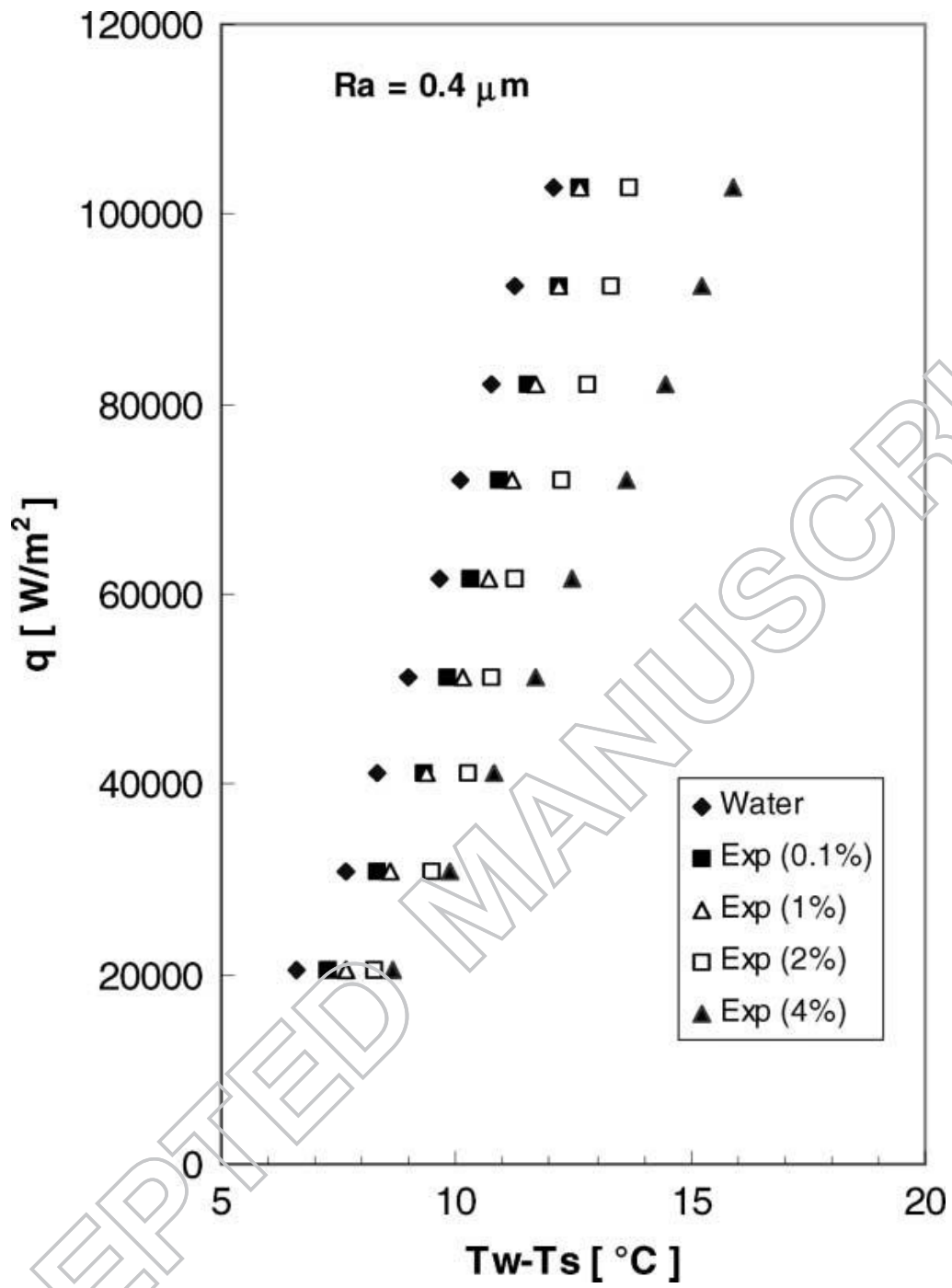
Fig. 11. (a) Pool boiling characteristics of $Al_2O_2$-water nanofluids at different particle concentrations on a smooth heater [70].
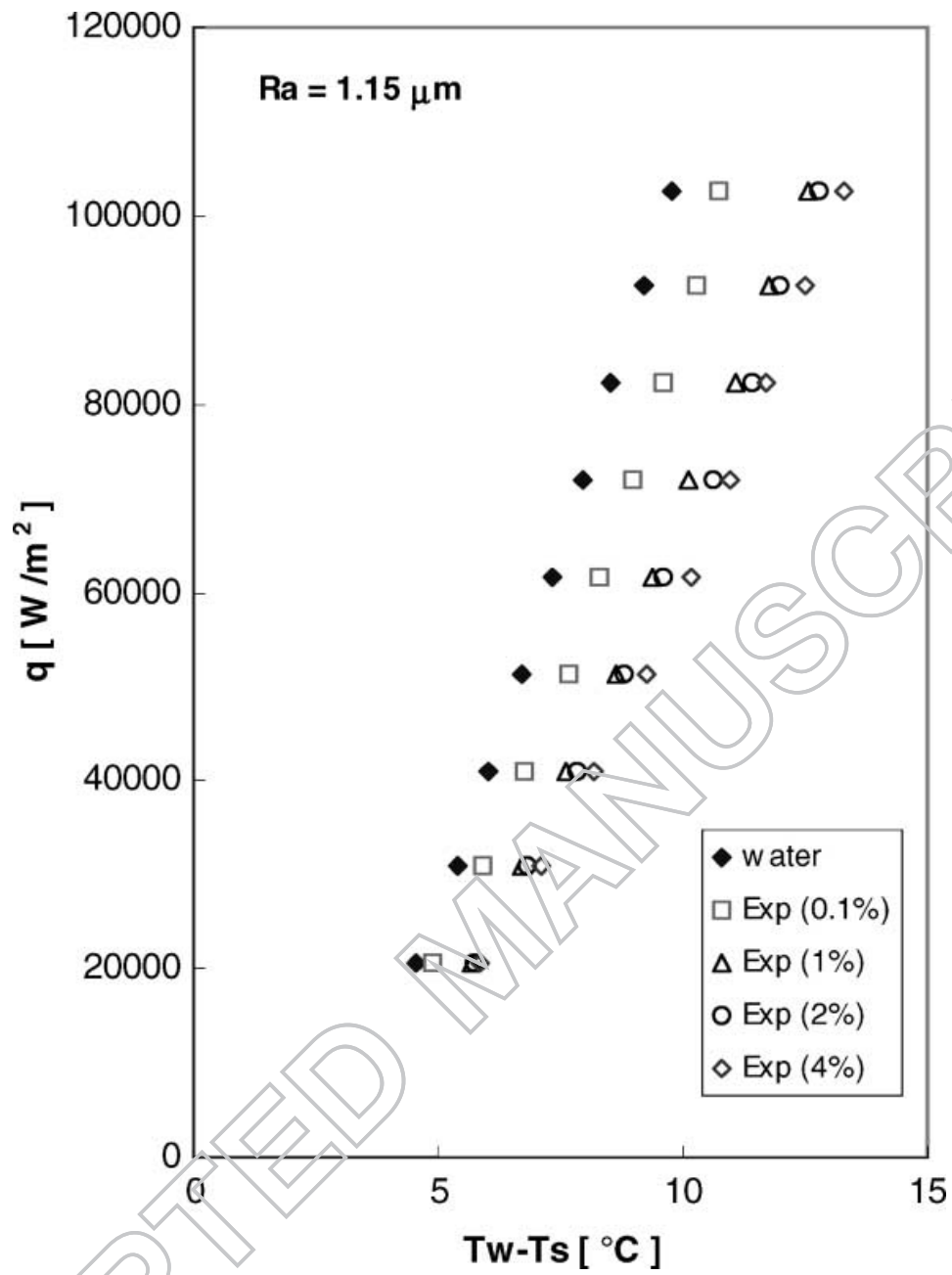
Fig. 11. (b) Pool boiling characteristics of $Al_2O_2$-water nanofluids at different particle concentrations on a rough heater [70].
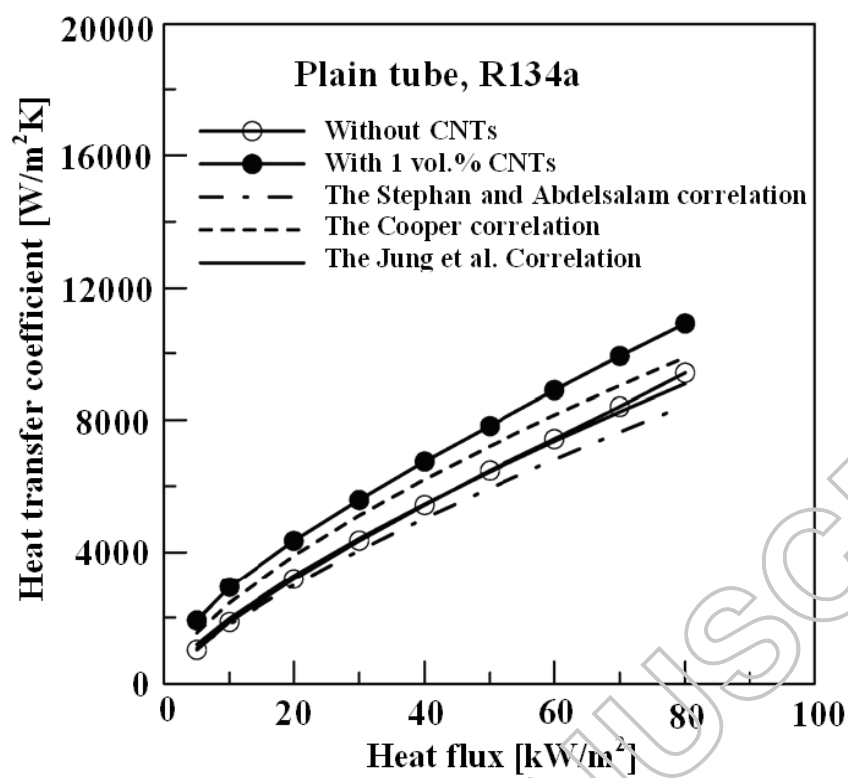
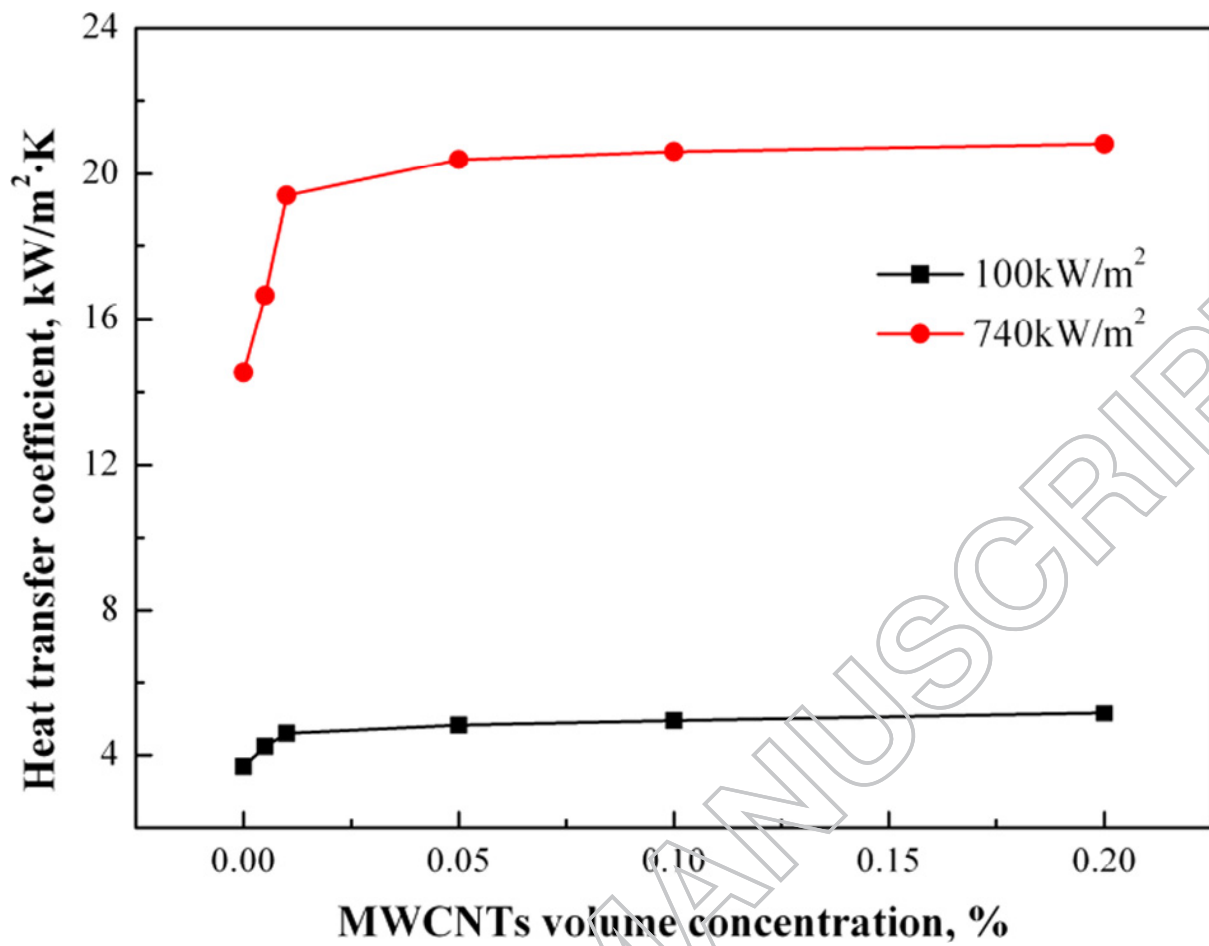Fig. 12. Boiling heat transfer coefficients with 1 vol.% CNTs for R134a [86].

Fig. 13. Variation of the boiling heat transfer coefficients of the MWCNTs nanofluids with the concentrations at two different heat fluxes of 100 kW/m$^2$ and 740 kW/m$^2$ [15].
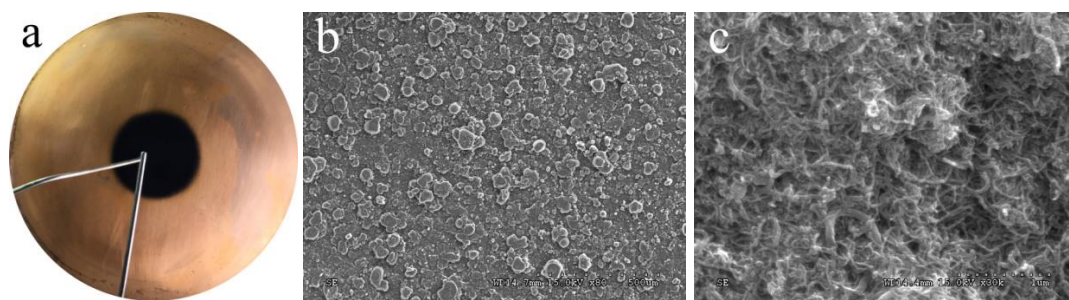
Fig. 14. Macroscopic and microscopic photographs of nanoparticles deposition: (a) by camera, (b) by ×80 SEM, (c) by ×30k SEM [15].
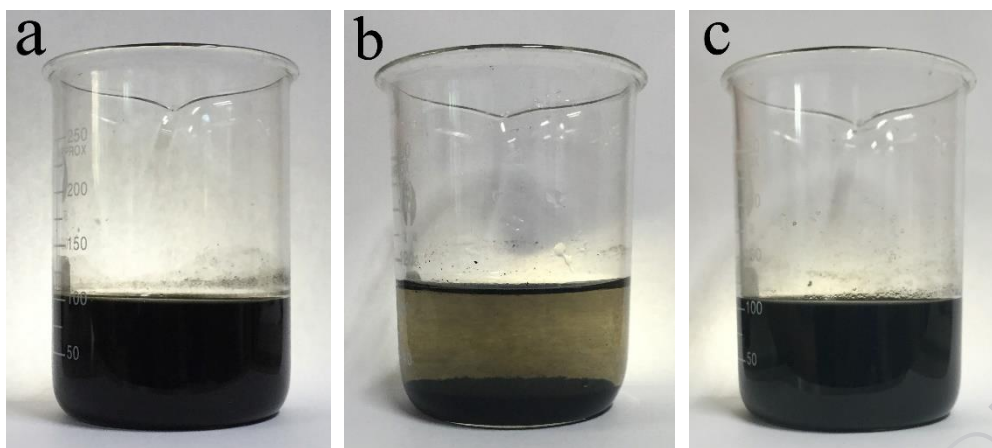
Fig. 15. Agglomeration condition of the MWCNTs nanofluids: (a) before boiling, (b) without GA after boiling, (c) with GA after boiling. [15].

Fig. 16. Evolution of 11-nm $Al_2O_3$ nanofluid droplet evaporation/dryout with sequential photographs and schematic sketch by Chon et al. [88].

Fig. 17. Boiling curves at different concentrations of $Al_2O_3$-water nanofluids [74].

Fig. 18. Sample pictures of bubbles growing on a heated wire (300 kW/m$^2$) [74].

Fig. 19. Effect of nanoparticle concentration on CHF enhancement in nanofluids. (a) $Al_2O_3$-water nanofluid on flat Cu plate with 10 × 10 mm$^2$ area [74]. b) various nanofluids on NiCr wire with 0.2-mm diameter [94].

Fig. 20. Effect of nanoparticle size on CHF enhancement in nanofluids by Jo et al. [99].

Fig. 21. Images of nanoparticle coating generated, on the heater surface [103].

Fig. 22. Static contact angles of 5-μL sessile droplets on stainless steel surfaces. (a) Pure water droplet on surface boiled in pure water, (b) alumina nanofluid droplet on surface boiled in pure water, (c) pure water droplet on surface boiled in alumina nanofluid, (d) alumina nanofluid droplet on surface boiled in alumina nanofluid [90].

Fig. 23. Effect of mass concentration of nanoparticles on boiling heat transfer coefficient of CuO-water nanofluids [108].

Fig. 24. (a) Fouling resistance of CuO–water nanofluids versus time at $T_{bulk}$ = 50°C; influence of concentration of nanofluids; (b) Influence of mass flux on fouling resistance of nanofluids [115].

Fig. 25. SEM images of heating surface before (a) and after (b) boiling [119].

Fig. 26. Effects of pressure and nanoparticle volume concentration of the Nusselt number [119].

Fig. 27. Comparison of CHF values for pure water and nanofluid on a clean surface, and pure water on a nanoparticle coated surface [122].

Fig. 28. CHF occurrence flow chart of bare and nanoparticle-coated specimens [124].

Fig. 29. (a) Flow boiling curve at measurement location tc4 for pure water and 1% $Al_2O_3$ and (b) photo of particles after being removed from microchannels [135].

Fig. 30. Variation of the critical heat flux with mass flux for deionized water and 0.001–0.1 vol.% alumina nanofluids (initial subcooling of 45°C) [140].

Fig. 1. The effective thermal conductivity of ethylene glycol is improved by up to 40% through the dispersion of 0.3 vol. % Cu nanoparticles [18].

(a)



(b)

Fig. 2. Scanning electron micrographs of carbon nanotube samples: (a) single-walled nanotubes obtained by arc discharge [28]; (b) multiwalled carbon nanotubes obtained by chemical vapor deposition [32].

Fig. 3. Effective thermal conductivity of CNT suspensions with respect to the pure fluid as a function

of nanotube volume ratio, and the prediction of (A) Hamilton-Crosser equation; (B) the Boonecaze

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CA left: 87.5
CA right: 87.5

a

CA left: 71.6
CA right: 71.6

b

Fig. 10. Static contact angle of (a) a smooth copper surface and (b) a nanoparticles deposition surface [15].

Fig. 11. (a) Pool boiling characteristics of $Al_2O_2$-water nanofluids at different particle concentrations on a smooth heater [70].

Fig. 11. (b) Pool boiling characteristics of Al$_2$O$_2$-water nanofluids at different particle concentrations on a rough heater [70].

Fig. 12. Boiling heat transfer coefficients with 1 vol.% CNTs for R134a [86].

Fig. 13. Variation of the boiling heat transfer coefficients of the MWCNTs nanofluids with the

concentrations at two different heat fluxes of 100 kW/m$^2$ and 740 kW/m$^2$ [15].

Fig. 14. Macroscopic and microscopic photographs of nanoparticles deposition: (a) by camera, (b) by ×80 SEM, (c) by ×30k SEM [15].

Fig. 15. Agglomeration condition of the MWCNTs nanofluids: (a) before boiling, (b) without GA after boiling, (c) with GA after boiling. [15].

Fig. 16. Evolution of 11-nm $Al_2O_3$ nanofluid droplet evaporation/dryout with sequential photographs and schematic sketch by Chon et al. [88].

Fig. 17. Boiling curves at different concentrations of $Al_2O_3$-water nanofluids [74].

Fig. 18. Sample pictures of bubbles growing on a heated wire (300 kW/m$^2$) [74].

(a)



(b)

Fig. 19. Effect of nanoparticle concentration on CHF enhancement in nanofluids. (a) $Al_2O_3$-water nanofluid on flat Cu plate with $10 \times 10$ mm$^2$ area [74]. b) various nanofluids on NiCr wire with 0.2-mm diameter [94].

Fig. 20. Effect of nanoparticle size on CHF enhancement in nanofluids by Io et al. [99].

Fig. 21. Images of nanoparticle coating generated, on the heater surface [103].

Fig. 22. Static contact angles of 5-μL sessile droplets on stainless steel surfaces. (a) Pure water droplet on surface boiled in pure water, (b) alumina nanofluid droplet on surface boiled in pure water, (c) pure water droplet on surface boiled in alumina nanofluid, (d) alumina nanofluid droplet on surface boiled in alumina nanofluid [90].

Fig. 23. Effect of mass concentration of nanoparticles on boiling heat transfer coefficient of CuO-water nanofluids [108].

(a)



**(b)**

Fig. 24. (a) Fouling resistance of CuO–water nanofluids versus time at $T_{bulk}$ = 50°C; influence of

concentration of nanofluids; (b) Influence of mass flux on fouling resistance of nanofluids [115].

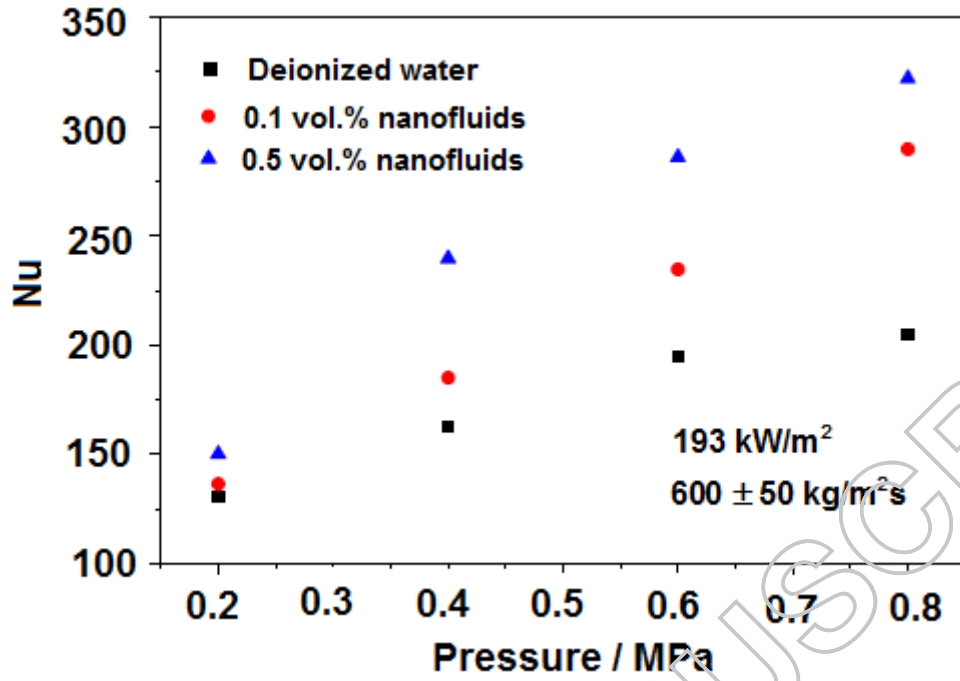Fig. 25. SEM images of heating surface before (a) and after (b) boiling [119].

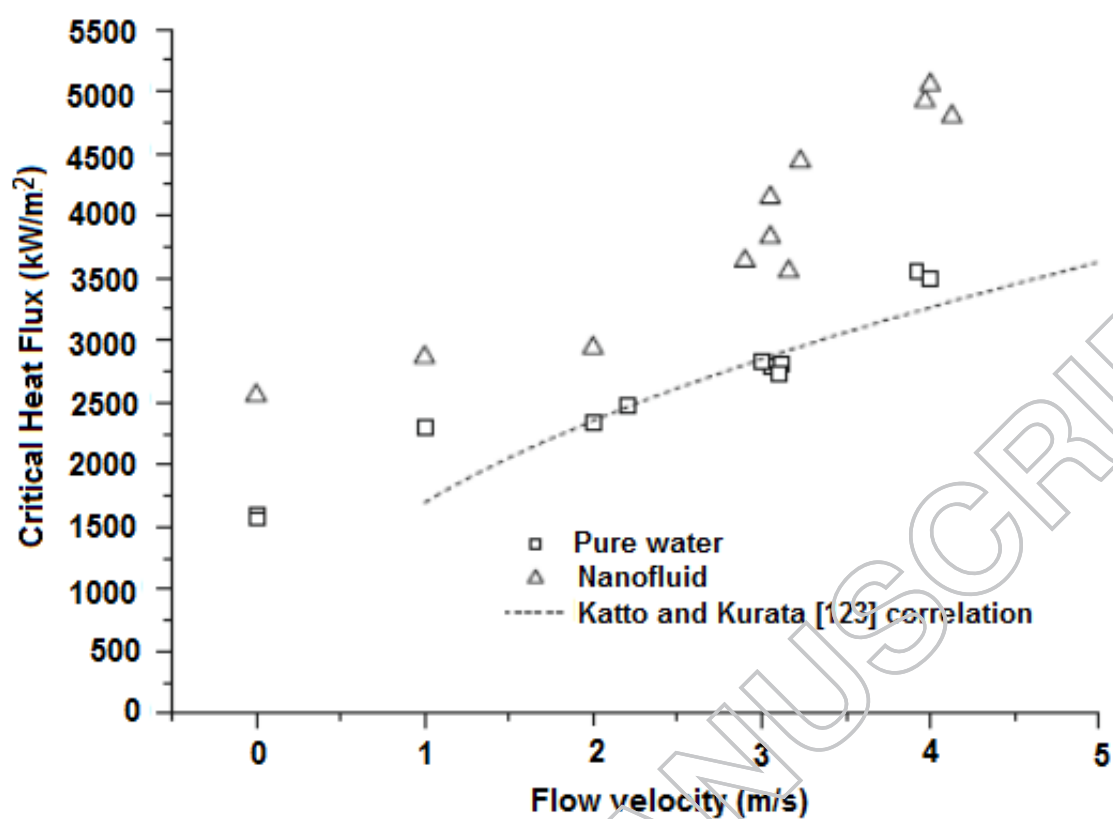Fig. 26. Effects of pressure and nanoparticle volume concentration of the Nusselt number [119].

Fig. 27. Comparison of CHF values for pure water and nanofluid on a clean surface, and pure water on a nanoparticle coated surface [122].
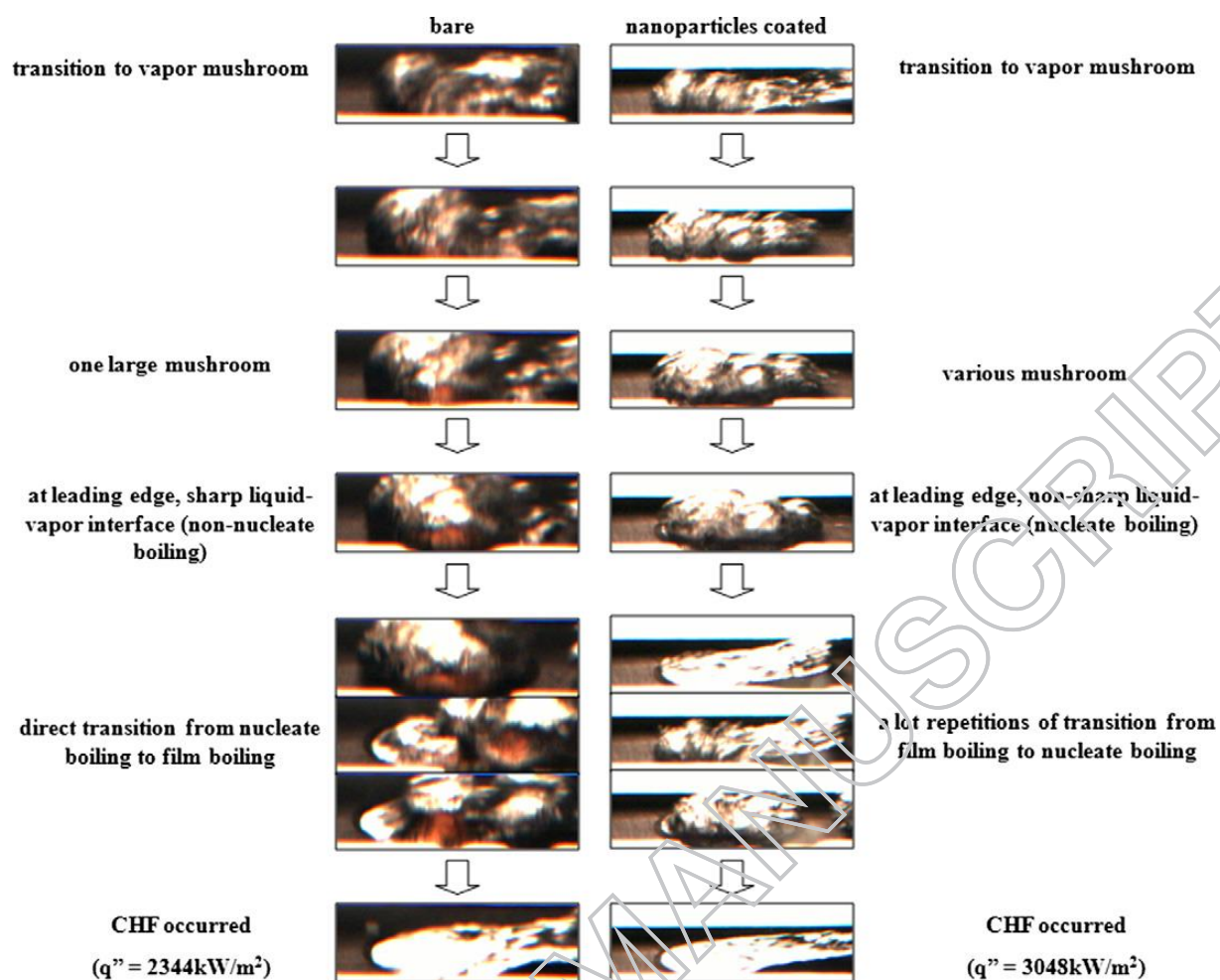
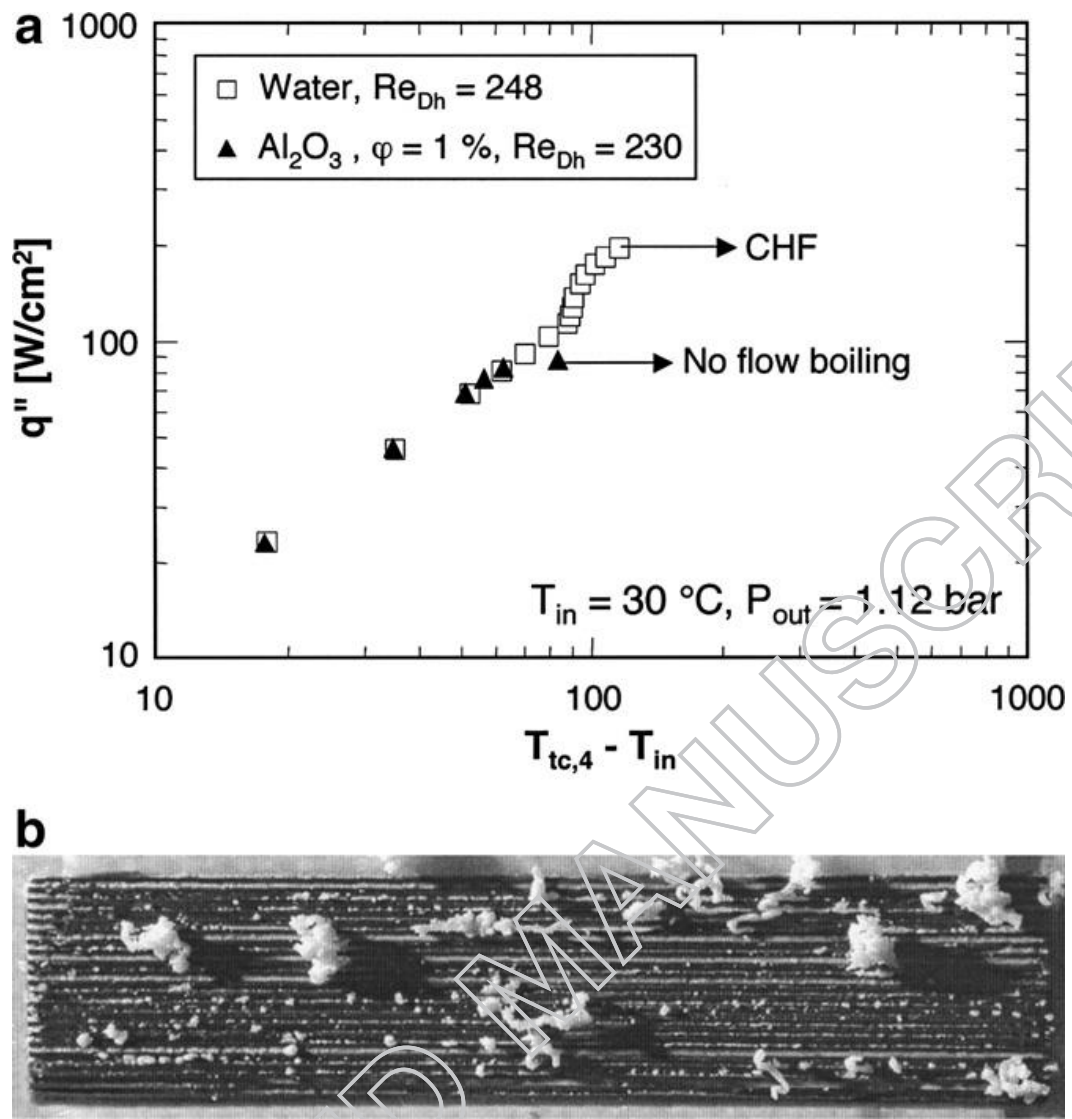Fig. 28. CHF occurrence flow chart of bare and nanoparticle-coated specimens [124].

Fig. 29. (a) Flow boiling curve at measurement location tc4 for pure water and 1% $Al_2O_3$ and (b) photo

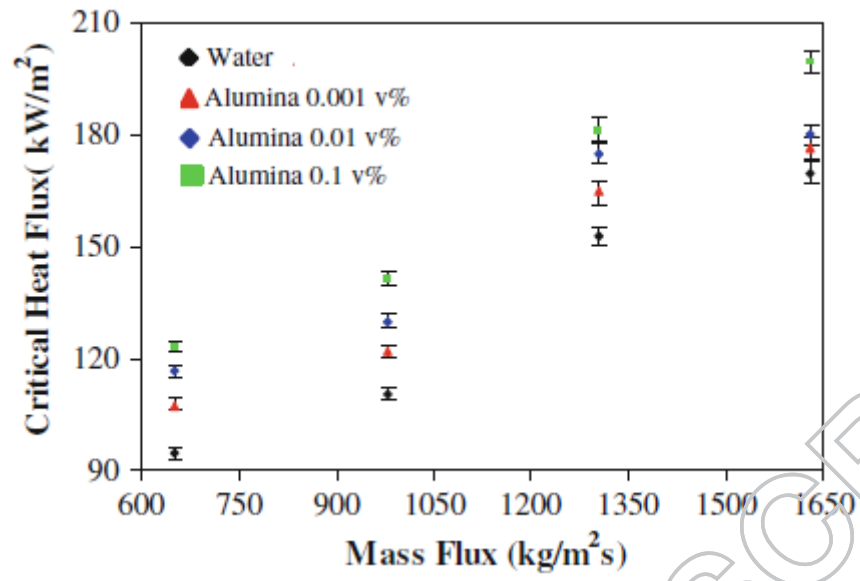of particles after being removed from microchannels [135].

Fig. 30. Variation of the critical heat flux with mass flux for deionized water and 0.001–0.1 vol.%

alumina nanofluids (initial subcooling of 45∘C) [140].

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