



Review of pool boiling enhancement with additives and nanofluids

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ABSTRACT

Enhancement of nucleate pool boiling by modifying fluid properties has drawn considerable attention in recent years. This paper provides a comprehensive review of published literature concerning enhancement methodologies of surfactant and polymer additives, and nanofluids. Each method is discussed in detail in terms of measured impact on the nucleate boiling heat transfer coefficient and critical heat flux (CHF), mechanisms proposed for any heat transfer enhancement, and predictive models. It is shown that adding surfactant to base liquid shifts the nucleate boiling region of the boiling curve towards lower surface superheats, thereby promoting earlier boiling incipience and increasing the nucleate boiling heat transfer coefficient, but the heat transfer merits of polymer addition are polymer specific. Despite significant enhancement in CHF with most nanofluids, there are many contradictory findings concerning influence of nanofluids on nucleate boiling heat transfer coefficient. These contradictions are the result of many complex influences of base liquid, nanoparticles, and initial surface roughness. Despite the potential heat transfer benefits of nanofluids, there are several serious practical concerns that must be considered carefully before deploying nanofluids in practical cooling applications.

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Nomenclature

c_p	specific heat at constant pressure	λ_m	modified wavelength for nanofluids
g	gravitational acceleration	μ	dynamic viscosity
h	heat transfer coefficient	ν	kinematic viscosity
h_{fg}	latent heat of vaporization	ρ	density
k	thermal conductivity; coefficient in Eq. (9)	σ	surface tension
q''	heat flux	ϕ	concentration
q''_{CHF}	critical heat flux		
r	bubble radius		
R_a	average surface roughness	<i>Subscripts</i>	
T	temperature	<i>bare</i>	bare surface
t	time	<i>f</i>	liquid
ΔT_{sat}	surface superheat	<i>g</i>	vapor
v_{fg}	liquid-vapor specific volume difference	<i>i</i>	incipience
		<i>nf</i>	nanofluid
<i>Greek symbols</i>		<i>sat</i>	saturation
α	contact angle	<i>vol</i>	volume
θ	orientation angle	<i>w</i>	wall/solid
λ_{bare}	wavelength in Zuber's model	<i>wt</i>	weight

1. Introduction

1.1. Pool boiling applications

Heat transfer processes are essential to daily operation in virtually every modern industry. Most of these processes employ a primary fluid to acquire, transport, and reject the heat, with liquids being preferred because of their superior thermophysical properties. This is especially the case when the liquid undergoes phase change (by boiling and/or condensation), thus capitalization on both its sensible and latent heat [1,2]. In fact, phase change processes are prevalent in a vast number of applications. They include cooling of nuclear reactor cores, fusion reactor blankets, particle accelerator targets, magnetohydrodynamic (MHD) electrode walls, supercomputers and data centers, aircraft and spacecraft avionics, hybrid vehicle power electronics, laser and microwave directed energy weapon electronics, advanced radars, X-ray medical devices, engine heads, and turbine engine blades [3]. Phase change

cooling is also crucial for quenching of metal alloy parts in pursuit of superior mechanical properties.

Boiling processes can be implemented in a variety of schemes [4], including pool boiling [5,6], macro/mini/micro-channel flow boiling [7], jet-impingement [8], and spray [9,10], as well as hybrid configurations combing two or more of these schemes [11]. Pool boiling is especially popular in many industries by virtue of its passive (pump-free) operation as well as both simplicity and cost effectiveness [12]. But, in the absence of a pump to increase coolant flow velocity in order to enhance heat transfer rate, other methods are necessary to enhance pool boiling by modifying thermophysical properties of the liquid itself, modifying the boiling surface, or both.

One application for which such enhancement might be crucial is thermal management in space applications. Here, absence of gravity is known to greatly compromise boiling heat transfer effectiveness by triggering critical heat flux (CHF) at unusually low heat flux values [13–16]. Without additional enhancement, pool boiling

is unlikely to pose a viable cooling option for these applications. A key merit in the use of nanoparticles to enhance nucleate pool boiling in microgravity is weak tendency for surface sedimentation, which is often reported as a key concern during long-term exposure of the heating surface to nucleate boiling in Earth gravity.

1.2. Pool boiling and quench curves

Before discussing the different pool boiling enhancement methods, it is crucial to relate these methods to specific boiling regimes. These regimes are identified with the aid of two types of performance curves: the boiling curve, Fig. 1(a), and the quench curve, Fig. 1(b). The boiling curve depicts variations of wall heat flux with wall-to-saturation temperature difference (wall superheat). This curve is highly effective at identifying the different heat transfer regimes prevalent at different levels of superheat: (a) single-phase liquid cooling, corresponding to low superheats, (b) nucleate boiling, dominated by bubble nucleation, growth, and departure along the surface, (c) transition boiling, where portions of the wall incur bubble nucleation while others are blanketed with vapor, and (d) film boiling, corresponding to high wall superheats causing vapor blanketing over the entire surface [12]. These four regimes are demarcated by three important transition points: (i) onset of boiling (incipient boiling) corresponding to first bubble formation on the wall, (ii) critical heat flux (CHF), where bubble nucleation in nucleate boiling is replaced by localized vapor blankets merging together across the surface, and (iii) minimum heat flux (Leidenfrost point), corresponding to onset of breakup of the continuous vapor blanket in film boiling when decreasing the wall superheat. These transition points mark profound changes in heat transfer effectiveness between the different regimes, with the nucleate boiling regime providing the highest heat transfer coefficients and the film boiling regime the lowest.

On the other hand, the quench curve, Fig. 1(b), is a better representation of the variations in cooling rate encountered when the surface is quenched from initially high temperature corresponding to film boiling to near room temperature corresponding to film boiling to near room temperature. Unlike the boiling curve, which is a measure of only surface thermal interactions, the quench curve also accounts for thermal mass of the quenched part.

The large variations in heat transfer coefficient associated with the afore-mentioned boiling curve regimes are reflected in appreciable variations in cooling rate along the quench curve, evidenced by significant slope changes between successive regimes. The quench curve emphasizes the importance of the Leidenfrost point, whereupon large changes in cooling rate can have profound influences on microstructure and therefore mechanical properties of a quenched metal alloy part.

The present study is focused mainly on the nucleate boiling regime and CHF, the former being the most effective of all four pool boiling regimes, while CHF is the most important design and safety parameter for applications involving heat-flux-controlled surfaces. Exceeding CHF is known to precipitate a rapid and unsteady transition from the highly heat transfer efficient nucleate boiling to the highly deficient film boiling, and is accompanied by a sharp increase in wall temperature, potentially leading to physical damage, meltdown, or burnout of the surface. From a practical point of view, optimum cooling is achieved by maintaining operation within the nucleate boiling regime, above the onset of boiling, but safely below CHF (typically around 50–70% of CHF [17]). This is why two primary goals in most pool boiling enhancement studies are to increase both nucleate boiling heat transfer coefficient and CHF. A separate category of studies concerns improving heat transfer in film boiling to reduce overall quench time.

1.3. Pool boiling enhancement techniques

Methodologies that have been proposed to improve pool boiling heat transfer can be classified into two major categories [18]: *active* and *passive*. The active techniques involve use of external power to achieve mechanical mixing, surface and/or liquid rotation, vibration, suction or injection, or inducing an electrostatic or magnetic field. However, these active techniques are both costly and inconvenient for applications demanding compact cooling architectures. In contrast, the passive techniques require no application of external power, but rely on modifications to fluid properties or the surface itself (shape, roughness, fins, etc.) or both. The present study is focused entirely on pool boiling

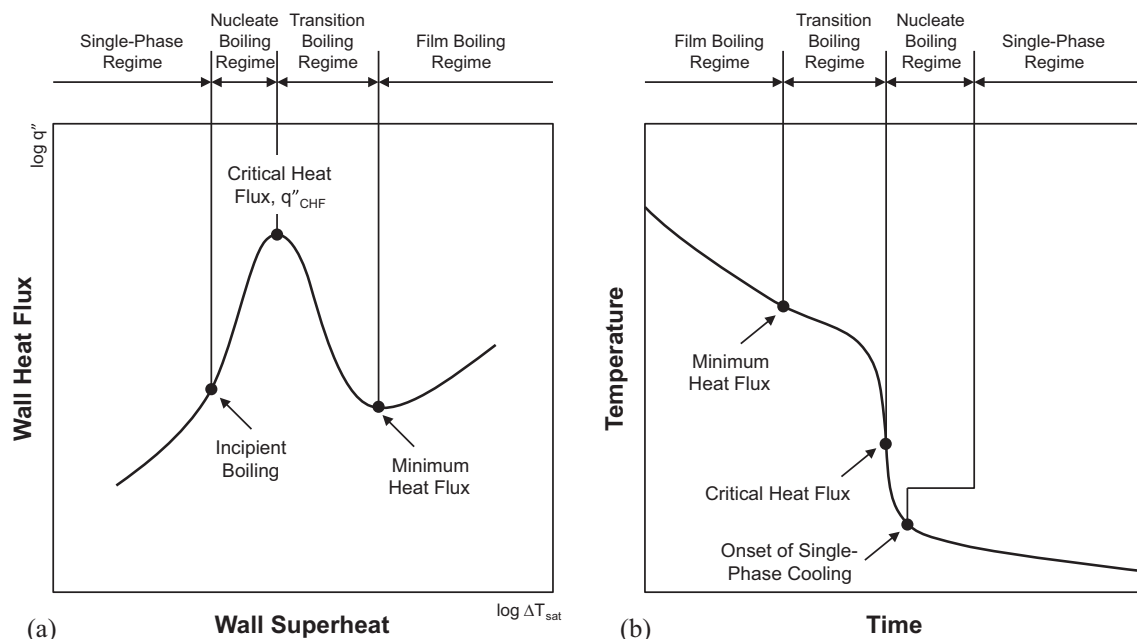


Fig. 1. (a) Pool boiling curve and (b) quench curve.

enhancement using passive methods involving modifications to fluid properties.

Pool boiling performance of popular heat transfer fluids, such as water, ethylene glycol, and refrigerants, is dictated by thermophysical properties of these fluids, and poor values of specific properties impose stringent limits on their effectiveness, especially in high-heat-flux applications. By mixing additives into the pure liquid, it is possible to greatly modify vital properties such as surface tension and thermal conductivity, resulting in measurable enhancement in pool boiling performance.

Overall, enhancement of nucleate boiling heat transfer encompasses several goals, including:

- (1) Initiating nucleate boiling (incipient boiling) at lower wall heat flux and lower wall superheat.
- (2) Preventing or reducing temperature excursion and sharp temperature drop sometimes encountered at boiling incipience.
- (3) Reducing wall superheat throughout the nucleate boiling region by increasing number of active nucleation sites, bubble departure frequency, and/or effective surface area.
- (4) Delaying CHF to higher wall heat flux values.

Notice that the combined outcome of (1), (2), and (4) above is to extend the range of nucleate boiling region, which represents the most effective portion of the pool boiling curve.

1.4. Previous reviews on use of additives and nanofluids

Cheng et al. [19] and Wasekar and Manglik [20] provided comprehensive reviews of studies on heat transfer enhancement with surfactants and polymeric additives prior to 1999 and 2007, respectively. But use of nanofluids has been the subject of numerous recent reviews, most including enhancement of both pool boiling and forced convection. Examples include Das et al. [21], Trisaksri and Wongwises [22], Wang and Mujumdar [23], Taylor and Phelan [24], Wen et al. [25], Godson et al. [26], Siddique et al. [27], Kim [28], Murshed et al. [29], Barber et al. [30], Ahn and Kim [31], Wu and Zhao [32], Cheng and Liu [33], Vafaei and Borca-Tasciuc [34], Celen et al. [35], Kamatchi and Venkatachalapathy [36], Bahiraei and Hangi [37], Kshirsagar and Shrivastava [38], and Fang et al. [39]. On the other hand, Ciloglu and Bolukbasi [40] reviewed articles prior to 2015 dedicated entirely to pool boiling, and whose goal was to identify reasons behind often conflicting findings regarding pool boiling of nanofluids. Other reviews concerning pool boiling of nanofluids, such as Yu et al. [41], Li et al. [42], Özerinç et al. [43], Kleinstreuer and Feng [44], Ghadimi et al. [45], Saidur et al. [46], Ramesh and Prabhu [47], Yu and Xie [48], Mahian et al. [49], Sidik et al. [50], Haddad et al. [51], Shahrul et al. [52], Kasaeian et al. [53], Devendiran and Amirtham [54], were focused mainly on nanofluid preparation methods, inspection instruments and techniques, thermophysical properties, and applications.

Table 1 provides a summary of prior reviews segregated into (a) articles dedicated either entirely or in part to pool boiling of nanofluids, and (b) those addressing nanofluid preparation, properties, and applications. Excluded from this table are reviews of nanofluid heat transfer dedicated entirely to forced convection.

1.5. Objectives of present review

This study is part of a series of recent review articles by the present authors concerning phase change mechanisms that are of vital interest to the heat transfer community, including fluid mechanics of liquid drop impact on a liquid film [55] and on a heated wall [56], spray cooling single-phase and nucleate boiling heat transfer,

and CHF [57], and high temperature boiling regimes and quenching applications [58], and mechanisms and models of pool boiling CHF [12].

The present review will provide a very comprehensive assessment of passive enhancement techniques for pool boiling heat transfer, including surfactant and polymer additives, and nanofluids. Unlike prior reviews, this paper will also address the combined influences of additives and nanofluids, especially that surfactant additives are often used as stabilizers for nanofluids. Discussed in conjunction with each of the passive enhancement methods are detailed impact on nucleate boiling heat transfer and CHF, enhancement mechanisms, and predictive models. Also discussed are important practical concerns in the use of additives and nanofluids, and recommendations for avoiding potential drawbacks.

2. Surfactants and polymer additives

2.1. Surfactants

2.1.1. Description and classification

A surfactant is mostly an organic amphiphilic compound with long chain molecules having both a hydrophobic component - 'tail', and a hydrophilic component - 'head'. Surfactants adsorb at the liquid-vapor interface with their head directed towards the liquid and tail (mostly hydrocarbon) towards the vapor [59]. Adding a surfactant to water in very small concentrations causes no appreciable changes to physical properties except for surface tension, which is depressed considerably. As the surfactant is added, the surfactant molecules spend several seconds or even hours migrating towards the interface, and finally achieve equilibrium (static) surface tension. During the period preceding equilibrium, the surface tension changes with time, which is why it is referred to as 'dynamic surface tension'. The equilibrium time is a function of surfactant type, molecular weight, concentration, temperature, and interface conditions. The equilibrium surface tension tends to decrease asymptotically with increasing concentration, Fig. 2 (a), and the asymptotic limit is referred to as 'critical micelle concentration' (CMC) of the surfactant, above which surface tension ceases to decrease and aggregates of molecules termed 'micelles' begin to form within the liquid.

In general, surface tension affects pool boiling heat transfer in two ways [60]. The first is related to bubble nucleation on the surface. Formation of a bubble from a surface cavity of radius r , requires that wall temperature, T_i , exceeds the liquid's saturation temperature, T_{sat} , by a finite amount given by

$$T_i - T_{sat} = \frac{T_{sat} v_{fg}}{h_{fg}} \frac{2\sigma}{r}, \quad (1)$$

where v_{fg} , h_{fg} , σ are the liquid-vapor specific volume difference, latent heat of vaporization, and surface tension, respectively. By decreasing the surface tension, Eq. (1) shows that bubbles will require lower wall temperature to form, or that far more bubbles will form for a given amount of wall superheat; both trends are important manifestations of heat transfer enhancement. The second important influence of reducing surface tension is that bubble departure diameter, which is generally proportional to $\sigma^{1/2}$, also decreases appreciably, which in turn reduces inter-bubble coalescence and allows a large number of bubbles to form on the surface.

Depending on nature of the hydrophilic head, surfactants are classified into four types [20]: (a) anionic, such as carboxylic acids, sulfuric esters, and sulfonates, (b) nonionic, such as polyethenoxy and polyhydroxy surfactants, (c) cationic, such as fatty nitriles and amines, and (d) zwitterionics, such as long chain amino acids.

Table 1

Summary of reviews on nanofluid pool boiling, and on preparation, properties and applications of nanofluids.

Reviews dedicated entirely or in part to pool boiling of nanofluids		
Author(s)	Year	Remarks
Das et al. [21]	2006	Convection, boiling, and applications of nanofluids
Trisaksri & Wongwises [22]	2007	Convection, boiling, and preparation of nanofluids
Wang & Mujumdar [23]	2007	Convection and boiling of nanofluids
Taylor & Phelan [24]	2009	Experimental studies and nanofluid nucleate pool boiling data
Wen et al. [25]	2009	Conduction, single-phase convection, and boiling of nanofluids, and nanofluid preparation methods
Godson et al. [26]	2010	Free and forced convection, and boiling of nanofluids
Siddique et al. [27]	2010	Heat transfer enhancement by surface modification and use of nanofluids
Kim [28]	2011	Parametric effects of nanofluids on CHF
Murshed et al. [29]	2011	Convection, boiling, and droplet spreading of nanofluids
Barber et al. [30]	2011	Pool and flow boiling of nanofluids
Ahn & Kim [31]	2012	CHF enhancement with nanofluids and micro/nanostructure surface modification in pool and flow boiling
Wu & Zhao [32]	2013	Thermophysical properties, convection, boiling, and CHF of nanofluids
Cheng & Liu [33]	2013	Two-phase flow, nucleate pool boiling, flow boiling, and condensation of refrigerant-based nanofluids
Vafaei & Borca-Tasciuc [34]	2014	Mechanisms and effects of nanoparticle deposition on boiling and CHF
Celen et al. [35]	2014	Thermophysical properties, pool and flow boiling, and applications of nano-refrigerants
Kamatchi & Venkatachalapathy [36]	2015	Parametric effects on pool boiling CHF, and preparation methods of nanofluids
Bahiraei & Hangi [37]	2015	Thermophysical properties, natural convection, forced convection, and boiling, as well as practical applications of magnetic nanofluids
Kshirsagar & Shrivastava [38]	2015	Thermal conductivity, nucleate pool boiling, and CHF of nanofluids
Ciloglu & Bolukbasi [40]	2015	Applications and pool boiling heat transfer of nanofluids
Fang et al. [39]	2016	Nanofluid heat transfer and CHF in pool and flow boiling
Reviews dedicated to nanofluid preparation methods, thermophysical properties, and applications		
Yu et al. [41]	2008	Nanofluid thermal conductivity and heat transfer enhancement
Li et al. [42]	2009	Thermal conductivity, synthesis, and characterization of stationary nanofluids
Özerinç et al. [43]	2010	Thermal conductivity of nanofluids
Kleinstreuer & Feng [44]	2011	Experimental and theoretical studies concerning nanofluid thermal conductivity
Ghadimi et al. [45]	2011	Preparation and stability improvement methods, stability inspection instruments, and measurement of thermal properties of nanofluids
Saidur et al. [46]	2011	Applications and challenges of nanofluids
Ramesh & Prabhu [47]	2011	Thermophysical properties, wetting, and boiling heat transfer of nanofluids
Yu & Xie [48]	2012	Preparation methods and stability mechanisms of nanofluids
Mahian et al. [49]	2013	Nanofluid applications in solar thermal engineering systems
Sidik et al. [50]	2014	Preparation methods and challenges of nanofluids
Haddad et al. [51]	2014	Preparation methods of non-metallic and metallic nanofluids
Shahrul et al. [52]	2014	Preparation methods and specific heat of nanofluids
Kasaeian et al. [53]	2015	Application of nanofluids in solar systems
Devendiran & Amirtham [54]	2016	Preparation, characterization, thermal properties, and applications of nanofluids

2.1.2. Impact on bubble behavior and nucleate boiling heat transfer

Early experiments by Morgan et al. [61], Jontz and Myers [62], and Saltanov et al. [63] demonstrated the effectiveness of commercial surfactants in shifting the boiling curve for water to lower wall superheats, thereby bringing about earlier boiling incipience as well as precipitating an increase in the nucleate boiling heat transfer coefficient, h . The influence on the later is clearly reflected by the relation

$$h \propto \sigma^n, \quad (2)$$

where n ranges from 0 to -3.3 [64]. Tzan and Yang [65], Hetsroni et al. [66], Gannett and Williams [67], and Zhang and Manglik [68], showed experimentally that h increases with increasing surfactant concentration at low concentration because of the reduction in surface tension. However, they also showed that h reaches a maximum before decreasing with further increases in concentration, which was attributed to increases in liquid viscosity at high concentrations, especially for low liquid temperatures, as shown in Fig. 2 (b). Using the surfactant Habon G, Hetsroni et al. obtained boiling curves for water exhibiting an S-shaped behavior with respect to wall superheat. In follow-up study, Sher and Hetsroni [69] constructed a theoretical model based on the premise that liquid-vapor and solid-liquid surface tensions are controlled by a surfactant diffusion mechanism, and expressions for the surface tensions were substituted into Rohsenow's correlation for nucleate boiling [70] to yield an explicit expression for heat transfer in the nucleate

boiling region as a function of surfactant bulk concentration. The modified expression was successful at predicting the S-shaped nucleate boiling curve for surfactants that decrease liquid-vapor surface tension but increase solid-liquid surface tension. Using surfactant Surflon S-121, Inoue et al. [71] measured enhancement in water nucleate pool boiling heat transfer, which resulted from increased number of nucleation sites, but the surfactant lost its enhancement ability for concentrations above 1000 ppm.

Using hydroxyethyl cellulose (HEC) as surfactant, Zhang and Manglik [68] observed appreciable differences in bubble dynamics along a horizontal cylindrical heater when compared to pure water, as shown in Fig. 3(a). When the HEC concentration was lower than a critical value of 600 ppm, boiling was quite vigorous, evidenced by smaller-sized and more regularly shaped bubbles, and reduced tendency to coalesce. Furthermore, bubbles nucleated earlier, with faster coverage of the heated surface and higher departure frequency, which were all outcomes of reduced surface tension at the liquid-vapor interface. However, for concentrations higher than critical value, bubbles were observed to originate from the underside of the cylindrical heater and coalesce into larger bubbles as they slid along the cylindrical periphery, and the boiling enhancement abated considerably. Hu et al. [72] observed similar bubble behavior when adding surfactants sodium dodecyl sulfate (SDS) and Triton X-114 into water. Hetsroni et al. [73] also observed boiling behavior similar to that of Zhang and Manglik with addition of alkyl glycoside surfactant into water. Follow-up

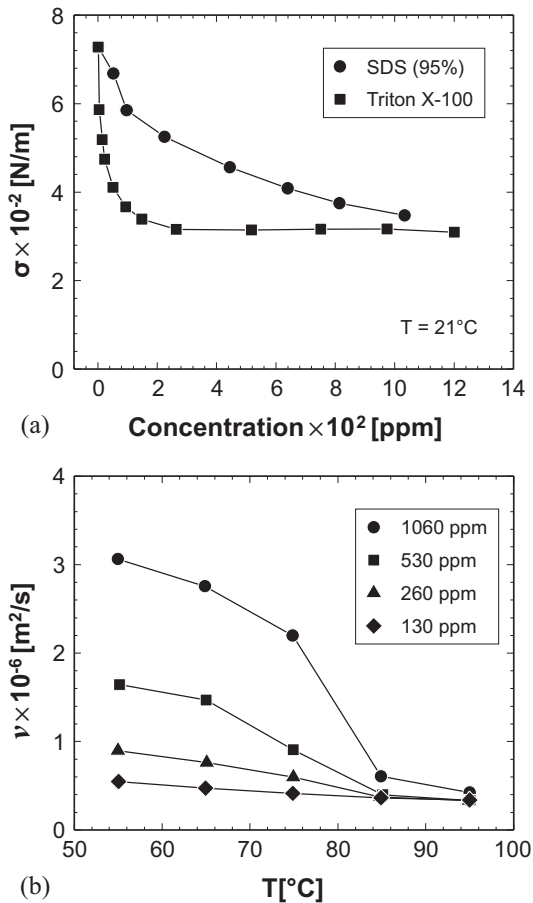


Fig. 2. (a) Variation of equilibrium surface tension with surfactant concentration for sodium dodecyl sulfate (SDS) and Triton X-100 in water (adapted from Cheng et al. [19]). (b) Variation of kinematic viscosity with temperature at various concentrations of Habon G (adapted from Hetsroni et al. [66]).

study by Hetsroni et al. [74] compared bubble growth in a 600-ppm alkyl surfactant solution to that in pure water at two heat-flux levels. At 1 W/cm^2 , bubble shape, lifetime, and volume in the surfactant solution were similar to those for water. But at 5 W/cm^2 , the surfactant activated more surface sites, leading to more vigorous boiling, and bubbles formed into clusters with individual bubble lifetime shorter than in water. The departure diameter in the solution decreased with increasing heat flux, which was opposite to the trend in pure water. These findings prove that the influence of surfactant on bubble dynamics in nucleate boiling depends on both concentration and heat flux.

2.1.3. Enhancement mechanisms

Yang and Maa [75] attributed the enhancement of pool boiling heat transfer coefficient with surfactants to the Marangoni effect, suggesting that depletion of molecules adsorbed at the vapor-liquid interface due to vapor bubble expansion might cause surface tension to increase locally despite an overall decrease in surface tension compared to that of the pure liquid. Surfactants therefore may render vapor bubbles more stable and less prone to coalesce with other bubbles. Yang [76] proposed that a liquid film is produced between adjacent vapor bubbles during their growth periods, and the film would flow outwards, causing the vapor-liquid interfaces on both sides to stretch. He added that surfactant concentration in the vicinity of the stretching interface is lower than in the absence of stretching, and the ensuing local increase in surface tension tends to resist further stretching. However, Wu et al.

[77] argued that neither equilibrium nor dynamic surface tension changes could explain the influence of surfactant on nucleate boiling heat transfer. Follow-up study by Wu et al. [64] showed that enhanced nucleate boiling heat transfer in surfactant solutions could be satisfactorily correlated with the portion of surface area occupied by vapor bubble. Hetsroni et al. [78] reported that neither equilibrium surface tension nor solution viscosity could explain surfactant effects on subcooled nucleate boiling heat transfer. Wasekar and Manglik [79] numerically predicted the development of a surface concentration gradient at the bubble interface, which tended to oppose the temperature gradient and reduce thermocapillary and diffusocapillary Marangoni convections. They also indicated that surfactant adsorption time is determined solely by surfactant concentration.

For highly wetting liquids, such as FC-72, Ammerman et al. [80] reported that latent heat contribution to total heat flux is dominant throughout the nucleate boiling regime excepting the low flux region, where natural convection is relatively significant. In follow-up study, Ammerman and You [81] investigated the enhancement mechanisms of surfactants by measuring the volumetric flow rate of vapor departing from the surface with the aid of a technique combining photography and laser-Doppler anemometry. They suggested that the enhancement with surfactant addition is influenced by the relative contributions of convection and latent heat to total heat flux. They showed that adding anionic surfactant, such as SDS, to water increases the contribution of convection in the fully developed boiling region, which was attributed to decreased bubble agglomeration on the heating surface and increased bubble departure frequency. However, in the partially developed boiling region, the reduction in surface tension promoted nucleation by activating dormant surface cavities, thereby increasing the contribution of latent heat to total heat flux.

Wasekar and Manglik [82] found that diffusion kinetics of surfactant molecules and micelles at saturation temperature are quite different from those at room temperature. They also showed that the reduction of dynamic surface tension with increasing temperature is not uniform, pronounced for low (<1000 ppm) and high (>2500 ppm) concentrations but rather insignificant for intermediate concentrations. Using two different anionic surfactants, SDS and sodium lauryl ether sulfate, and two nonionic surfactants, Triton X-100 and Triton X-305, with molecular weights of 288.3, 422, 624, and 1526, respectively, Wasekar and Manglik [83] showed that maximum heat transfer enhancement increases with decreasing molecular weight. They also pointed out that dynamic surface tension is perhaps an important predictor of boiling behavior. Zhang and Manglik [59] also showed that surfactant with lower molecular weight tends to reduce surface tension faster and provide better enhancement than one with higher molecular weight.

Zhang and Manglik [68] reported that adsorption of macromolecules, or agglomerates of smaller monomers on the heating surface may promote the formation of nucleation sites, which, together with the decreased dynamic surface tension, is responsible for growth in number of vapor bubbles in surfactant solutions. In a later study, Zhang and Manglik [84] reported that surfactant adsorption-desorption at the vapor-liquid interface alters surface tension, and this interfacial influence is time dependent, decreasing with increasing concentration until CMC is reached, at which micelles (colloid-sized clusters or aggregates of monomers) begin to form. This is why heat transfer reaches optimum enhancement at CMC but begins to weaken at higher concentrations. Similar observations were made by Hu et al. [72], who reported changes to surface wettability from surfactant physisorption at the solid-liquid interface. They also suggested that, when the concentration exceeds CMC, surfactant molecules tend to form bilayers or micellar layers on the solid surface, rendering the surface strongly

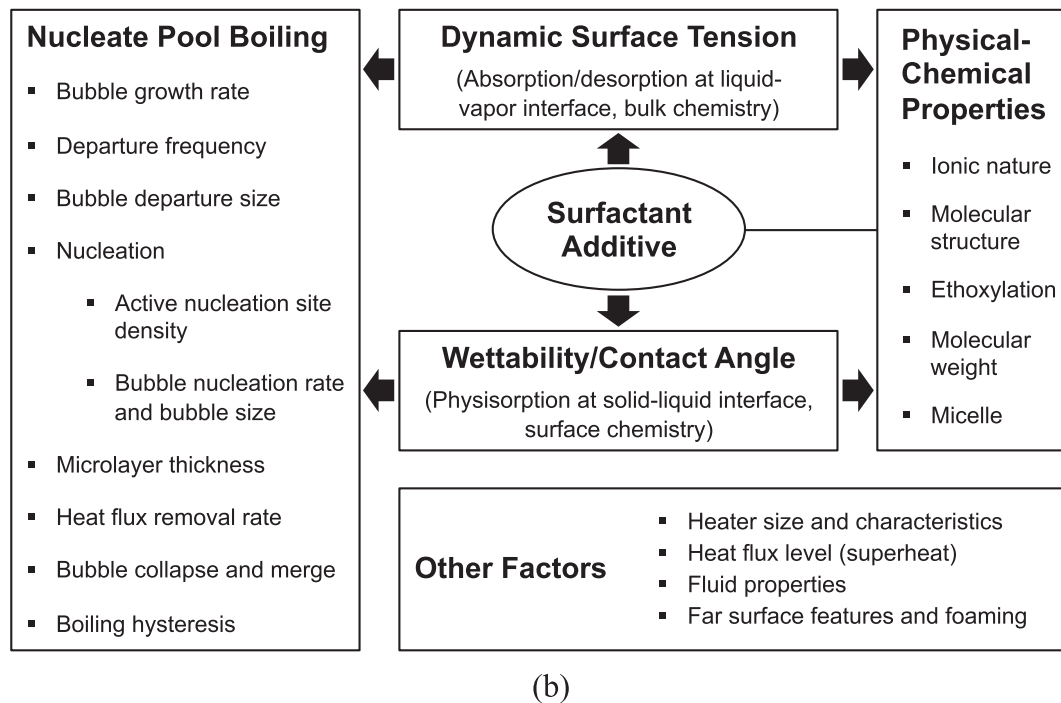
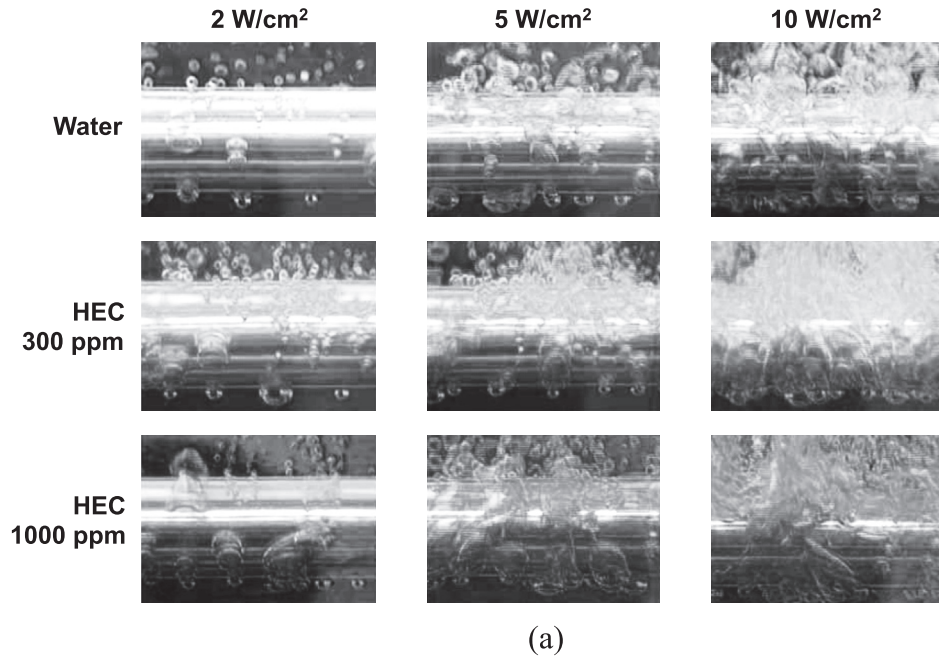


Fig. 3. (a) Boiling behavior for different concentrations of aqueous HEC-QP300 at different heat fluxes. (b) Characterization of nucleate pool boiling and its determinants in aqueous surfactant solutions. Adapted from Zhang and Manglik [68,84].

hydrophilic, which suppresses nucleation and bubble growth, thereby weakening the boiling process. Shown in Fig. 3(b) is a summary of the complex inter-relationships of various influences in aqueous surfactant solutions according to Zhang and Manglik.

Interestingly, Jeong et al. [85] performed water quenching experiments in which addition of tri-sodium phosphate surfactant resulted in visible surface deposits that were believed to reduce contact angle. This is evidence of a need to perform long-duration boiling experiments and to monitor deposition effects when investigating the influence of surfactants on pool boiling.

2.2. Other polymer additives

2.2.1. Description

A polymer is a substance comprised mostly of large molecules (macromolecules), which are created by ‘polymerization’ of many smaller molecules - chemical units called monomers - and is broadly categorized as either natural or synthetic [68]. The primary effect of adding a polymer into water is to increase solution viscosity, which is accentuated with increases in molecular weight and concentration [20]. Depending on polymer chemistry and

concentration, complete molecular adsorption of the additive to the vapor-liquid interface usually takes from seconds to minutes [19], much longer than the time scale of milliseconds associate with bubble nucleation in pool boiling. Excepting a few polymers with surface-active characteristics, namely polymeric surfactants (e.g., HEC and polyethylene oxide (PEO)), most polymer additives do not cause appreciable changes to surface tension.

2.2.2. Impact on boiling heat transfer

Kotchaphakdee and Williams [86] addressed heat transfer enhancement effects of aqueous solutions of HEC polymers having three different molecular weights (Natrosol 250L, Natrosol 250 M, and Natrosol 250H), and polyacrylamide (PA) polymers with two different molecular weights (Separan NP-10 and Separan NP-20), in concentrations of 62 to 500 ppm, and showed that both polymer types enhance nucleate boiling heat transfer. Since HEC is a surfactant and PA not, the boiling enhancement was attributed for both types mostly to reduction in bubble coalescence caused by increased solution viscosity. Paul and Abdel-Khalik [87] investigated the enhancement characteristics of aqueous solutions of the polymers Separan AP-30 and Natrasol 250HHR. Shown in Fig. 4(a) is the frequency distribution of bubble departure diameter for pure water. Fig. 4(b) and (c) show that addition of Separan AP-30 and Natrasol 250HHR, respectively, decreases average departure diameter and increases average departure frequency per nucleation site; both of which improve nucleate boiling heat transfer. However, Wang and Hartnett [88] found that the boiling performance of 250-ppm aqueous AP-30 solution was inferior to that for pure water, while addition of 250 ppm of the surfactant sodium lauryl sulfate (SLS) to the aqueous AP-30 solution did produce significant improvement in nucleate boiling heat transfer. Athavale et al. [89] reported that HEC (QP-300) renders the solution non-Newtonian, besides serving as surface-active agent. In low concentrations, HEC enhanced nucleate boiling heat transfer over the entire heat flux range tested. However, high concentrations (above 1.0×10^{-9} mol/cc) degraded heat transfer at low heat fluxes encompassing incipience boiling and the partially developed boiling region, but enhanced the nucleate boiling heat transfer coefficient by up to 45% at higher heat fluxes spanning the fully developed boiling region. However, using HEC polymers (Natrosol 250HR, 300HR, and 250GR), Yang and Maa [90] observed no appreciable improvement in the nucleate boiling heat transfer coefficient, and CHF even decreased slightly.

Levitskiy and co-workers [91,92] proposed that, in very low polymer concentrations (~ 0.01 wt%), generation of normal stresses with deformation of the thin liquid layer between a growing vapor bubble and heating surface accelerates bubble departure, thereby increasing the nucleate boiling heat transfer coefficient. However, high concentrations (~ 1 wt%) degrade boiling performance as increased solution viscosity both resists vapor bubble growth and suppresses microconvection near the surface. Lowery and Westwater [93] reported that methanol with nonionic agents (Span 20, Lot 1759C, and sorbitan monolaurate), cationic agents (Hyamine 1622, Lot 379A, and diisobutyl phenoxyethoxyethyl dimethyl benzyl ammonium chloride), and anionic agents (Aerosol OT, Lot A6839, and dioctyl sodium sulfosuccinate) generally enhanced nucleate boiling heat transfer despite having no effect on surface tension, and attributed the enhancement to improved nucleation with the polymer addition.

Kandlikar and Alves [60] showed that adding a small amount of ethylene glycol to water increases the nucleate boiling heat transfer coefficient slightly. As surface tension of the mixture was essentially unaffected, the boiling enhancement was ascribed to changes in contact angle and wetting characteristics. Wen and Wang [94] confirmed the important role of wettability by adding surfactants to water; they were also successful in correlating their experimen-

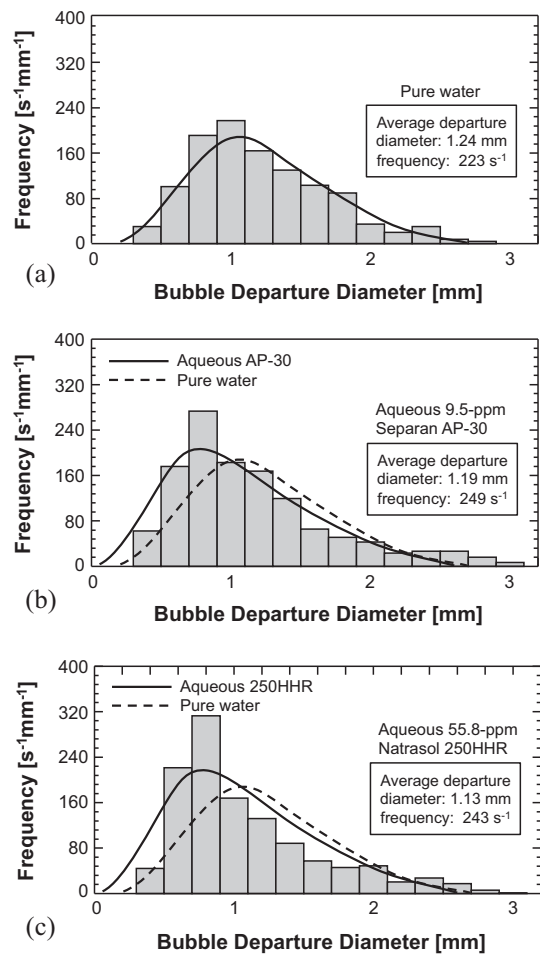


Fig. 4. Frequency distributions of bubble departure diameter for (a) pure water at $q'' = 35.2$ W/cm², (b) 9.5-ppm aqueous Separan AP-30 solution at $q'' = 36.4$ W/cm², and (c) 55.8-ppm aqueous Natrasol 250HHR solution at $q'' = 35.7$ W/cm². Adapted from Paul and Abdel-Khalik [87].

tal data by incorporating contact angle into Mikic and Rohsenow's original nucleate boiling correlation [95]. Liu et al. [96] devised a model using Artificial Neural Networks (ANNs) of molecular structures of additives that agreed well with experimental data from several sources. Using Triton SP polymer solution, Yang et al. [97] reported that the heat transfer coefficient does not differ from that for water, and suggested the positive effects of reduced surface tension and negative effects of reduced contact angle offset one another. By testing different polymers, galactomannan polysaccharide (Galactasol 211), polyacrylamide (Separan MGL), two polymers consisting of both acrylamide and acrylic acid monomers (Separan NP-10P and AP-30), two polyethylene oxides (Aldrich No. 18202-8 and No. 18946-4), and three HECs (Natrosol 250MR, 250HR, and 250HHR), Paul and Abdel-Khalik [98] concluded that polymer type, concentration, and molecular weight are important only insofar as they affect the solution's viscosity. Zhang and Manglik [68] showed that adding polyacrylic acid (Carbopol 934) to water degraded nucleate boiling heat transfer.

2.3. Practical concerns

Overall, the extent of pool boiling enhancement with surfactants and polymers depends on concentration, type and chemical composition, as well as wall heat flux. Several mechanisms have been proposed to explain the observed enhancement, including Marangoni convection, dynamic surface tension, increased number

of active nucleation sites, surfactant adsorption and desorption, foaming, and changes in kinetics of bubble formation and surface wettability. But, given the contradictory findings from different studies, these mechanisms warrant further careful investigation. Also, aside from dependence of any boiling heat transfer enhancement on additive type and concentration, there exists a critical concentration for optimum enhancement, which complicates additive selection and operation with proper concentration.

Two important concerns must be pointed out concerning the use of surfactants or other polymers. The first is degradation of surfactants after many heating-cooling cycles. This is evident from a study by Hetsroni et al. [78], who observed formation of large vapor clusters at incipient boiling accompanied by high wall superheat in degraded Habon G solution. By increasing wall heat flux further, the clusters collapsed and precipitated considerable reduction in wall temperature, a severe form of boiling hysteresis termed 'incipience excursion'. Yang et al. [97] observed similar incipience excursion with Triton SP polymer solutions. The second important concern is that the majority of surfactants that have been investigated in pursuit of enhanced nucleate boiling performance are not environmentally friendly [73].

3. Nanofluids

3.1. Definition, preparation, and property determination

3.1.1. Definition

Nanofluids, which have attracted considerable attention in the heat transfer community in the past decade, are heat transfer fluids containing nanoparticles (typically 1–100 nm in size) that are uniformly and stably suspended in a liquid [99]. Nanoparticles materials include chemically stable metals (e.g., gold, silver, copper), metal oxides (e.g., alumina, zirconia, silica, titania), and various forms of carbon (e.g., diamond, graphite, carbon nanotubes, fullerene) [100]. The first study concerning nanofluids is attributed to Masuda et al. [101], who, in 1993, reported profound changes to thermal conductivity and viscosity of nanofluids containing dispersed, ultra-fine (13-nm) particles of Al_2O_3 , SiO_2 , and TiO_2 , compared to those of the pure liquid. However, the concept of nanofluids was proposed two years later by Choi and Eastman [102]. Since then, numerous studies have been conducted in pursuit of better understanding of nanofluids, and most concern thermal conductivity enhancement in single-phase nanofluids [103–107]. However, nanofluids were not examined in conjunction with pool boiling until 2003 with publication of articles by Das et al. [108] and You et al. [109].

3.1.2. Preparation methods

Nanofluids are prepared using either two-step or one-step processes [99]. In a typical two-step method, nanoparticles, nanotubes, or nanofibers are initially produced in the form of dry powder by physical or chemical treatments such as inert gas condensation and chemical vapor deposition. This step is followed by powder dispersion into the base liquid. A primary concern with the two-step method is aggregation of nanoparticles in the fluid. Additionally, while the two-step method works fairly well for oxide nanoparticles, it is not as effective for heavier metal nanoparticles. In the one-step method, synthesis and dispersion of nanoparticles into the base fluid are achieved simultaneously. And, despite superior dispersibility and stability compared to two-step methods, the one-step method is more complicated because of stringent preparation requirements. It should be noted that most studies on nanofluid pool boiling have been conducted using two-step methods.

Improper preparation may lead to particle sedimentation and creation of zones of high thermal resistance. Two important requirements for preparation of nanofluids are stability and good dispersion, which can be achieved by [110]: (a) changing solution pH by adding acid to keep nanoparticles away from their isoelectric point, (b) adding surfactants and/or dispersants, and (c) ultrasonic vibration or electrostatic stabilization. The first two methods have been shown to affect rheological behavior of the fluid as well as nucleate boiling heat transfer [111–113].

Common instruments and techniques for inspecting the stability of nanofluids include UV–Vis spectrophotometry, zeta potential, sediment photograph capture, Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), light scattering, three-omega, and sedimentation balance method, of which TEM and SEM are the most popular.

Shown in Fig. 5 are examples of Al_2O_3 and TiO_2 nanoparticle dispersions in distilled water without the use of additives. In the absence of additives, there is weak electrostatic repulsion between nanoparticles, which causes them to agglomerate into colloidal state and form an irregular cluster. Fig. 5 shows that the aggregation is more severe with the TiO_2 nanoparticles.

3.1.3. Determination of properties

Since nanoparticle motion in a liquid-solid solution depends strongly on the hydrodynamic forces acting upon surfaces of the solid particles, the influence of nanoparticles dispersed in solution is generally correlated to volume concentration (vol%) rather than mass concentration (wt%) [114]. However, it is quite difficult to measure precise volume of nanoparticles. This is why many investigators often rely on the following relation to estimate the volume concentration [115],

$$\phi_{vol} = \frac{1}{\left(\frac{1-\phi_{wt}}{\phi_{wt}}\right) \frac{\rho_w}{\rho_f} + 1}, \quad (3)$$

where ϕ_{vol} and ϕ_{wt} signify the volume and mass concentrations, and ρ_w and ρ_f the densities of solid particles and pure liquid, respectively. Knowing ϕ_{vol} , the density and specific heat of the nanofluid are expressed as [106].

$$\rho_{nf} = \rho_f(1 - \phi_{vol}) + \rho_w\phi_{vol} \quad (4a)$$

and

$$\rho_{nf}c_{p,nf} = \rho_f c_{p,f}(1 - \phi_{vol}) + \rho_w c_{p,w}\phi_{vol}, \quad (4b)$$

respectively, and the thermal conductivity as [103],

$$k_{nf}/k_f = 1 + n\phi_{vol}, \quad (5)$$

where n is an empirical shape factor, determined by ratio of surface area of a sphere with volume equal to that of the particle to surface area of the particle. For dynamic viscosity of nanofluids, Brinkman [116] recommended the relation

$$\mu_{nf} = \mu_f(1 + 2.5\phi_{vol}). \quad (6)$$

It should be noted that, while Eqs. (3)–(6) are widely used in the study of nanofluid pool boiling, alternative relations have been used in specific studies.

3.2. Water-based nanofluids

3.2.1. Oxide nanoparticles

3.2.1.1. CHF enhancement contrasted with little or no influence on nucleate boiling heat transfer coefficient. You et al. [109] measured boiling heat transfer performance of water-based 0.005 g/l alumina (Al_2O_3) nanofluid and demonstrated appreciable enhancement in CHF (up to 200%) compared to pure water, but virtually no difference in the nucleate boiling heat transfer coefficient. Later, they

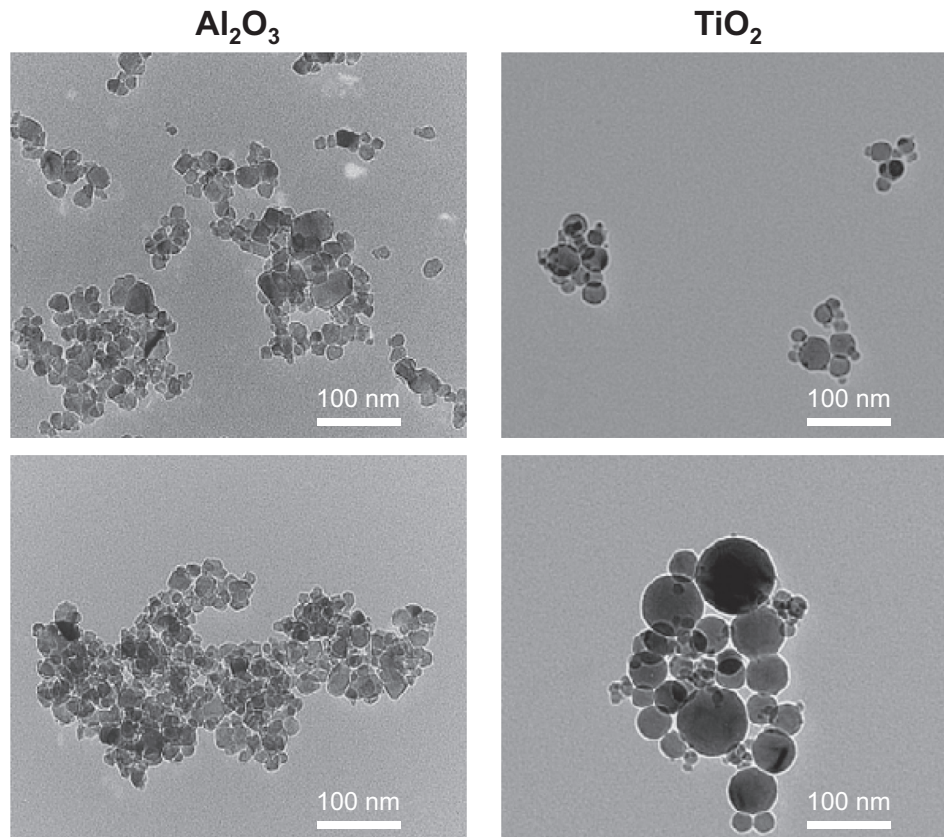


Fig. 5. Transmission Electron Microscope (TEM) images depicting agglomeration of nanoparticles in distilled water. Adapted from Kim et al. [114].

showed that the CHF enhancement was more significant as surface orientation was changed from upward-facing to downward-facing [117]. They also reported an increase in bubble size coupled with a significant decrease in bubble frequency with the nanofluid. However, Lee et al. [118] showed that bubble departure frequency in water-based Al_2O_3 and Fe_3O_4 nanofluids was almost two times higher than in pure water. As depicted in Fig. 6, You et al. [109] showed that the CHF enhancement was realized by increasing nanoparticle concentration only for relatively small concentrations up to 0.1 g/l, above which concentration had no further enhancement benefits. Overall, the CHF enhancement measured by You et al. cannot be explained by hydrodynamic instability hypotheses in the well-known Zuber model [119–121]. CHF enhancement was

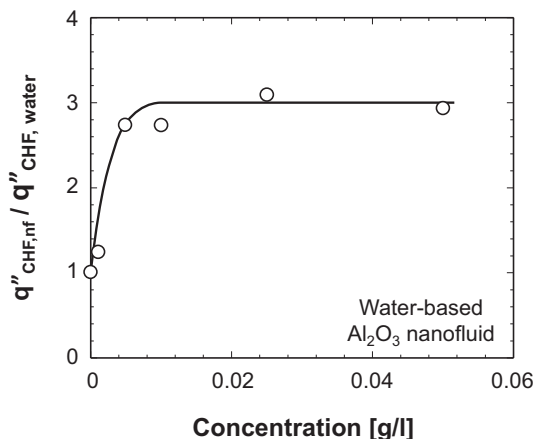


Fig. 6. Ratio of CHF for water-based Al_2O_3 nanofluid to that for pure water versus nanoparticle concentration. Adapted from You et al. [109].

also reported by Vassallo et al. [122], who measured 60% increase in CHF using water-based 0.5 vol%, 50-nm SiO_2 nanofluid. And, like You et al., they did not measure any significant enhancement in the nucleate boiling heat transfer coefficient. They also reported that, while 50-nm nanoparticles remained dispersed in the liquid, 3- μm particles quickly accumulated on the heating surface. Sakashita [123] found CHF enhancement with water-based TiO_2 nanofluid to decrease with increasing pressure, becoming nonexistent around 0.8 MPa. Vazquez and Kumar [124] measured 250–300% enhancement in CHF with water-based SiO_2 nanofluids having concentrations from 0.2 to 0.4 vol%, and pointed out that the enhancement was strongly influenced by heating surface geometry. Sulaiman et al. [125] reported CHF enhancement of 150–200%, fairly independent of nanoparticle material tested (Al_2O_3 , TiO_2 , and SiO_2), concentration (within a range of 0.04–1 g/l), or particle dispersion.

3.2.1.2. Enhancement of nucleate boiling heat transfer coefficient. In contrast to many prior studies, Wen and Ding [111] showed that water-based Al_2O_3 nanofluid did enhance the nucleate boiling heat transfer coefficient, and the enhancement increased with increasing particle concentration, reaching 40% at 1.25 wt%. Similar findings were reported by Tu et al. [126] for the same nanofluid. In follow-up study, Wen et al. [127] measured increases in the nucleate boiling heat transfer coefficient of water-based TiO_2 nanofluid with increasing particle concentration, which reached ~50% at 0.7 vol%. Salari et al. [128] also reported enhancement in nucleate boiling heat transfer with water-based TiO_2 nanofluid within a range of 0.1–0.3 wt%. Wen and Ding proposed several factors that influence nanofluid nucleate boiling performance, including (a) instability caused by sedimentation of non-homogenous nanofluid, and layering of agglomerates on the heating surface, both of which reduce nucleate boiling heat transfer effectiveness, (b) dispersants

and/or surfactants used to stabilize nanoparticle suspension, (c) surface roughness and contamination caused by surfactant failure, and (d) thermal measurement techniques and characteristic size of boiling system. Ali et al. [129] examined nucleate boiling of TiO₂ nanofluid at high nanoparticle concentrations, and reported 24% and 38% enhancement in the nucleate boiling heat transfer coefficient for 12 and 15 wt%, respectively.

Yang and Liu [130] compared the boiling performance of 'functionalized' SiO₂ nanofluid, treated by grafting silanes to the nanoparticle surfaces [131], to that of conventional nanofluids without the treatment. The functionalization improved both the dispersion and stability of the nanoparticles, evidenced by absence of sedimentation over a 12-month period even for concentrations as high as 10 wt%. Additionally, the boiling surface was free from deposits in the functionalized nanofluid, but the functionalization greatly increased nanofluid viscosity. Despite better stability and dispersion, the functionalized nanofluid achieved only slight enhancement in the nucleate boiling heat transfer coefficient, and CHF remained virtually unchanged. Karimzadehkhoei et al. [132] examined the effects of nanoparticle type on nucleate boiling heat transfer by testing TiO₂ and CuO nanoparticles in concentrations of 0.001–0.2 wt%. For water-based TiO₂ nanofluid, the most dilute concentration tested (0.001 wt%) improved the nucleate boiling heat transfer coefficient by up to 15%, but the enhancement decreased to below 5% with increasing concentration. But the performance of water-based CuO nanofluid was quite different, as the heat transfer coefficient decreased slightly for the lowest concentration (0.001 wt%), and then increased with increasing concentration, by up to 36% at 0.2 wt%. Soltani et al. [133] also reported enhancement in nucleate boiling heat transfer with increasing concentration for water-based Al₂O₃ nanofluid with nanoparticle concentrations of 0.3–2 wt%. On the other hand, enhancement trends for water-based SnO₂ nanofluid were non-monotonic, with the nucleate boiling heat transfer coefficient decreasing slightly at 0.5 wt%, and then steadily increasing as concentration was increased within the range of 1.0–3.0 wt%. Salari et al. [134] examined the boiling characteristics of water-based Fe₃O₄ nanofluid modified with nonylphenol ethoxylate nonionic surfactant and pH setting. They reported enhancements in both the nucleate boiling heat transfer coefficient and CHF with increasing concentration in the range of 0.1–0.3 wt%. Interestingly, increased surface fouling with time did not compromise the nucleate boiling heat transfer coefficient, behavior they explained by bubble interactions causing partial detachment of the porous deposited layer. Overall, these studies prove that nucleate boiling heat transfer performance of nanofluids is highly dependent on both nanoparticle type and concentration.

3.2.1.3. Deterioration of nucleate boiling heat transfer coefficient. Interestingly, several other investigations point to deterioration in nucleate boiling performance with nanofluids. For example, Bang and Chang [115] found that addition of 47-nm Al₂O₃ nanoparticles into water decreased the nucleate boiling heat transfer coefficient, and increasing the nanoparticle concentration led to further heat transfer deterioration. They attributed these adverse effects to (a) variations in surface roughness causing a decrease in number of active nucleation sites, and (b) relatively poor thermal conductivity of alumina layer deposited on the heating surface. Similar deterioration trends were observed by Ciloglu [135] with water-based 0.01, 0.05 and 0.1 vol% SiO₂ nanofluids, and Sarafraz et al. [136] with water-based 0.1 and 0.3 wt% Al₂O₃ nanofluids. Aside from the adverse effects pointed by Bang and Chang, Ciloglu suggested another adverse effect of the deposited layer: blockage of bubble formation on the heating surface. However, Ciloglu did measure up to 45% enhancement in CHF, which he attributed to improved surface wettability. Jung et al. [137] mea-

sured deterioration in the nucleate boiling heat transfer coefficient of water-based Al₂O₃ nanofluid in the range of 0–0.1 vol%, both with and without the use of polyvinyl alcohol stabilizer, compared to that for pure water because of the combined effects of nucleation site blockage and added thermal resistance created by the deposited layer. But they too measured some improvement in CHF in the absence of stabilizer, which they suggested was the result of an increase in effective area of the boiling surface [138]. The CHF enhancement was compromised with addition of the stabilizer, presumably because the deposited layer was smoother than without the stabilizer.

Other evidence of deterioration of nucleate boiling performance comes from studies by Das et al. [108,139], Chopkar et al. [140], and Narayan et al. [141] involving Al₂O₃ and ZrO₂ nanofluids. These authors reported measurable shifts in the nucleate boiling region of the boiling curve towards high wall superheats, which they ascribed to reduced surface roughness brought by particle trapping on the surface. This behavior was quantified further by Das et al., who pointed out that their heating surface had relatively large roughness features, 0.2–1.2 μm, one to two orders of magnitude larger than the 20–50 nm nanoparticles, meaning that the nanoparticles could easily plug surface cavities [142]. On the other hand, Bang and Chang [115] employed a very smooth surface having roughness features smaller than the 47-nm nanoparticles tested, which allowed the particle deposition during nucleate boiling to increase the surface roughness. However, despite the increased roughness, they too observed deterioration in nucleate boiling heat transfer, contradicting findings from a majority of studies concerning surface roughness effects. Hu et al. [143], however, explained that particle size alone cannot explain the changes in surface roughness since even very fine particles could form clusters that are larger than surface cavities, therefore aiding in cavity blockage and resulting in deterioration of nucleate boiling heat transfer. Duangthongsuk et al. [144] reported deterioration of nucleate boiling heat transfer of water-based nanofluid with 120-nm Al₂O₃ nanoparticles on a surface having 3.14-μm roughness, and the deterioration was exasperated with increasing concentration over a range of 0.00005–0.03 vol%.

Liu and Liao [145] emphasized the need to differentiate between nanofluids and nanoparticle suspensions; the first consists of base liquid, nanoparticles, and surfactant, while the second consists of only base liquid and nanoparticles. They conducted experiments with both nanofluids and nanoparticle suspensions using water-based and alcohol-based 0.2–2 wt% CuO and SiO₂ nanoparticles, and also assessed the influence of adding 0.5 vol% sodium dodecyl benzene sulfate (SDBS) surfactant. They showed that, above a surface temperature of 112 °C, water-based nanofluids produced a gradually thickening porous agglutination layer on the heating surface, resulting in nucleate boiling performance that changed over time. However, no surface agglutination was observed with the nanoparticle suspensions, and boiling behavior was steady throughout the nucleate boiling region. Different behaviors were observed with alcohol-based nanofluids compared to water-based nanofluids, in that agglutination occurred with neither alcohol-based nanofluids nor alcohol-based nanoparticle suspensions. Overall, the nanofluids and suspensions yielded poorer nucleate boiling performances than the base liquid's because of a decrease in number of active cavities. However, CHF did improve because of a reduction in contact angle. Chopkar et al. [140] also found that adding 1.0 vol% tetramethyl ammonium hydroxide surfactant to the nanofluid adversely influenced boiling heat transfer performance, Fig. 7, evidenced by gradual deterioration observed with repeated tests using the same surface.

3.2.1.4. General parametric effects on nucleate boiling performance of nanofluids. Dadjoo et al. [146] addressed the effects of surface

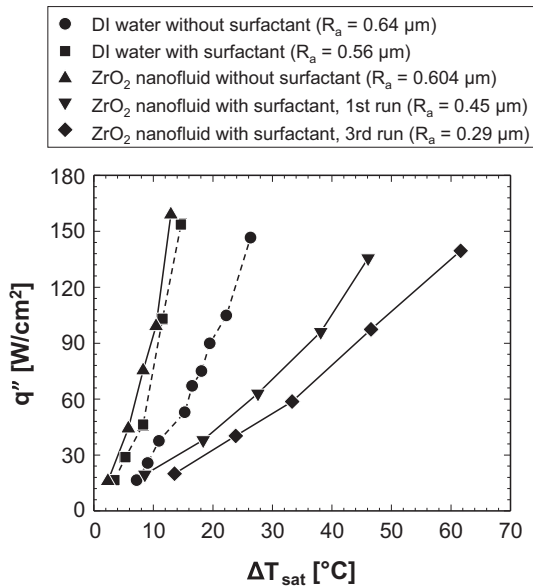


Fig. 7. Surfactant effects on nucleate boiling for pure water and water-based 0.005 vol% ZrO₂ nanofluid. Adapted from Chopkar et al. [140].

orientations, from upward-facing (0°) to vertical (90°), and surface roughness on pool boiling heat transfer for SiO₂ nanofluid. The nucleate boiling heat transfer coefficient increased with increasing concentration up to a critical concentration value of 0.005 vol%, and CHF was enhanced for concentrations below 0.01 vol%. While the nucleate boiling heat transfer coefficient for both water and nanofluid decreased with increasing orientation angle, CHF decreased for water but increased for nanofluid to a maximum at 90° for all concentrations. And the influence of surface roughness depended on relative size of roughness features and nanoparticles. The nucleate boiling heat transfer coefficient was enhanced for a sanded surface with roughness features greater than nanoparticle size, but deteriorated for a polish surface. Gerardi et al. [147] measured 50% deterioration in nucleate boiling heat transfer coefficient for water-based SiO₂ and diamond nanofluids relative to pure water, while CHF was enhanced by 100%. They also provided useful measurements of bubble departure diameter and frequency, growth and waiting times, and nucleation site density, using infrared thermometry. Ham et al. [148] reported that, compared to pure water, CHF for Al₂O₃ nanofluid with optimum concentration of 0.05 vol% was improved by 224.8% and 138.5% for surface roughnesses of $R_a = 0.1775$ and 0.2928 μm , respectively, and attributed these trends to improved wettability and increased surface roughness. However, the nanoparticles decreased the nucleate boiling heat transfer coefficient on a consistent basis.

Sarafraz and Hormozi [149] examined pool boiling performances of dilute (0.1–0.4 wt%) water-based CuO nanofluids prepared using the two-step method and stabilized using pH control, stirring, and sonication to ensure stability up to 1080 h. They also investigated the effects of adding surfactants to the nanofluid, including SDS, SDBS, and Triton X-100, with the same concentration of 0.1 wt%. In the absence of surfactant, they measured significant deterioration in the nucleate boiling heat transfer coefficient of nanofluids compared to pure water, which they attributed to much larger roughness features of the heating surface (0.34 μm) compared to nanoparticle size (50 nm). This large size difference promoted filling of surface cavities with the nanoparticles, which reduced the number of active nucleation sites. However, in the presence of surfactant, the nucleate boiling heat transfer coefficient was enhanced relative to pure water, and this

was explained by significant intensification of bubble formation resulting from the reduction in surface tension. Surfactant addition was also observed to increase wettability.

Moreno et al. [150] reported that nucleate boiling heat transfer for water-based Al₂O₃ nanofluids was similar to that for water below 70 W/cm^2 , but decreased at higher heat fluxes, and the deterioration was exasperated at high nanoparticle concentrations (~ 0.5 g/l). CHF, on the other hand, was independent of concentration. Okawa et al. [151] reported that nucleate boiling heat transfer for water-based TiO₂ nanofluids with high nanoparticle concentrations (0.4–2 g/l) first degraded with time, then improved, before finally reaching equilibrium performance.

Harish et al. [152] reported that water-based Al₂O₃ nanofluids with nanoparticles smaller than 50 nm enhanced nucleate boiling heat transfer from a rough surface ($R_a = 0.308$ μm), but degraded it from a smooth surface ($R_a = 0.053$ μm). Narayan et al. [153] arrived at somewhat similar conclusions, reporting that the nucleate boiling heat transfer coefficient for water-based Al₂O₃ nanofluid with 47 -nm nanoparticles was enhanced by up to 70% for a rough surface ($R_a = 0.524$ μm) but deteriorated below 45% compared to pure water for a smooth surface ($R_a = 0.048$ μm). However, Wen [154] reported that nucleate boiling heat transfer for water-based Al₂O₃ nanofluid was enhanced for a smooth surface ($R_a = 0.025$ μm), but did not change for a relatively rough surface ($R_a = 0.42$ μm). Using water-based Fe₃O₄ nanofluid, Salimpour et al. [155], found that nucleate boiling heat transfer from a rough surface ($R_a = 0.42$ μm) was compromised at low heat fluxes but improved at high fluxes. On the other hand, heat transfer from a smooth surface ($R_a = 0.0073$ μm) was enhanced at low heat fluxes, but did not change at high heat fluxes. Their parallel studies [156,157] achieved optimum performance at Fe₃O₄ nanoparticle concentration of 0.1 vol%, which provided up to 43% enhancement in the nucleate boiling heat transfer coefficient for the rough surface, and to a lesser extent for the smooth surface. Suriyawong and Wongwises [158] reported an optimum concentration of 0.0001 vol% for water-based TiO₂ nanofluid, and also indicated that the nucleate boiling heat transfer coefficient for 4 - μm surface roughness was 12% higher than for 0.2 - μm roughness for aluminum surfaces, and 13% higher for copper surfaces. Liu et al. [159] reported that water-based CuO nanofluids enhanced nucleate boiling heat transfer performance and CHF by 160% and 120%, respectively, at 74.5 -kPa operating pressure, and optimum enhancement was reached with a nanoparticle concentration of about 1 wt%. Hegde et al. [160] reported a maximum CHF enhancement for water-based CuO nanofluid of 130%, corresponding to an optimum concentration of 0.2 vol%, above which the enhancement decreased to a constant value. Manetti et al. [161] compared nucleate boiling results for two concentrations of water-based Al₂O₃ nanofluids, 0.0007 and 0.007 vol%, and two surface roughnesses, $R_a = 0.05$ and 0.23 μm . They measured up to 75% enhancement in the nucleate boiling heat transfer coefficient for the smooth surface compared to only 15% for the rough surface. Boiling performance was affected mainly by surface roughness of the deposited layer, which in turn was highly dependent on both nanofluid concentration and initial surface roughness. The boiling performance degraded appreciably with increasing heat flux at high concentrations, regardless of surface roughness. Overall, Al₂O₃ nanofluids were effective only at the lower concentration and moderate heat fluxes up to 40 W/cm^2 .

Das et al. [162] surveyed several publications involving nanofluid nucleate pool boiling and concluded that heat transfer was compromised for heater surface roughness values approaching nanoparticle size because of a reduction in nucleating site density. But when the surface roughness and nanoparticle size differed significantly, nucleate boiling heat transfer was enhanced because of more abundant nucleation sites, or degraded by a lesser amount

than the former case depending on nanoparticle concentration. Overall, heat transfer was enhanced at mostly low concentrations (0.32–1.25 wt%), but deteriorated at relatively high concentrations (4–16 wt%).

Okawa et al. [151] explored the effects of boiling time on CHF enhancement and surface modification for water-based TiO₂ nanofluids. Overall, increasing boiling time precipitated an asymptotic decrease in static contact angle and increased CHF, and the boiling time required to achieve maximum CHF (up to 91% enhancement) decreased sharply with increasing nanoparticle concentration. For example, CHF reached maximum value within one minute for high nanoparticle concentrations of 0.4–2 g/l, compared to over one hour for a relatively low concentration of 0.004 g/l. Okawa et al. also found that adhesion of nanoparticles to the heating surface was not firm, and partial detachment of the deposition layer was unavoidable at high nanoparticle concentrations, which ultimately reduced CHF considerably. Their co-workers, Sulaiman et al. [163], showed that nucleate boiling heat transfer was compromised for upward-facing surfaces and enhanced for those downward-facing. Kwark et al. [164,165] reported continued growth of the nanoparticle deposition layer on the heating surface during boiling experiments, rendering nanofluid pool boiling a transient process, influenced by both heat flux and duration of experiment, which is fundamentally different from the steady-state pool boiling with pure liquids. However, studies point to the existence of an upper limit for deposition layer thickness. Phan et al. [166] reported that this upper limit depended on nanoparticle concentration and duration of experiment, and that the deposition improved surface wettability but decreased the nucleate boiling heat transfer coefficient due to increased adhesion energy. Park et al. [167] noted the existence of a critical boiling duration, exceeding which CHF enhancement gradually abated because of a decrease in deposition layer porosity.

Sayahi and Bahrami [168] studied the effects of type and size of nanoparticles, and surfactant on nucleate pool boiling of nanofluids with 0.03 wt% concentration. Water-based Al₂O₃ nanofluids were observed to enhance the heat transfer coefficient, but addition of 0.01 wt% SDS surfactant decreased the enhancement due to increased viscosity. They also found that water-based SiO₂ nanofluids had an adverse influence on nucleate boiling, especially for smaller nanoparticles, but water-based ZnO nanofluids with SDS enhanced the heat transfer coefficient appreciably. In an earlier study by Shoghl and Bahrami [169], both water-based CuO and ZnO nanofluids compromised nucleate boiling, but addition of SDS proved very beneficial. Jung et al. [170] addressed effects of the ionic additive nitric acid on CHF enhancement of water-based TiO₂ nanofluids. Without the acid, CHF increased appreciably with increasing nanoparticle concentration up to 0.0001 vol%, but remained fairly constant thereafter. With the acid, CHF was enhanced in a similar manner up to 0.0001 vol%, but further increases in concentration degraded the enhancement appreciably as the nanoparticle deposition layer became smoother and more uniform. Golubovic et al. [171] showed that nanoparticle size had negligible influence on CHF, but CHF was increased by 50% and 33% using Al₂O₃ and BiO₂ nanoparticle suspensions, respectively, in distilled water.

Ahn and Kim [172] reported an intermediate bend in the nucleate boiling region of the boiling curve at high heat fluxes nearing CHF for water-based Al₂O₃ nanofluid, Fig. 8, a phenomenon that was also reported by Coursey and Kim [173], Liu and Liao [145], and Milanova and Kumar [174]. Fig. 8 shows that this bend also existed for pure water boiling on a nanoparticle-coated surface, which implies that its occurrence was closely related to the coating itself. Ahn and Kim reported the existence of a vapor film within large vapor mushrooms in the upper nucleate boiling region, and suggested that the bend was induced by a combination of nucleate

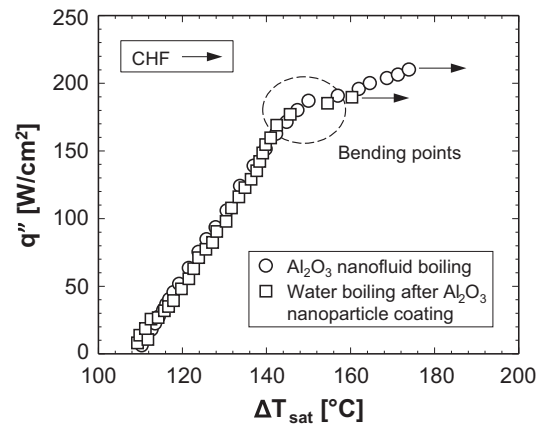


Fig. 8. Bending in upper nucleate boiling region prior to CHF with boiling of water-based Al₂O₃ nanofluid and pure water on Al₂O₃ nanoparticle coating. Adapted from Ahn and Kim [172].

boiling and film boiling. Co-existence of vapor and liquid areas on the nanoparticle coating was also observed over a broad range of heat fluxes by Cornwell et al. [175]. When boiling pure water on an uncoated surface, exceeding CHF precipitated an immediate rise in surface temperature and transition to film boiling. However, with nanofluid boiling and pure water boiling on a nanoparticle coating, CHF was associated with a gradual increase in surface temperature during which nucleate boiling was maintained for a few additional seconds.

3.2.1.5. Water-based magnetic nanofluids. Given the difficulties in maintaining fine dispersion and removal of nanoparticles within conventional nanofluids, Lee et al. [176] recommended the use of water-based magnetite (Fe₃O₄) nanofluids, in which those difficulties could be overcome by application of an external magnetic field. They showed experimentally that dilute water-based Fe₃O₄ nanofluids (0.0001–0.01 vol%) improved CHF significantly (170% to 240%) with increasing concentration, better than the enhancement with water-based Al₂O₃ and TiO₂ nanofluids at similar concentrations. Abdollahi et al. [156] showed experimentally a decrease in the nucleate boiling heat transfer coefficient in the presence of a positive magnetic field gradient (i.e., with magnetic field increasing vertically away from the horizontal heating surface), in contrast to improved performance with a negative magnetic field gradient. Mohammadpourfard et al. [177] arrived at the same latter conclusion with the aid of numerical model. Abdollahi et al. also reported that the influence of magnetic field on nanoparticles was intensified with increasing nanoparticle concentration. Shojaeian et al. [178] reported that magnetic actuation reduced the deposition and sedimentation of nanoparticles significantly during nucleate pool boiling of water-based Fe₃O₄ nanofluids [179], however eventual formation of a thick and porous layer was unavoidable, and this layer increased the surface roughness.

3.2.1.6. Overall trends for water-based oxide nanofluids. The studies discussed thus far provide strong evidence that water-based oxide nanofluids enhance CHF significantly, and the extent of enhancement is influenced by nanoparticle material, size, concentration, and surface condition. However, there are many conflicting observations concerning influence of nanofluids on the nucleate boiling heat transfer coefficient. Findings point to the heat transfer coefficient remaining unchanged, increasing, or decreasing compared to that of the base liquid, but most studies suggest that the heat transfer coefficient is influenced positively or negatively by the same parameters that contribute to CHF enhancement, in addition

to heat flux level; they also point to an optimum concentration for maximum CHF enhancement. One reason for the conflicting findings regarding the heat transfer coefficient is the use of additives in some studies to stabilize nanoparticle suspension. Clearly, these contradictory findings warrant more systematic experimental investigation of nanofluid performance using broad varieties of nanoparticle materials, sizes, and concentrations, different surface materials and roughnesses, and different operating pressures. Even more importantly is to perform repeated experiments to investigate time-dependent variations in the heat transfer coefficient caused by nanoparticle buildup on the heating surface.

3.2.2. Metal nanoparticles

Despite disagreements among investigators regarding effectiveness of water-based oxide nanofluids, these nanofluids have received significant attention during the past decade. In contrast, far less attention has been given to metal nanofluids, which can be explained by the great difficulty maintaining a suspension of metal nanoparticles in the base liquid. Kathiravan et al. [180,181] investigated nucleate pool boiling of water-based 0.25–1.0 wt% Cu nanofluids and achieved maximum CHF enhancement of nearly 50% compared to that of pure water at 1.0 wt%. However, as shown in Fig. 9, adding 9.0 wt% SDS surfactant into the nanofluid reduced the CHF enhancement to only one-third that without the surfactant. Additionally, the nucleate boiling heat transfer coefficient decreased with increasing nanoparticle concentration. Zhou [182] reported that single-phase convection was enhanced but nucleate boiling heat transfer was compromised with acetone-based Cu nanofluids. Krishna et al. [183] showed that the heat transfer coefficient for water-based Cu nanofluids at a low concentration of 0.01 vol% decreased in the low-heat-flux nucleate boiling region compared to that for pure water, but increased as concentration was increased to 0.1 vol%; increasing concentration had the opposite effect in the high-heat-flux region. Krishna et al. attributed these complex trends to the net effect of several parameters, including thermal conductivity of the microlayer, sorption layer formation, and active nucleation site density.

Kole and Dey [184] reported simultaneous enhancement of both the nucleate boiling heat transfer coefficient and CHF for water-based Cu nanofluids with increasing concentration in the range of 0.005–0.5 wt%. They also reported better enhancement for a heating surface made from copper than from brass. The nucleate boiling heat transfer coefficient also increased as surface roughness was increased from $R_a = 0.06$ to $0.22 \mu\text{m}$, before decreasing as the roughness was increased further to $0.7 \mu\text{m}$; the latter trend was attributed to blockage of active nucleation sites by nanoparticle deposits.

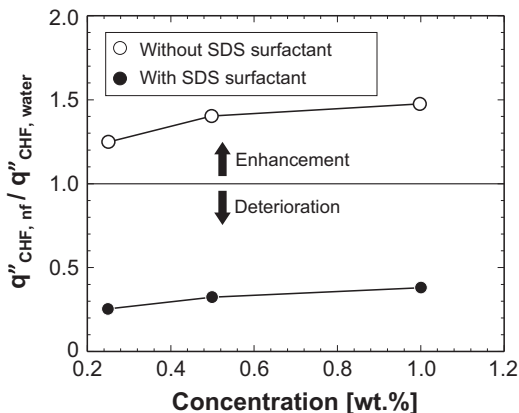


Fig. 9. Ratio of CHF for water-based Cu nanofluid to that for water with and without 9.0 wt% SDS surfactant. Adapted from Kathiravan et al. [181].

Shi et al. [185] studied the effects of adding Fe nanoparticles into water, and pointed out the dependence of nucleate boiling heat transfer on nanoparticle thermal properties, size, and concentration, as well as heat flux. The nanoparticles increased effective thermal conductivity of the fluid and decreased surface tension, both of which contributed to better nucleate boiling heat transfer. On the other hand, trapping of nanoparticles in surface cavities produced a smoothing effect to the surface, which tended to decrease the nucleate boiling heat transfer coefficient. Therefore, they suggested that any enhancement or deterioration in heat transfer performance was the net outcome of these two competing factors.

Cieslinski and Kaczmarczyk [186] compared the boiling performances of water-based nanofluids with oxide (Al_2O_3) nanoparticles to those with metal (Cu) nanoparticles on the surfaces of both copper and stainless steel tubes. For the smooth copper tube, nucleate boiling heat transfer coefficient was independent of nanoparticle material but decreased as nanoparticle concentration was increased from 0.01 to 1.0 wt%. On the other hand, nucleate boiling heat transfer coefficient for the stainless steel tube improved with both nanoparticle materials. The heating surface material did not influence boiling heat transfer for the 0.1 wt% Cu nanofluid.

3.2.3. Carbon nanotubes and graphene oxide

More recently, significant attention has been given to nanofluids using carbon nanotubes (CNTs) and graphene oxide (GO) suspensions. Liu et al. [187] investigated nucleate pool boiling heat transfer of water-based nanofluids with 15-nm diameter and 5- to 15- μm long multi-walled CNTs in 0.5–4.0 wt% concentrations and pressures from 7.4 to 103 kPa, in which the CNTs were treated with nitric acid to promote good dispersion in the nanofluid. The CNT nanofluids enhanced the nucleate boiling heat transfer coefficient and CHF considerably compared to pure water, and the enhancement improved significantly with decreasing pressure. For all pressures tested, maximum nucleate boiling heat transfer enhancement was achieved with 2.0 wt% CNT concentration. Liu et al. also conducted boiling experiments with pure water on a CNT-coated surface for comparison, and found CNT nanofluids to provide better enhancement of both the nucleate boiling heat transfer coefficient and CHF. This finding proves that liquid–solid contact angle and heated surface microtopography are not the only parameters influencing the heat transfer enhancement.

Park and Kim [188] reported that multi-walled CNT nanofluids CM-95 and CM-100 provide optimum enhancement in the nucleate boiling heat transfer coefficient and CHF at a concentration of 0.001 vol%. They also pointed out the important enhancement role of CNT shape; better enhancement was achieved with longer CNTs ($\sim 200 \mu\text{m}$) of CM-100 than with shorter (10–20 μm) CNTs of CM-95. Park and Kim also conducted experiments in which CM-100 CNTs were oxidized by first adding the CNTs to a mixture of sulfuric acid and nitric acid. This treatment improved dispersibility of the nanofluid by altering the original graphite structure's polarity and reducing Van der Waals forces, resulting in further enhancements in both the nucleate boiling heat transfer coefficient and CHF. The oxidized CNTs were also capable of maintaining good dispersibility over a relatively long duration.

Kumar and Milanova [189] explored the nucleate boiling performance of water-based single-walled CNT suspensions. These suspensions proved effective at enhancing both the nucleate boiling heat transfer coefficient and CHF; enhancement in the latter was attributed to surface tension difference between the nanofluid and base liquid. A maximum CHF enhancement four times that of the CNT suspension was achieved by adding surfactant with a weight concentration ratio to that of CNTs of one to five.

Park and Jung [190] reported up to 30% enhancement in the nucleate boiling heat transfer coefficient with R22- and water-based 1.0 vol% CNT nanofluids in which the CNTs (20-nm diameter and 1- μm long) were treated with acid for better dispersion. One important finding from their experiments was the absence of nanoparticle deposition on the heating surface, which is in contrast with most other studies concerning conventional oxide and metallic nanoparticles. The observed heat transfer enhancement was attributed to CNTs' ability to generate more bubbles by penetrating into the thermal boundary layer adjacent to the surface. Follow-up study by Park et al. [191], however, showed that the nucleate boiling heat transfer coefficient for water-based CNTs (10–20-nm diameter and 10 to 50- μm long) in concentrations of 0.0001–0.05 vol% was inferior to that for pure water. In these experiments, polyvinyl pyrrolidone polymer was added to the base liquid to aid CNT dispersion without influencing heat transfer performance. The deterioration in heat transfer coefficient was attributed to the surface deposition layer, which served as thermal resistance and reduced number of active nucleation sites. However, CHF for CNT nanofluids increased with increasing concentration because of improved surface wettability, reaching maximum enhancement of 200% at 0.001 vol%, beyond which CHF enhancement decreased due to appreciable agglomeration of CNTs. Similar results were reported by Park et al. [192], who used DISPERBYK 184 as dispersant in CNT nanofluids.

Kathiravan et al. [193] compared the nucleate boiling performances for water-based CNT nanofluids with concentrations ranging from 0.25 to 1.0 vol%. They performed experiments both with and without addition of 9.0 wt% sodium lauryl sulfate surfactant. For a constant heat flux of 50 W/cm², they achieved 1.5, 2.6 and 3.0-fold enhancement in nucleate boiling heat transfer coefficient with nanofluids without surfactant in CNT concentrations of 0.25 vol%, 0.5 vol%, and 1.0 vol%, respectively, compared to pure water. However, the largest enhancement with surfactant was only 1.7 fold, achieved with 0.5 vol% CNT, and further increases in CNT concentration degraded boiling performance. Overall, the boiling enhancement was attributed to the ability of high thermal conductivity CNTs to penetrate close to, and touch the heating surface, thereby aiding generation of vapor bubbles. Like Park and Jung [190], Kathiravan et al. observed no surface fouling or deposition. Using SDBS surfactant, Murshed et al. [194] reported maximum CHF enhancement of 492% with water-based single-walled CNT nanofluids, corresponding to an optimum surfactant to CNT weight ratio of one to five.

Sarafraz et al. [195] measured the nucleate boiling performance for water-based CNT nanofluids in concentrations of 0.1–0.3 wt%, in which nonylphenol ethoxylates surfactant was used to aid CNT dispersion. Their experiments were performed both with and without addition of carboxyl group functionalizer, the purpose of which was to improve repulsive forces in the nanofluid. Overall, the functionalized CNT nanofluids provided several advantages, including enhanced nucleate boiling and CHF, and improved stability, whereas the non-functionalized nanofluids enhanced CHF slightly but degraded nucleate boiling. There were also appreciable differences in growth behavior of deposition layer: rectilinear for the functionalized nanofluids, and asymptotic for the non-functionalized; the latter yielded larger contact angle.

Amiri et al. [196] studied water-based CNT nanofluids treated with different functional groups to enhance CNT dispersion. The CNTs were functionalized to form three types of CNT nanofluids using two different methods, covalent functionalization with cysteine and silver nanoparticles, and non-covalent functionalization with gum arabic. The non-covalent functionalization produced by adding several surfactants reduced the effective heat transfer area and induced foaming, while the covalent functionalization prevented both of these problems and provided good nanofluid stabil-

ity. The covalent CNT nanofluids enhanced the nucleate boiling heat transfer coefficient appreciably due to decreased thermal resistance at the surface in the absence of nanoparticle deposition, while the non-covalent CNT nanofluids weakened boiling performance with presence of the deposition layer. By increasing CNT concentration over a range of 0.01 to 0.1 wt%, the nucleate boiling heat transfer coefficient for covalent nanofluids increased while that for non-covalent nanofluids decreased, however, CHF was enhanced for both. CNT size also played a measurable role, as both the nucleate boiling heat transfer coefficient and CHF increased with increasing CNT diameter, apparently due to increased specific surface area. Xing et al. [197] tested water-based CNT nanofluids that were subjected to either covalent functionalization with carboxyl and hydroxyl, or non-covalent functionalization with CTAB surfactant. They arrived at the same conclusions concerning effects of CNT concentration (over a range of 0.1–1 wt%) on boiling performance as Amiri et al.; they also did not observe any CNT deposition with the covalent nanofluids.

Park et al. [198] investigated CHF enhancement with water-based 0.0001 vol% GO nanofluid with addition of boric acid, lithium hydroxide, and trisodium phosphate, in the application of external reactor vessel cooling (ERVC). They showed that GO nanofluids were stable in this complex cooling configuration, and, compared to pure water, enhanced CHF by up to ~40% for the vertical surface orientation and ~200% for the horizontal orientation. These enhancement levels were superior to those achieved with SiO₂ and Al₂O₃ nanofluids for the same concentration and orientations between 0 and 90°. Kamatchi et al. [199] reported that CHF with reduced GO (RGO) nanofluids could be increased by 145–245% with an increase in concentration from 0.01 to 0.3 g/l.

Ahn et al. [200] studied the enhancement potential of suspensions of reduced GO in water, where the GO was treated chemically with hydrazine. The chemical treatment was intended to produce different levels of flakiness in the deposited layer for different GO concentrations during nucleate boiling, which, as shown in Fig. 10(a), include base graphene layer (BGL), self-assembled foam-like graphene (SFG), and thickly aggregated graphene layer (TGL). Results showed how greatly increased thermal conductivity of the fluid caused boiling to commence earlier than with the base fluid. Notice that BGL is hydrophilic, while SFG and TGL are both hydrophobic. Enhanced wettability of the deposited layer promoted water absorption through porous structures within the layer, which helped increase CHF. But increasing GO concentration was observed to compromise nucleate boiling heat transfer, which was attributed to thermal resistance caused by TGL formation on the heating surface. Follow-up work by Ahn et al. [201,202] revealed an interesting boiling phenomenon for reduced GO colloids. Unlike the rapid rise in wall temperature following CHF with pure water, the wall temperature with reduced GO colloid began to increase quite slowly while the wall heat flux was maintained at CHF, Fig. 10(b) and (c). They attributed this phenomenon to delayed hot/dry spot formation caused by heat-spreading action in BGL and SFG, and the advantageous effects of boiling on a porous medium. Sulaiman et al. [125] observed a similar phenomenon with SiO₂ nanofluids, but attributed the same behavior to partial detachment of the nanoparticle deposition layer at high heat fluxes nearing CHF.

3.3. Nanofluids using other base fluids

3.3.1. Ethylene glycol/water mixtures

Aside from water, a few researchers investigated pool boiling of nanofluids using pure organic liquids or their aqueous solutions as base fluid. One of the most investigated among those is mixture of

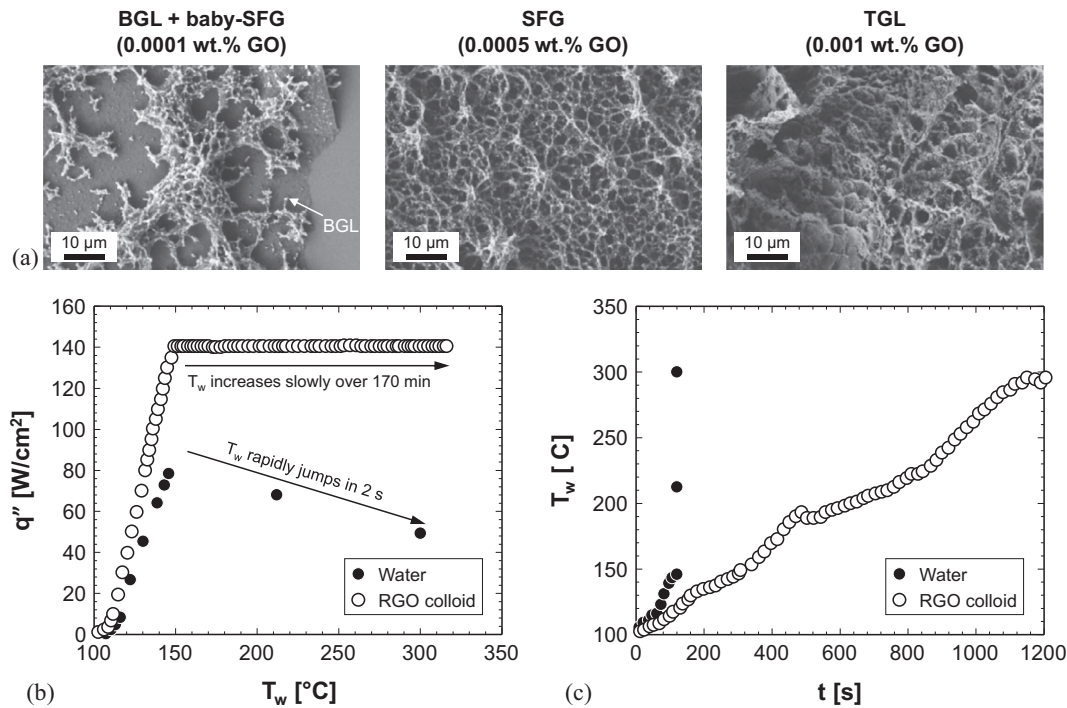


Fig. 10. (a) SEM images of base graphene layer (BGL), self-assembled foam-like graphene (SFG), and thickly aggregated graphene layer (TGL) at different concentrations of reduced GO in water (adapted from Ahn et al. [200]). (b) Boiling curves and (c) wall temperature evolutions for water and reduced GO colloid (adapted from Ahn et al. [202]).

ethylene glycol and water, a popular antifreeze used in automotive cooling systems.

He et al. [203] investigated the pool boiling characteristics of ethylene glycol/deionized water-based ZnO nanofluids. Compared to the base solution, appreciable heat transfer improvement was observed in the natural convection region, but enhancement in the nucleate boiling region was comparatively mild. On the other hand, there was significant enhancement in CHF, which was attributed to reduction in wettability and nanoparticle coating of the heating surface. Overall, boiling heat transfer was influenced by both volume fraction of ethylene glycol in water and nanoparticle concentration. Similar experiments with ethylene glycol/deionized water-based ZnO nanofluids were performed by Kole and Dey [204,205]. They reported a 22% enhancement in nucleate boiling heat transfer coefficient with 0.016 vol% ZnO, but increasing the nanoparticle concentration decreased the heat transfer coefficient. Using ethylene glycol/water-based ZnO nanofluids, Raveshi et al. [206] achieved an optimum enhancement in nucleate boiling heat transfer coefficient of 64% with a nanoparticle concentration of 0.75 vol% and 50 vol% ethylene glycol in water. Heris [207] and Mohamadifard et al. [208] reported 55% and 64% enhancement in the nucleate boiling heat transfer coefficient for ethylene glycol/water-based CuO and Al₂O₃ nanofluids, respectively, where the nanoparticle concentration was set at 0.5 wt% and glycol concentration at 60 vol%. In contrast, Sheikhbahai et al. [209] reported that ethylene glycol/water-based 0.01–0.1 vol% Fe₃O₄ nanofluids had an adverse effect on nucleate boiling performance but improved CHF appreciably compared to the base fluid mixture. But applying an electric field to the nanofluid enhanced nucleate boiling heat transfer without affecting CHF. Sarafraz and Hormozi [210] also found that ethylene glycol/water-based 0.1–0.3 wt% Al₂O₃ nanofluids adversely influenced nucleate boiling heat transfer, and their performance worsened with increasing nanoparticle concentration as deposition of nanoparticles, whose size was comparable to initial surface roughness, decreasing the surface rough-

ness and reducing the number of active nucleation sites. Sarafraz et al. [211] experimented with ethylene glycol/water-based 0.025–0.1 vol% ZrO₂ nanofluids and 50 vol% glycol. They observed mild enhancement in the nucleate boiling heat transfer coefficient with increasing nanoparticle concentration, reaching 12% at 0.1 vol%. CHF also increased because of decreasing contact angle.

Hu et al. [212] studied ethylene glycol/deionized water-based graphene nanosheet (GN) nanofluids with 60 vol% glycol. Nucleate boiling performance was enhanced for GN concentrations below 0.02 wt%, which was caused by enhanced surface wettability brought by nanoparticle deposition from broken nanosheets. However, further increases in GN concentration had an adverse effect on nucleate boiling heat transfer because of appreciable GN sedimentation and subsequent blockage of nucleation sites. For concentrations below 0.02 wt%, CHF increased appreciably with increasing concentration but leveled out beyond this critical concentration. While, in a different study involving ethylene glycol/water-based SiO₂ nanofluids [143], the optimum concentration was 0.75 vol%, and the nucleate boiling heat transfer coefficient increased as nanoparticle size was increased from 84 to 120 nm.

3.3.2. Refrigerants

Naphon and Thongjir [213] examined the pool boiling characteristics of nanofluids comprised of TiO₂ nanoparticles suspended in two types of base fluids, R141b and ethyl alcohol. They reported deterioration in the nucleate boiling heat transfer coefficient compared to the base fluids. However, the heat transfer coefficient increased as operating pressure was increased from 50 to 150 kPa, but decreased with increasing nanoparticle concentration in the range of 0.01–0.075 vol%. Additionally, application of magnetic field to the nanofluids enhanced the boiling performance [214]. Trisaksri and Wongwises [215] reported somewhat similar trends for R141b-based 0.01–0.05 vol% TiO₂ nanofluids over a pressure range of 200–500 kPa, but the nucleate boiling heat transfer coefficient remained unchanged at the high end of the pressure range

(400 and 500 kPa). However, by adding SDBS surfactant to R141b-based Cu nanofluids, Diao et al. [216] reported enhancement in the nucleate boiling heat transfer coefficient coupled with CHF degradation compared to pure R141b. Park and Jung [217] noted that R123- and R134a-based 1.0 vol% CNT nanofluids produced measurable enhancements in nucleate boiling heat transfer. The enhancement was more pronounced (up to 36.6%) at relatively low heat fluxes (below 30 W/cm²), but abated with increasing heat flux because of vigorous bubble generation. And, unlike oxide and metal nanoparticles, no surface fouling was observed with CNTs even after three weeks of testing. Eid et al. [218] reported that the nucleate boiling heat transfer coefficient for R134a-based Al₂O₃ nanofluids was doubled by increasing nanoparticle concentration up to 0.25 vol% because of increased surface roughness, but the enhancement abated above this concentration. Tang et al. [219] showed that R141b-based Al₂O₃ nanofluids with surfactant SDBS enhanced nucleate boiling heat transfer for 0.001, 0.01 and 0.1 vol% nanoparticle concentrations, however, the heat transfer deteriorated at 0.1 vol% in the absence of surfactant. They also pointed out that nanoparticle deposition on the heating surface had negligible effect on the contact angle of R141b.

Kedzierski [220] explored pool boiling performance of a nanofluid obtained by adding 0.5 wt% nanolubricant RL68H2Cu into R134a, the nanolubricant itself consisting of CuO nanoparticles mixed into polyolester lubricant RL68H. A 0.5 vol% CuO concentration in the nanolubricant yielded neither improvement nor degradation in nucleate boiling heat transfer compared to R134a and polyolester mixtures without nanoparticles. However, 1.0 vol% CuO in the nanolubricant did enhance heat transfer by 50% to 275% [221]. Kedzierski [222] achieved 155% enhancement in nucleate boiling heat transfer coefficient by adding 2 wt% Al₂O₃ nanolubricant (RL68H1AlO) in R134a. Follow-up work by Kedzierski [223] showed how enhanced surfaces, such as those with rectangular fins, required nanoparticle concentrations higher than those for a smooth surface to achieve similar heat transfer enhancement. This proves that boiling heat transfer enhancement depends on nanoparticle deposition density on the heating surface rather than nanoparticle concentration in the nanofluid. Adding 2.6 vol% diamond into the nanolubricant allowed R134a nanofluids to achieve considerable nucleate boiling enhancement for 0.5 and 1.0 wt% nanolubricant, compared to degradation for 2.0 wt% [224]. Overall, nucleate boiling performance deteriorated with time.

Ding and Peng [225,226] examined changes in concentration of CuO nanoparticles in R113, and in R113 and RB68EP oil mixture caused by CuO migration. A somewhat similar study was carried out by Mahbulul et al. [227], who investigated effects of heat flux, liquid level height, vessel size, insulation, and lubricating oil on the nanoparticle migration. Peng et al. [228] investigated nucleate pool boiling for a nanofluid obtained by adding diamond/ester oil (VG68) suspension containing 0–15 wt% diamond into R113 with nanoparticles/oil concentrations of 0–5 wt%. They showed enhancement in the nucleate boiling heat transfer coefficient with increasing nanoparticle concentration in 0–15 wt%, but the heat transfer coefficient decreased by up to 63.7% with increasing nanoparticles/oil concentration in 0–5%. Follow-up study by Peng et al. [229] produced the same trend with Cu nanoparticles. The same study produced a 23.8% enhancement in nucleate boiling heat transfer coefficient when nanoparticle size was decreased from 80 to 20 nm, a trend which contradicts the findings of Narayan et al. [141]. Peng and coworkers [230,231] also addressed effects of surfactants SDS, CTAB, and Span-80 on nucleate boiling for R113-based Cu nanofluids with and without VG68, and showed that surfactants generally improved boiling performance. The ratio of nucleate boiling heat transfer coefficient with surfactant to that without surfactant increased with increasing surfactant concentra-

tion at first and then decreased at high concentrations. The same ratio also increased with decreases in surfactant molecular weight, nanolubricant concentration, and heat flux.

Nanofluid experiments were also conducted with other organic base fluids. Umesh and Raja [232] reported 15–25% enhancement in nucleate boiling heat transfer coefficient with pentane-based 0.005 vol% CuO nanofluids, but the enhancement was inferior with 0.01 vol%. Sarafraz et al. [233] added 0.5–1.5 vol% Al₂O₃ nanoparticles and 1–5 vol% glycerol into pure water, and reported enhancement in nucleate boiling heat transfer coefficient with increasing nanoparticle concentration, reaching 25% with 1.5 vol% Al₂O₃. Soltani et al. [234] reported up to 25% enhancement in nucleate boiling heat transfer coefficient with nanofluid obtained by adding Al₂O₃ nanoparticles into non-Newtonian carboxy methyl cellulose aqueous solution. Kong et al. [235] reported that FC-72-based Al₂O₃ nanofluids enhanced nucleate boiling heat transfer to some extent, but the enhancement was adversely affected by addition of surfactant FSO-100, the intent of which was to maintain nanofluid stability and homogeneity. Jung et al. [236] tested boiling performance of H₂O/LiBr-based binary Al₂O₃ nanofluids with polyvinyl alcohol as stabilizer. In general, there was no improvement in nucleate boiling heat transfer coefficient compared to that of the base fluid. In fact, the nucleate boiling heat transfer coefficient even deteriorated when Al₂O₃ concentration was increased from 0.01 to 0.1 vol%, but CHF did improve.

3.4. Bath quenching in nanofluids

3.4.1. CHF enhancement

As discussed earlier, boiling performance of different fluids can be assessed using either steady state, heat-flux-controlled experiments or transient quenching experiments. The former involves increasing surface heat flux in small increments and waiting following each increment to allow surface temperature to achieve steady state. The second method involves preheating a small object that satisfies the lumped capacitance criterion to relatively high temperature before submerging it into a liquid bath. Transient temperature-time data acquired during the quench are then converted into a boiling curve using the lumped capacitance method. The quench method was adopted in several nanofluid studies, with special focus on CHF enhancement potential compared to the base liquid.

Xue et al. [237] investigated quenching of a nickel-plated copper sphere in water-based CNT nanofluids, and derived boiling curves from the measured temperature-time history of the sphere. Their results showed that, compared to pure water, CNT nanofluids caused earlier occurrence (*i.e.*, at higher surface temperature) of the Leidenfrost point, as well as enhanced both transition boiling heat transfer and CHF. The CHF enhancement was attributed to deposition of CNTs on the surface, and enhancements in Leidenfrost point and transition boiling to changes in wettability resulting from use of gum arabic as dispersant during preparation of the nanofluid. Babu and Kumar [238,239] reported that CHF for multi-walled CNT nanofluids during quenching was influenced by both initial nanofluid bath temperature and CNT concentration. They achieved CHF enhancement when CNT concentration was increased up to 0.5 wt%, above which increased viscosity produced an adverse effect on CHF. Their experiments yielded a maximum heat flux of 420 W/cm² with 40 °C bath temperature and 0.5 wt% nanoparticle concentration. Babu and Kumar [240] provided further evidence of the influence of surfactant on CHF. In their quenching experiments, CHF for CNT nanofluid without surfactant was 37.5% higher than for pure water. However, CNT nanofluid with surfactant Triton X100 produced prolonged film boiling, hindered heat transfer rates significantly, and reduced CHF by 24.9% compared to water. Zhang et al. [241] performed quenching

experiments with a nickel-plated copper sphere having a relatively high contact angle of 100.6° in pure water. They showed that aqueous colloidal suspensions with extremely dilute graphene oxide nanosheets increased CHF moderately (13.2% for 0.0001 wt% graphene, and 25.0% for 0.0002 wt%) by virtue of enhanced surface wettability. In follow-up study, Fan et al. [242] investigated quenching of a stainless steel sphere with a contact angle in pure water of $\sim 25^\circ$ using the same nanofluids but with graphene concentrations as high as 0.1 wt%, and demonstrated CHF enhancement with increasing concentration. But unlike many other investigators, who attributed the CHF enhancement to improved surface wettability, Fan et al. found that the wettability changed only slightly and even deteriorated with the nanofluids, and attributed the CHF enhancement instead to better solid-liquid contact caused by increased surface roughness.

Chun et al. [243] reported findings from experiments involving quenching of a thin platinum (Pt) wire in pure water, Si nanofluid, and SiC nanofluid, the latter two having nanoparticle concentrations in the range of 0.001–0.01 vol%. For all three fluids, there were no appreciable differences in the quenching curve, though CHF for the Si nanofluid was slightly higher, and that for SiC nanofluid slightly lower, compared to that for pure water. However, initially Si and SiC nanoparticle-coated Pt wires produced considerably higher CHF during quenching than bare Pt wires quenched in nanofluids. Additionally, the nanoparticle-coated cases did not encounter stable film boiling, and therefore yielded very high cooling rates. However, quenching experiments by Lotfi and Shafii [244] using Ag and TiO_2 nanofluids, and Khoshmehr et al. [245] using multi-walled CNT nanofluids, showed lower CHF than for pure water, and CHF was independent of number of quench runs [245]. Lotfi and Shafii also reported a decrease in CHF for 0.5–4 wt% Ag and 0.125–1.0 wt% TiO_2 nanofluids with decreasing nanoparticle concentration, while Khoshmehr et al. reported an increase in CHF with decreasing concentration for 0.1–0.8 wt% multi-walled CNT nanofluids.

By performing quenching experiments with a copper sphere in water-based graphene oxide nanosheet nanofluids, Zhang et al. [246] showed that CHF enhancement with increasing nanosheet concentration was non-monotonic. Recent experiments by Fan et al. [247], in which nonionic surfactant functionalized by aromatic groups was used as dispersant, showed that boiling heat transfer enhancement for 0.5 wt% CNT nanofluid was closely related to CNT size. Better enhancement was achieved with thicker and longer CNTs, reaching levels as high as 60% and 100% for CHF and Leidenfrost temperature, respectively, with 60-nm diameter and 5- μm long CNTs. The quenching process was progressively accelerated upon consecutive runs due to cumulative deposition of CNTs. Fan et al. attributed the heat transfer enhancement to both greatly increased surface roughness and formation of porous structure by CNT deposits, rather than to surface wettability, which remained nearly unchanged. The finding concerning surface wettability contradicts that of Jeong et al. [85], who measured contact angle during nucleate boiling at $150 \pm 10^\circ\text{C}$ for both pure water and nanofluid during quenching experiments. They reported that wettability was indeed enhanced because of nanoparticle deposition on the surface.

3.4.2. Quench acceleration with nanofluids

Park et al. [248] performed quenching experiments with a stainless steel sphere that was submerged in water-based 5–20 vol% Al_2O_3 nanofluids with subcooling ranging from 20 to 80°C . They showed that film boiling heat transfer was compromised with the nanofluids compared to that with pure water, especially at low subcooling. Additionally, film boiling heat transfer with the nanofluids showed only weak dependence on nanoparticle concentration above 5 vol%. Interestingly, re-quenching proceeded much

faster than with a fresh sphere, which they attributed to the nanoparticle layer deposited on the sphere's surface during the previous quench preventing formation of stable vapor film, thus bypassing the film boiling regime during the re-quench.

Kim et al. [249] quenched metal spheres made from stainless steel and zircaloy in water-based nanofluids containing low concentration (less than 0.1 vol%) Al_2O_3 , SiO_2 , and diamond nanoparticles. They showed that film boiling heat transfer in nanofluids was almost identical to that in pure water. However, subsequent quenches proceeded faster due to gradual accumulation of nanoparticle deposits on the sphere tending to destabilize the vapor film. And CHF for the Al_2O_3 and SiO_2 nanofluids was enhanced gradually with repeated quenches, also because of gradual growth of the deposition layer, but CHF for the diamond nanofluid remained unchanged. Bolukbasi and Ciloglu [250] reported similar film boiling and CHF trends with water-based 0.001–0.1 vol% SiO_2 nanofluids, and also found that nucleate boiling heat transfer was inferior to that for pure water during the first quench but not after repeated quenches. Follow-up study by Kim et al. [251] provided further evidence of quench acceleration with repeated quenches of a stainless rod in water-based Al_2O_3 nanofluid. Notice in Fig. 11(a) the repeatability in temperature response of the rod to repeated quenches in pure water, in contrast with accelerated response to repeated quenches in the nanofluid in Fig. 11(b). Kim et al. attributed the latter accelerated response to growth of the nanoparticle deposition layer, whose gradual improvement in wettability and increased roughness intensified intermittent liquid-solid contact in the film boiling regime. Khoshmehr et al. [245,252] reported that quench time for a silver rod in

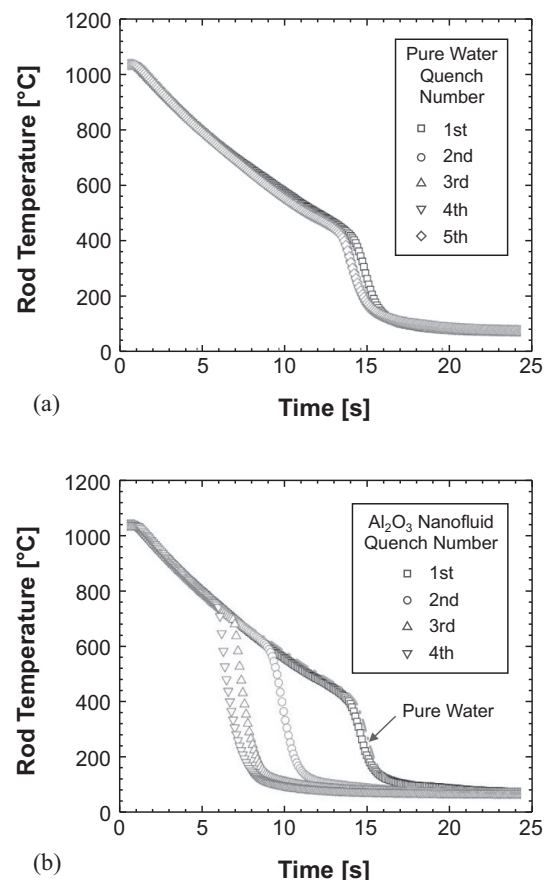


Fig. 11. Temperature-time plots for repeated quenching of stainless steel rod in (a) pure water and (b) 0.1 vol% Al_2O_3 nanofluid, both at $\Delta T_{\text{sub}} = 20^\circ\text{C}$. Adapted from Kim et al. [251].

deionized-water-based multi-walled CNT and Fe_3O_4 nanofluids also decreased with repeated quenching. They also found the quench to proceed more rapidly on a rough surface than on a smooth surface.

Lotfi and Shafii [244] measured considerable deterioration in quench rate for a silver sphere in water-based Ag and TiO_2 nanofluids compared to that in pure water. The deterioration with the nanofluids was attributed to accumulation of nanoparticles at the liquid-vapor interface inhibiting vapor release. Within the nanoparticle concentration ranges tested (0.5–4 wt% for Ag and 0.125–1 wt% for TiO_2), quench time for the nanofluids decreased with increasing concentration. But with subsequent quenching, nanoparticle deposition on the surface resisted formation of a stable vapor film, which is why the film boiling regime vanished altogether and quench accelerated through the nucleate boiling regime.

3.5. Combination of nanofluids and modified surfaces

There is abundant evidence in the heat transfer literature that extending surface area, such as with fins, is very effective at enhancing CHF for pure liquids. Additionally, modifying the surface with porous attachments is known to enhance the nucleate pool boiling heat transfer coefficient by increasing number of active nucleation sites. Given these merits and the fact that nanofluids can enhance nucleate boiling heat transfer and CHF under specific conditions, some investigators set out to combine the merits of nanofluids and modified surfaces.

Sarafraz et al. [136] investigated the boiling performance of water-based Al_2O_3 nanofluids on a plain surface and a surface with concentric circular microstructures. For the plain surface, the nanofluid caused deterioration in nucleate boiling heat transfer coefficient because of increased thermal resistance by the deposition layer, but increased CHF. On the other hand, the nanofluid enhanced both nucleate boiling and CHF from the structured surface. The enhancement in nucleate boiling heat transfer coefficient was intensified with increases in heat flux and nanoparticle concentration (over a range of 0.1–0.3 wt%), and decreases in nanoparticle size (from 50 to 20 nm) and interspace between microstructures, but was insensitive to variations in height of microstructures. The CHF enhancement was intensified with increases in size and concentration of nanoparticle, and interspace between microstructures, and was attributed to capillary wicking action assisting liquid inflow inside the deposition layer and rewetting of dryout patches. Sarafraz and Hormozi [253] also examined nucleate boiling characteristics of smooth and micro-finned surfaces in pure water and water-based CNT nanofluids. Compared to the smooth surface, the micro-finned surface yielded 56% and 77% enhancement in the nucleate boiling heat transfer coefficient, and CHF enhancement of 75% and 95%, with nanoparticle concentrations of 0.1 and 0.3 wt%, respectively. A micro-finned surface with smaller fins was noted to provide better nucleate boiling performance but inferior CHF compared to a surface with larger fins.

Mori et al. [254,255] investigated the boiling characteristics of a honeycomb porous plate covering a 30-mm diameter heating surface in water-based TiO_2 nanofluids. Appreciable CHF enhancement was achieved, which increased with increasing nanoparticle concentration, reaching a maximum of 320 W/cm^2 with 0.1 vol% concentration. Interestingly, CHF was achieved even with the downward-facing surface orientation [256]. Aside from merits of the porous plate, the significant CHF enhancement was attributed to nanoparticle deposition assisting vapor escape and liquid replenishment of the surface. However, the nucleate boiling heat transfer coefficient for the porous plate decreased with increasing nanoparticle concentration. Follow-up study by Aznam et al. [257] involved boiling experiments with the honeycomb porous plate

and a gridded metal structure in water-based TiO_2 nanofluids, which yielded CHF values as high as 310 W/cm^2 .

Chang and Wang [258] reported deterioration in nucleate boiling heat transfer coefficient for a low-finned U-tube in R141b -based TiO_2 nanofluids in comparison with that for pure R141b , and attributed the deterioration to increased thermal resistance caused by the nanoparticle deposition layer. They then attempted to minimize formation of the deposition layer with the aid of an ultrasonic vibration crusher. This technique was successful at enhancing the nucleate boiling heat transfer coefficient of the nanofluids by 30% and 12% for 0.0001 and 0.001 vol% concentrations, respectively, compared to that with pure R141b . However, ultrasonic vibration failed to prevent formation of the deposition layer for a relatively high concentration of 0.01 vol%, and the nucleate boiling heat transfer coefficient actually decreased by 8% compared to pure R141b . It should be mentioned that ultrasonic vibration was also used to enhance nucleate boiling heat transfer for a smooth U-tube in R141b -based TiO_2 nanofluids [259].

Niu and Li [260] measured higher bubble departure frequencies on a porous surface compared to a polished surface, regardless of working fluid. Nanofluids and porous structures each showed improvements in heat transfer performance; even better performance was achieved by combining the two. Xu and Zhao [261] investigated pool boiling heat transfer on surfaces coated with open-celled copper foam in water-based Al_2O_3 and SiC nanofluids, and showed nucleate boiling performance was influenced by several factors, including nanoparticle material, size and concentration, and foam structure (pore density and cell size), which all influenced nanoparticle deposition.

Cieśliński and Kaczmarczyk [262] compared pool boiling performances of pure water and water-based Cu and Al_2O_3 nanofluids on a smooth stainless-steel tube and one having a 0.15-mm thickness porous aluminum coating. While the nanofluids enhanced the nucleate boiling heat transfer coefficient for the smooth tube, the porous surface showed significantly poorer performance with addition of even small amounts of nanoparticles. Cieśliński and Kaczmarczyk attributed the deterioration with nanofluids to nanoparticle trapping inside the porous matrix. This deterioration was further exacerbated upon increasing nanoparticle concentration over a range of 0.01 to 1.0 wt%, or decreasing operating pressure. Overall, their article points to potential drawbacks in combined use of nanofluids and modified surfaces, stemming mostly from deactivation of nucleation sites by nanoparticle deposition into inner features of the modified surface.

4. Enhancement mechanisms

4.1. Nanoparticle deposition and capillary wicking

Strong evidence of dominant heat transfer mechanisms with nanofluids comes from works by Kim et al. [114,263,264], who compared CHF values for water-based Al_2O_3 (47-nm particles) and TiO_2 (23-nm particles) nanofluids on a bare heating surface to those for pure water on an initially nanoparticle-coated surface. As shown in Fig. 12(a), no appreciable differences in surface characteristics were detected with the nanofluid compared to pure water with the same nanoparticle concentration on the surface. Fig. 12(b) shows that, for all nanoparticle concentrations, CHF for pure water from the nanoparticle-coated surface was at least as good as that for nanofluids from the bare surface. This showed that the primary reason for CHF enhancement in pool boiling of nanofluids was modification to surface topography and microstructure due to nanoparticle coating. Furthermore, CHF enhancement by nanoparticle coating could deteriorate because of interaction of nanoparticles suspended in the nanofluid with

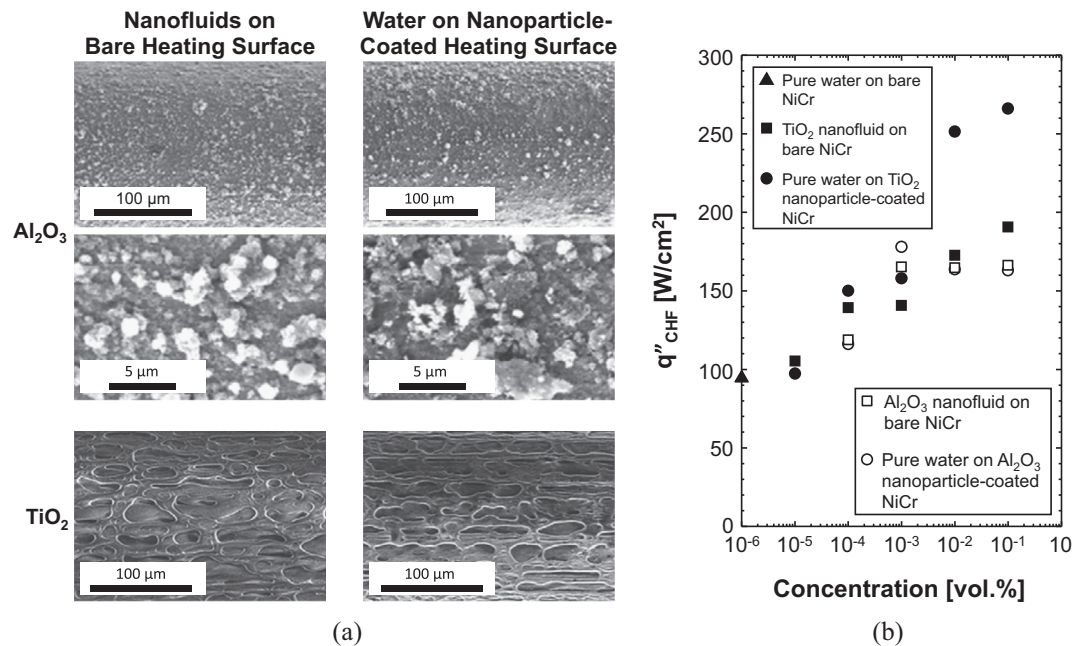


Fig. 12. (a) SEM images of heating surface following pool boiling with water-based 0.01 vol% nanofluid on bare surface and with pure water on nanoparticle-coated surface. (b) Comparison of CHF enhancement for nanofluids on bare surface and for pure water on nanoparticle-coated surface. Adapted from Kim et al. [114].

the coating, as these nanoparticles might clog micro-flow passages within the coating [114]. A follow-up study by Kim and Kim [265] related CHF enhancement to surface wettability, roughness, and maximum capillary wicking height of the nanoparticle-coated surface. Because of concerns that electrical heating might promote migration of nanoparticles from the nanofluid to the surface by electrophoretic effects [266,267], Kim et al. [268] employed conduction heating instead of electrical heating when comparing nanofluid boiling on a bare surface to pure water boiling on a nanoparticle-coated surface. Their results confirmed their prior finding, that CHF enhancement in nanofluids was mainly the result of nanoparticle deposition on the surface. Sharma et al. [269] confirmed the same finding with transient boiling experiments. Experiments by Kwark et al. [165] revealed that nanoparticle coating during pool boiling of low-concentration nanofluids was formed by microlayer evaporation, and the ensuing changes in surface wettability increased CHF. Bang et al. [270] suggested that CHF enhancement during nanofluid boiling was the result of improved wettability combating formation of localized hot spots.

Mourgues et al. [271] reported that pool boiling of water-based ZnO nanofluids on a bare stainless steel surface and pure water on a ZnO nanoparticle-coated surface produced the same CHF enhancement, which confirmed the findings of Kim et al. [114,263,264] concerning the enhancement mechanism. But they also reported that nanofluid experiments culminated in formation of a 70- μm nanoparticle layer after five boiling tests, which produced two contradictory effects: (a) additional thermal resistance that increased wall temperature, and (b) enhanced CHF resulting from modified surface topography. This points to a trade-off between two trends that are both important to cooling applications. On the downside, Mourgues et al. also showed that evolution of the nanoparticle coating was highly transitory, as the coating thickness increased with each test, which is an important drawback since pool boiling applications demand repeatability in cooling performance. Song et al. [272] also reported virtually identical CHF enhancement with pure water on a SiC nanoparticle-coated surface and water-based SiC nanofluid on a bare surface. They also reported surface dimension effects and nonlinear dependence of

CHF on nanoparticle concentration. The CHF enhancement was appreciable for 0.0001 and 0.01 vol% concentrations, but weaker or nonexistent for 0.001 vol%. Ahn et al. [273] reported similar results for pool boiling of reduced GO colloid boiling on a plain surface and water boiling on a surface coated with graphene layers.

White et al. [274] attempted to isolate effects of deposition layer from those of suspended nanoparticles. This was accomplished by performing a series of pool boiling experiments on a surface, alternating between water and water-based 2.3 vol% ZnO nanofluid containing no dispersant. They showed that nucleate boiling heat transfer coefficient for water increased with increasing number of tests, which they attributed to gradual increases in surface roughness of the deposition layer. Results for the nanofluid were less monotonic, as the heat transfer coefficient increased at first compared to water before the deposited layer completely formed, and this enhancement was attributed to thermal properties of the nanofluid. However, once the layer fully covered the surface, the heat transfer coefficient decreased steadily because of suppression of bubble nucleation at the surface and bubble motion by the suspended nanoparticles. Ahmed and Hamed [275] performed similar experiments using water-based 0.01–0.5 vol% Al_2O_3 nanofluid followed by experiments with pure water on the same nanoparticle-deposited surface, the purposes of which were to separate the effects of nanoparticle deposition from those of the nanofluid's properties. Low nanoparticle concentrations were observed to enhance nucleate boiling compared to the base liquid, and slow rate of deposition at low concentrations meant that the enhancement was mostly the outcome of increased thermal conductivity of the nanofluid, especially that deposition in these experiments both reduced the number of active nucleation sites and constituted a thermally insulating layer on the surface. On the other hand, the water boiling experiments showed significant deterioration in heat transfer coefficient, which were brought about by insulating characteristics and deactivation of nucleation sites by the deposition layer. It should be emphasized that activation or deactivation of nucleate sites on the boiling surface are complex phenomena closely related to both initial surface roughness and nanoparticle size. These issues will be discussed in a later section.

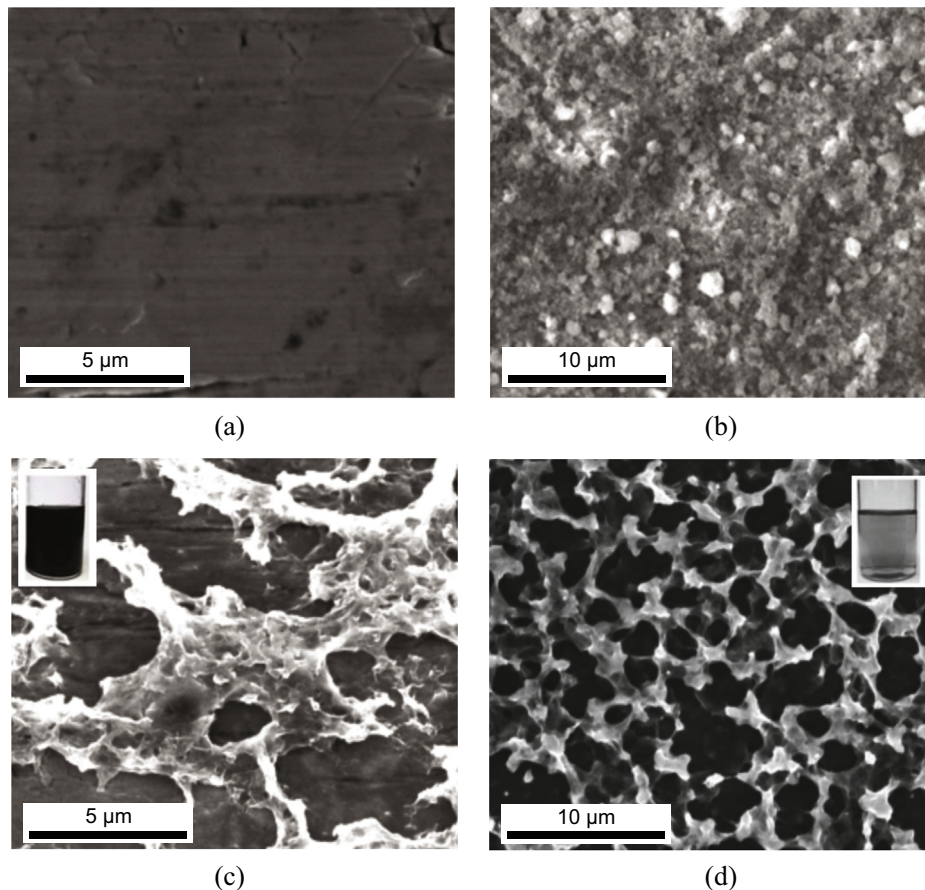


Fig. 13. SEM images of heating surface after pool boiling in (a) water, (b) Al_2O_3 nanofluid, (c) graphene nanofluid, and (d) graphene oxide nanofluid. Adapted from Park et al. [282].

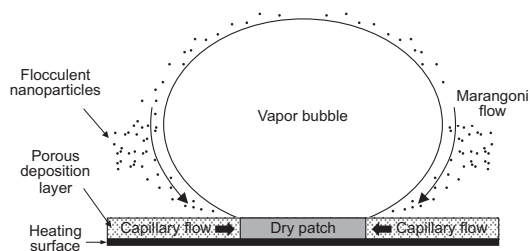


Fig. 14. Surfactant effects on nanofluid nucleate pool boiling. Adapted from Zhou et al. [284].

Hegde et al. [276] reported that CHF enhancement with water-based Al_2O_3 nanofluid was the result of formation of a porous deposition layer with abundant micro-cavities. Hegde et al. [160] also found that the changes to surface roughness after nanofluid boiling were both nanoparticle concentration and boiling time dependent. Milanova et al. [110] measured a 50% increase in CHF when no nanoparticles were deposited on the heating surface, regardless of type or size of oxide particles. Another factor that was reported as having a significant influence on nucleate boiling heat transfer was solution pH during preparation of the nanofluid [112].

Sefiane [277] reported that presence of nanoparticles in the liquid promoted pinning of meniscus contact line on the surface, which resulted from structural disjoining pressure stemming from ordered layering of nanoparticles [278]. Contact line pinning was suggested to enhance CHF by hindering the spread of dry spots, which is consistent with behavior reported by Vafaei and Wen

[279]. Wen [280] used the same hypothesis to construct a predictive model for pool boiling heat transfer, which will be discussed in a later section. Kim et al. [268] proposed that the nanoparticle layer improved stability of the evaporating microlayer or meniscus underneath a growing bubble, thus inhibiting irreversible growth of hot/dry spots even at high wall superheat, and therefore enhanced CHF.

Kim and Kim [281] observed that CHF enhancement with nanofluids was accompanied by a decrease in contact angle, but CHF continued to increase after contact angle reached a smaller constant value, which they attributed to capillary wicking. Park et al. [282] reported that water-based graphene oxide nanofluids and graphene nanofluids at the same concentration of 0.001 vol% enhanced CHF by 179% and 84%, respectively. Unlike the enhancement with metallic oxide nanoparticles, this significant CHF enhancement cannot be explained by improved surface wettability and capillarity alone, especially that surface contact angle actually increased after boiling with these nanofluids. They proposed that the CHF enhancement was the outcome of ordered self-assembly of graphene oxide and graphene particles in the porous surface layer [283], Fig. 13(a)–(d), which altered the critical Taylor wavelength in Zuber's hydrodynamic-instability-based CHF model [119–121].

Zhou et al. [284,285] observed swirling and flocculent nanoparticle clustering near the three-phase contact line during pool boiling of low-concentration nanofluids, but these phenomena abated with increasing heat flux. Addition of surfactant n-butanol enhanced CHF, especially at high nanoparticle concentrations. Fig. 14 depicts the influence of surfactant on nucleate boiling heat

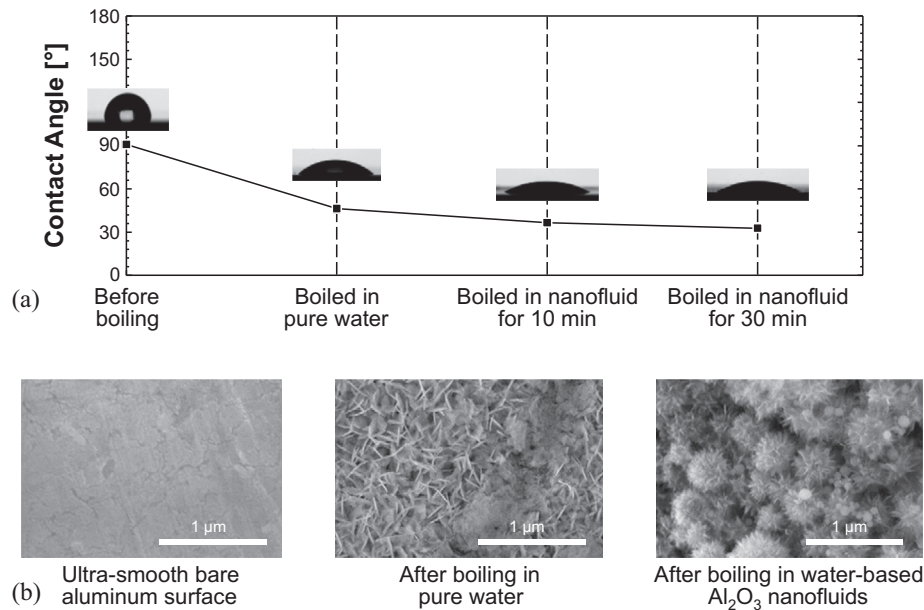


Fig. 15. (a) Contact angle of water before and after nucleate boiling in pure water and in 0.001 wt% water-based Al_2O_3 nanofluid. (b) Surface topography in pure water and in 1 wt% Al_2O_3 nanofluid. Adapted from Zhang and Jacobi [288].

transfer and CHF according to Zhou et al. It shows Marangoni flow induced by the surfactant pushing nanoparticles towards the heating surface to form the deposition layer, and capillary flow combating dryout by promoting passage of nanoparticles into the confined wedge of the vapor bubble.

4.2. Improved surface wettability

Kim et al. [100,286], Lee et al. [176], Zhang et al. [246], Golubovic et al. [171], and Shahmoradi et al. [287] all attributed significant CHF enhancement with nanofluids to improved wettability of the nanoparticle porous layer atop the heating surface. Coursey and Kim [173] proved that addition of nanoparticles to a poorly wetting system such as water-polished copper could result in significant enhancement, whereas a good wetting system such as ethanol-glass would show no improvement or even suffer appreciable degradation. Addition of nanoparticles in water was reported to improve wetting only after fouling of the surface by nanoparticles had occurred.

In comparison to pure water, Zhang and Jacobi [288,289] showed significant improvement in wettability with nucleate boiling for water-based Al_2O_3 nanofluid on an aluminum surface, Fig. 15(a), but noted a decrease in contact angle even in pure water due to growth of pseudoboehmite on the aluminum surface [290]. They also investigated the effects of boiling time, heat flux, nanofluid concentration, and substrate roughness. Boiling time affected wettability positively, but this effect became much weaker after 10 min of boiling. Wettability was also independent of heat flux for the 1.0 wt% nanoparticle concentration, while the effect of heat flux for a lower concentration of 0.01 wt% was rather random. Overall, wettability improved with increasing nanoparticle concentration and substrate roughness, the latter being itself increased with increasing concentration. The enhanced wettability was explained by growth of 'grass-like' nanostructured hydroxides of pseudoboehmite and nanoparticle deposition; the latter culminated in formation of 'fluffy' spheres, as shown in Fig. 15(b). However, Zhang and Jacobi did not address the effects of nanoparticle material, size, and shape, or substrate material on wettability.

4.3. Surface roughness versus particle size

Shoghl et al. [168] reported heat transfer deterioration with addition of ZnO and Al_2O_3 nanoparticles in water resulting from a decrease in surface roughness, compared to heat transfer enhancement with CNTs caused by a remarkable increase in surface roughness. They concluded that any enhancement or deterioration of boiling performance depended on nanoparticles type and on nanoparticle size compared to initial surface roughness. Bang and Chang [115], Das et al. [108,139], Harish et al. [152], Narayan et al. [153], Shahmoradi et al. [287], and Kim [291] all emphasized that the nucleate boiling enhancement achieved by increasing surface roughness was possible only for specific ranges of nanoparticle size.

Narayan et al. [153] proposed employing a 'surface-interaction' parameter, defined as ratio of average surface roughness to average nanoparticle size, to determine the potential for a nanofluid to enhance nucleate boiling performance. With this parameter having a value much greater than unity (i.e., with nanoparticles much smaller than surface roughness features), nucleate boiling heat transfer was enhanced considerably as the small particles deposited into initial nucleation sites and divided single sites into multiple ones. Similar behavior was reported by Dadjoo et al. [146] for a surface-interaction parameter greater than unity. On the other hand, with this parameter having a value near unity, nucleate boiling heat transfer was compromised significantly as the majority of nanoparticles deposited upon sites with comparable size and inhibited nucleation [153]. However, with a value much smaller than unity, heat transfer deterioration was less severe than with a value close to unity, as larger sized nanoparticles reduced the number of sites being deactivated. The surface-interaction parameter is also an effective tool for explaining the deterioration in nucleate boiling heat transfer coefficient with increasing nanoparticle concentration. For example, Shahmoradi et al. [287] observed a deterioration in nucleate boiling heat transfer coefficient for water-based Al_2O_3 nanofluid with surface-interaction parameter values below unity, and the deterioration worsened with increasing nanoparticle concentration below 0.1 vol%. They attributed the worsening deterioration to added thermal resistance provided by the nanoparticle deposition layer.

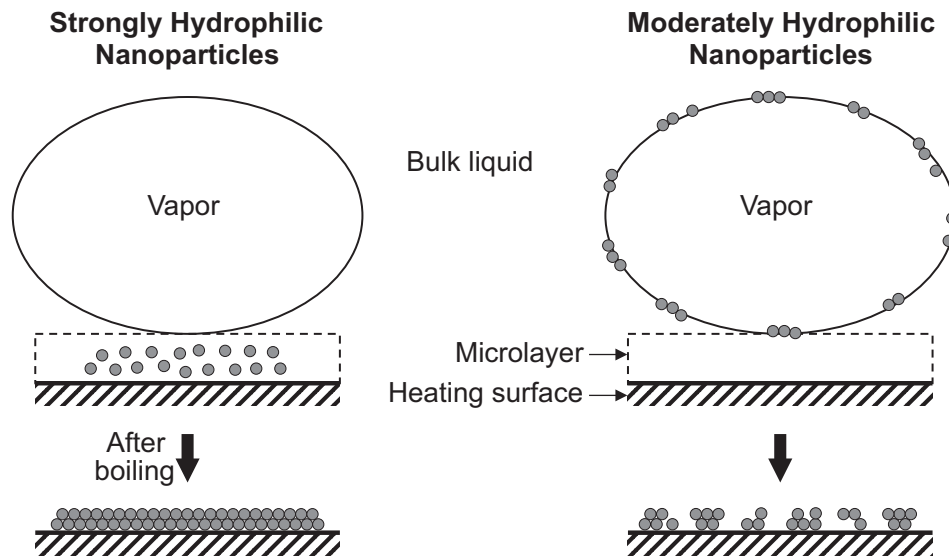


Fig. 16. Schematic depicting how differences in nanoparticle wettability influence adsorption along vapor-liquid interface and surface morphology. Adapted from Quan et al. [296].

Wen et al. [292] also demonstrated experimentally that any enhancement in nucleate boiling heat transfer strongly depended on relative sizes of nanoparticles suspended in the liquid and initial surface features. However, they also argued that, because surface modification by nanoparticles was a cumulative process, the heat transfer performance would continue to change with repeated boiling experiments with the same surface. Vafaei [293] reported an increase in cavity size when nanoparticles deposited in agglomerated form were greater than the surface roughness, which aided in activation of nucleation sites and enhanced the nucleate boiling heat transfer coefficient in the low heat flux region. But when deposited nanoparticles were smaller than the surface roughness, surface activation decreased, rendering the boiling performance less effective.

4.4. Effects of suspended nanoparticles on bubble dynamics and surface morphology

Aside from the nanoparticle deposition effects reported by many investigators as responsible for enhancement or deterioration of nucleate boiling performance, Wen [154] emphasized the importance of another factor, nanoparticle suspension in the liquid. He reported that the suspension had a profound influence on bubble formation by modifying important parameters of bubble dynamics, including departure volume, departure frequency, and contact angle. Vafaei et al. [293,294] suggested that nanoparticles affected liquid-vapor and liquid-solid surface tensions, which changed bubble contact angle, radius of triple line, bubble volume, and overall dynamics of the bubble growth. Using particle image velocimetry (PIV), Dominguez-Ontiveros et al. [295] also proved that nanoparticles had a significant influence on bubble dynamics.

Recent experiments by Quan et al. [296] showed how nanoparticle wettability could have a profound influence on nucleate boiling performance. As shown in Fig. 16, moderately hydrophilic nanoparticles were adsorbed at the vapor-liquid interface, inhibiting liquid drainage between adjacent bubbles, and therefore resisted bubble coalescence, which in turn decreased bubble departure diameter and enhanced both the nucleate boiling heat transfer coefficient and CHF. On the other hand, strongly hydrophilic nanoparticles were not adsorbed at the interface, which left the bubble coalescence unchanged. But, as shown in Fig. 16, nanoparticle wettability also influenced morphology of the surface deposi-

tion layer: a strongly hydrophilic nanoparticle layer tended to be relatively smooth, with evenly distributed particles, and that of a moderately hydrophilic layer rougher and more irregular.

5. Predictive models

Using a numerical two-fluid model, in which liquid was treated as the continuous phase and vapor bubbles in liquid as the dispersed phase, Li et al. [297] investigated nucleate pool boiling of dilute water-based SiO_2 nanofluid based on the supposition that suspension of nanoparticles does not alter hydrodynamics of the base fluid. They reported that changes to liquid properties due to presence of nanoparticles had negligible influence on boiling heat transfer in dilute nanofluids (less than 0.1 vol%), but improved surface wettability did play an important role. Li et al. [298] suggested that the classic heat partitioning model, which describes heat flux from the surface as consisting of three separate components (evaporation, quenching, and convection) was equally applicable to nucleate boiling of nanofluids, provided surface modification (active nucleation density) and nucleate boiling parameters (bubble departure diameter and frequency) were properly formulated. Later, Li et al. [299] constructed a new model to predict subcooled nucleate pool boiling heat transfer of dilute nanofluids, which incorporated a heat flux partitioning (HFP) model to account for Brownian motion of nanoparticles as well as closure correlations for active site density. The model results showed that surface wettability was only partially responsible for the heat transfer enhancement, and other factors, such as modification to surface morphology, needed to be accounted for more rigorously. Follow-up study by Li et al. [300] yielded an updated model, which was based on the premise that nanoparticle deposition is induced by evaporation of the liquid microlayer, within which average nanoparticle concentration is much higher than in the bulk liquid. Their analysis employed a modified HFP model, which included a separate heat flux component to account for effects of Brownian motion of nanoparticles in the liquid microlayer. The model results showed that, for dilute nanofluids, Brownian motion effects could be improved by increasing bulk concentration or decreasing nanoparticle size; but nanoparticle material had only a minor influence. Aminfar et al. [301] and Niknam et al. [302] also simulated nucleate pool boiling of nanofluids using the HFP model;

the latter also incorporated a relation for nucleation site density. Recently, Ham and Cho [303] proposed a new theoretical model for nucleate boiling of nanofluids based on the HFP model, and incorporated a developed contact angle model in their analysis.

Sayahi et al. [304] employed a Radial Basis Function (RBF) model to predict the influence of SDS surfactant as well as Al₂O₃, SiO₂, and ZnO nanoparticles on nucleate pool boiling heat transfer of water on a horizontal rod heater. Sadhu and Ghoshdastidar [305] used a coupled map lattice method to simulate nucleate boiling of water-based ZrO₂ and Ag nanofluids.

Wen [280] proposed a mechanism for CHF enhancement with nanofluids focused on the long-range structural disjoining pressure arising from confinement of nanoparticles in the liquid-vapor meniscus. He incorporated this mechanism into a four-zone dry patch model to calculate equilibrium meniscus shape in the presence of nanoparticles. The model results showed how enhanced wettability by the structural disjoining pressure served to inhibit dry patch development. Wen [306] also addressed the effects of nanoparticle size, concentration, and heat flux on the structural disjoining pressure.

Bi et al. [307] constructed a composite model for average heat flux for both pure fluids and nanofluids, incorporating the effects of microlayer evaporation, transient conduction associated with bubble departure, and microconvection resulting from bubble growth and motion. Surface characteristics resulting from nanoparticle deposition were also accounted for by addressing changes in the contact angle. Of the different effects considered, transient conduction was shown to be most dominant at high superheats. The model yielded a relationship between average heat flux and surface contact angle, which also aided in determination of CHF for nanofluids. Ganapathy and Sajith [308] proposed a semi-analytical model to investigate surface-particle interactions, incorporating several effects of nanoparticle deposition, including modifications to surface roughness, wettability, and increased resistance to heat transfer. The model results showed that nucleate boiling performance of nanofluids was influenced more by changes to surface roughness than to changes in surface wettability.

Park and Bang [309] investigated CHF enhancement for water-based 0.01 vol% ZnO, SiO₂, SiC, Al₂O₃, CuO, and graphene oxide nanofluids. Highest CHF enhancement (160%) was achieved with CuO nanofluid and lowest (90%) with ZnO nanofluid. The CHF enhancement with nanofluids was attributed to shorter Rayleigh-Taylor wavelengths. To predict CHF, Park and Bang incorporated a modified wavelength in Zuber's original hydrodynamic instability model [119–121],

$$q''_{CHF} = q''_{CHF,Zuber} \left(\frac{\lambda_{bare}}{\lambda_m} \right)^3, \tag{7a}$$

where

$$q''_{CHF,Zuber} = 0.131 \rho_g h_{fg} \left[\sigma g (\rho_f - \rho_g) / \rho_g^2 \right]^{1/4}, \tag{7b}$$

λ_{bare} is the theoretical wavelength in Zuber's model, and λ_m the modified wavelength for nanofluids. Note that the exponent of 3 on the right hand side of Eq. (7a) was obtained entirely by fitting experimental data. In a separate study, additional wavelength variations were attributed to nanofluid preparation [310].

In a recent study, the present authors [12,311] reviewed pool boiling CHF models for pure saturated liquids on smooth surfaces, and assessed existing models and correlations using a new consolidated CHF database consisting of 800 data points amassed from 37 sources, which included 14 working fluids, pressures from 0.0016 to 5.2 MPa, orientation angles from 0 to 180°, and contact angles from 0 to 113°. They showed that best predictions with models

incorporating surface wettability effects are achieved with Kandlikar's model [312] and a correlation by Liao et al. [313],

$$q''_{CHF} = \frac{1 + \cos\alpha}{16} \left[\frac{2}{\pi} + \frac{\pi}{4} (1 + \cos\alpha) \cos\theta \right]^{1/2} \times \rho_g h_{fg} \left[\sigma g (\rho_f - \rho_g) / \rho_g^2 \right]^{1/4}, \tag{8a}$$

and

$$q''_{CHF} = 0.131 \left[-0.73 + \frac{1.73}{1 + 10^{-0.021 \times (185.4 - \theta)}} \right] \left[1 + \frac{55 - \alpha}{100} (0.56 - 0.0013\theta) \right] \times \rho_g h_{fg} \left[\sigma g (\rho_f - \rho_g) / \rho_g^2 \right]^{1/4}, \tag{8b}$$

respectively. Given that wettability improvement by nanoparticle deposition is largely responsible for CHF enhancement with nanofluids, Eqs. (8a) and (8b) are recommended for CHF estimation, provided the contact angle is known. In fact, Kandlikar's model was used by Truong et al. [314], Jeong et al. [85], Kim et al. [268], Yang and Liu [130], Park et al. [191], and Gerardi et al. [147] to predict CHF for nanofluids.

Kim et al. [100] recommended an alternative expression to predict CHF for nanofluids based on the hot/dry spot theory of Theofanous and Dinh [315],

$$q''_{CHF} = k^{-1/2} \rho_g h_{fg} \left[\sigma g (\rho_f - \rho_g) / \rho_g^2 \right]^{1/4}, \tag{9}$$

where

$$k = \left(1 - \frac{\sin\alpha}{2} - \frac{\pi/2 - \alpha}{2\cos\alpha} \right)^{-1/2}. \tag{10}$$

However, the present authors [311] have shown that this method is inaccurate when compared to CHF data for pure liquids.

In all, while the volume of articles involving experimental investigation of the nucleate pool boiling characteristics of nanofluids is quite enormous, literature addressing theoretical modeling of nucleate boiling heat transfer and CHF is quite sparse. This is quite understandable, given that mechanisms of nucleate pool boiling for even pure liquids are quite complicated and still subject to debate. Addition of nanoparticles adds further complexity to the task of predicting nucleate boiling for nanofluids. An important limitation of most published nanofluid articles is that both trends and correlations are system specific, failing in many cases to fully address variations in base fluid, nanoparticle material, size and concentration, surface condition, and heat flux.

6. Practical concerns

In spite of the many contradictory findings regarding the influence of nanofluids on the nucleate pool boiling heat transfer coefficient, there is majority consensus that nanofluids do enhance CHF compared to their base fluids. Thus, nanofluids are potentially useful where CHF is the primary design concern in a specific cooling application. For example, nanofluids can be used to improve the capability of in-vessel retention (IVR) as part of severe accident management strategy for light-water reactors, where nanofluids are stored in a separate system at normal operating conditions, but discharged into the reactor cavity through injection lines within a few seconds from actuation. As suggested by Buongiorno et al. [316,317], nanofluids can achieve 40% enhancement in decay power removal, which would provide appreciable improvement in IVR safety margin or higher core power IVR for a prescribed safety margin.

However, nanofluids pose serious concerns for most applications involving their long-term use as coolants. Following is a

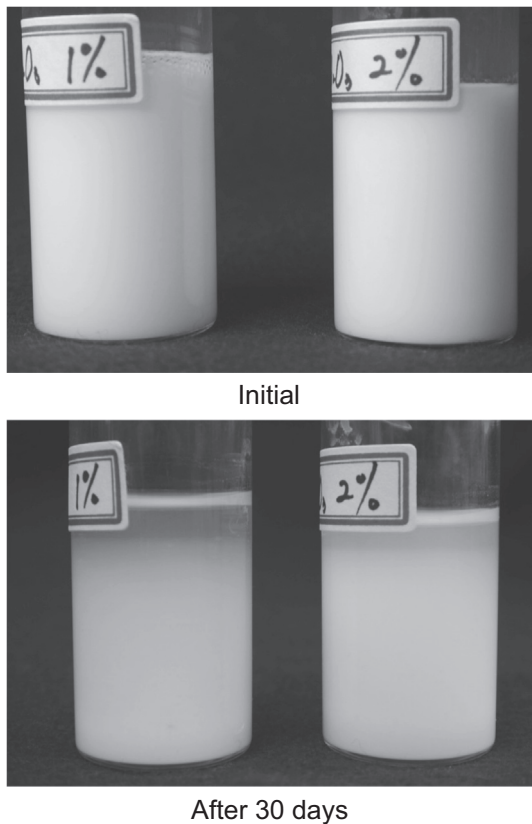


Fig. 17. Settling of water-based Al_2O_3 nanofluid over 30-day period. Adapted from Lee and Mudawar [319].

summary of concerns, which are focused on nucleate pool boiling, but may be relevant to other boiling regimes and configurations.

- (i) *Clustering, sedimentation, and precipitation of nanoparticles:* Despite assertions by several investigators that nanoparticles resist sedimentation far better than micro-particles, an overwhelming majority of published nanofluid articles provide strong evidence of nanoparticle deposition on the heating surface. This is clearly manifest in Fig. 17, which shows Al_2O_3 nanofluid well mixed shortly after preparation, and highly settled (evidenced by a strong concentration gradient) 30 days later. In fact, the majority of nanofluid pool boiling experiments were performed under conditions of fine dispersion of nanoparticles with nanofluid stability main-

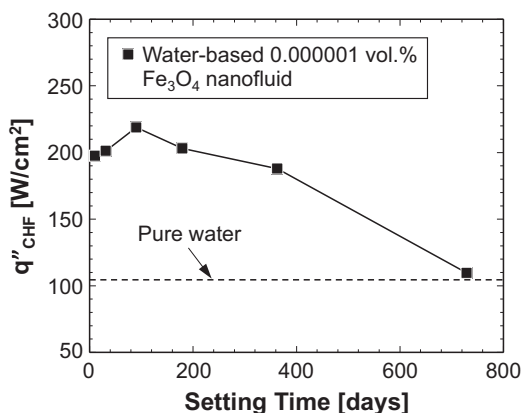


Fig. 18. Variation of CHF for water-based 0.000001 vol% Fe_3O_4 nanofluid with preservation time. Adapted from Lee et al. [318].

tained over a relatively short duration, and long-term performance was often excluded from study. Lee et al. [318] emphasized the long-term variations in pool boiling performance by investigating CHF enhancement and stability of water-based Fe_3O_4 nanofluids over multiple years rather than a few hours or days. Fig. 18 shows CHF enhancement with the nanofluid decreasing mildly during the first year, but more rapidly the second year. This is proof that long-term stability of nanoparticle dispersion is a serious concern, especially for applications demanding unaltered long-term cooling performance.

- (ii) *Clogging of flow passages:* While pool boiling in most applications does not require introduction of nanofluid with the aid of a pump or through valves or flow passages, some (e.g., nuclear reactor cooling) do require such provisions. Here, a major problem is potential clogging of intricate flow features as nanoparticles grow into larger clusters that may cause catastrophic failure of the entire cooling system. And, even without such provisions, similar clogging may occur within finned surfaces intended to increase surface area in pool boiling.
- (iii) *Erosion to heating surface:* Another major problem with nanofluids is erosion of metal heating surfaces by the nanoparticles. While the erosion might enhance boiling performance by increasing surface roughness, removing the oxide layer would greatly alter heat transfer performance and accentuate further settling. Additionally, some stabilizers that are used to prevent aggregation of nanoparticles, such as nitric acid, may be detrimental to the surface.
- (iv) *Deposition of nanoparticles:* Excepting CNT nanofluids, most nanofluids have been reported to involve deposition of a nanoparticle layer on the heating surface. This layer is undesirable for many applications, especially those involving cooling of sensitive electronic and power devices, where the deposited layer may eventually lead to device failure. Additionally, the deposition is a transient process, meaning that cooling performance is also time-dependent. And, in certain situations, nucleate boiling may lead to partial or complete delamination of the deposited layer, which may also be detrimental to sensitive devices.
- (v) *Transient cooling performance:* Nanoparticle deposition on the heating surface during nucleate pool boiling is a cumulative, time-dependent process, which is coupled with a decrease in nanoparticle concentration in the bulk fluid. Both of these phenomena can have profound influences on nucleate boiling performance. In addition, temporal variations of cooling performance over extended periods might compromise cooling reliability in most practical applications. It should be noted, however, that certain remedies have been proposed to overcome these drawbacks. For example, boiling of pure liquid on an initially nanoparticle-coated surface can provide the desired heat transfer performance while overcoming any temporal variations.
- (vi) *High cost and difficulties in production of nanofluids:* While only small concentrations of nanofluids are required in most cooling situations, certain applications (e.g., nuclear reactor cooling) may entail the use of large amounts of nanofluid, which would increase cooling cost appreciably. For most applications, however, there is an added cost of initial preparation of the nanofluid in pursuit of fine dispersion and improved stability of nanoparticles in the base fluid.
- (vii) *Lack of quality assurance in experiments using nanofluids:* Most investigators acquire nanoparticles for use in nanofluid experiments from different vendors, and different batches may be associated with appreciable variations in nanoparticle size, size distribution, thermal properties, and purity.

Such variations can have profound influences on consistency of nucleate boiling data from different studies for seemingly identical nanofluids and concentrations.

Nanofluids have been referred to ‘cooling media of the future’ [320], which may explain the enormous volume of nanofluid publications in recent years. Yet, one must remain mindful of both the merits and drawbacks of nanofluids, as well as the stringent performance requirements in practical cooling applications.

7. Concluding Remarks

This study reviewed published literature concerning pool boiling enhancement by modifying fluid properties. Included are effects of surfactant and polymer additives and nanofluids on nucleate boiling heat transfer coefficient and CHF, as well as heat transfer enhancement mechanisms and predictive models. Also reviewed are articles addressing quenching in nanofluids, and pool boiling heat transfer with combination of nanofluids and surface modification. The review is concluded by addressing important practical concerns associated with use of additives and nanofluids. Key observations from the review can be summarized as follows.

- (1) Adding surfactant into the boiling liquid shifts the nucleate boiling region of the boiling curve towards lower surface superheats, thereby bringing about earlier boiling incipience and increasing the nucleate boiling heat transfer coefficient. Maximum enhancement in boiling performance is achieved at a particular (optimum) surfactant concentration, which increases with decreasing molecular weight of surfactant, and exceeding optimum concentration degrades the enhancement because of an increase in fluid viscosity. Mechanisms proposed for the boiling enhancement include Marangoni convection, dynamic surface tension, surfactant adsorption and desorption at the vapor-liquid interface, increased number of active nucleation sites, foaming, changes in bubble dynamics, and improved surface wettability.
- (2) Effects of adding polymer into the boiling fluid on nucleate boiling heat transfer are polymer dependent. Polymers may improve nucleate boiling heat transfer coefficient below the optimum concentration, or compromise performance, depending on changes in fluid viscosity. While enhancement is caused by reduced bubble coalescence and enhanced nucleation, deterioration is attributed to reduction in vapor bubble growth rate, reduction in contact angle, and suppression of microconvection. Key practical concerns using surfactant and polymer additives include degradation in long-term use, severe incipience excursion, and environmental issues.
- (3) Nanofluids have unmistakable enhancing influence on CHF, and the enhancement is rooted in improved surface wettability by nanoparticle deposition. However, there are many contradictions concerning the influence of nanofluids on nucleate boiling heat transfer coefficient. These contradictions are the result of many complex influences, including those of liquid type, initial surface roughness, and heat flux, as well as nanoparticle material, size, concentration, preparation method, and functionalization method. These parameters have considerable influences on both thermophysical properties of the nanofluid and changes to surface characteristics, the latter including surface finish, active nucleation site density, wettability, and changes in triple line. These complexities are undoubtedly the main reason behind limited theoretical efforts aimed at modeling nanofluid boiling.

- (4) Bath quenching of metal parts in nanofluid is associated with cooling rates identical to, or even poorer than those of the base liquid. However, cooling rate is accelerated with repeated quenching due to growth of nanoparticle deposition layer on the surface. This layer tends to destabilize the vapor film at high surface temperatures and leads to premature disruption of the film boiling regime.
- (5) Mechanisms for nucleate boiling enhancement with nanofluids are closely associated with nanoparticle deposition on the surface, and include capillary wicking in the porous layer and improvements to both surface wettability and bubble dynamics. However, there are competing influences depending on size of nanoparticles in relation to initial surface roughness.
- (6) Despite the potential of nanofluids to enhance boiling performance, there are several important practical concerns that must be considered carefully before deploying nanofluids in practical cooling applications. They include clustering, sedimentation, and precipitation of nanoparticles, clogging of intricate features, erosion to heating surface, temporal changes in cooling performance, high cost, and lack of quality assurance.
- (7) While nanofluids improve thermal conductivity of the boiling fluid, most of their effectiveness is derived from surface modification. However, using other methods to modify the surface (e.g., micro/nano studs, nanotube/nanowire arrays, microporous structure, nanoparticle pre-deposition) may provide comparable or even superior heat transfer enhancement while avoiding the practical problems associated with nanofluid boiling.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.046>.

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