



Pool boiling enhancement by using nanostructured surfaces: a review

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ABSTRACT

Nanostructured surfaces are surfaces bearing nano-sized features that have characteristic lengths ranging on a scale of a few to a few hundreds of nanometres. Nanostructuring of surfaces is considered as a promising track in many micro-thermo-fluidic applications, as it is expected to allow noticeable heat transfer enhancement or hydraulic resistance reduction due to momentum transfer to the solid walls. This paper reviews and summarizes the recent experimental and theoretical works on the pool boiling with nanostructure surfaces

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Introduction

Heat transfer systems that operate in the nucleate boiling regime are limited by a critical heat flux (CHF), at which a vapour film envelopes the heated surface and severely deteriorates heat transfer. It is crucial that systems such as nuclear reactors operate below the critical heat flux to prevent a temperature excursion and subsequent failure of the heat transfer surface. Therefore, raising the upper limit of nucleate boiling could allow for higher safety margins, higher rates of heat transfer in existing systems, or a reduction in the size of new systems while maintaining the same heat transfer capability. [10] The nucleate boiling heat transfer coefficient dictates the operational temperature of a boiling surface at a given heat flux. Devices such as power electronics are highly sensitive to temperature rise. It is therefore desirable to increase the nucleate boiling heat transfer coefficient in two-phase cooling systems to optimize the performance and operating lifetime of such devices. An over reaching goal of thermal-fluid design has been to find a cost-effective means of enhancing CHF and boiling heat transfer. [11] The development of special surface geometries/structures is a critical issue for the performance-enhancement of the pool boiling heat transfer. Numerous studies and experiments on nucleate pool boiling, an effective way to remove high heat flux from a heated surface, have focused on enhancing the boiling heat transfer coefficient by fabricating micro-scaled surface geometries / structures. One approach that has success is to create a number of small micro-porous cavities on the boiling surfaces to increase the vapour/gas entrapment and the number of active nucleation sites. These cavities reduce the incipient and nucleate boiling wall superheats and increase the pool boiling heat transfer coefficient. While many of the previous studies on the surface structure focused on improving the heat transfer coefficient of pool boiling in micro-sized dimensions. However with the evolution of nanotechnology and nano-materials, current study focused on well-defined nano-materials suitable for use in pool boiling. Nano-textured surface effects on two-phase heat transfer and boiling are even more in their infancy. Recently, there has been an increased interest in evaluating the pool-

boiling performance of nanowire nanotube surfaces. The expected advantages of nano scale modifications include finer control over porosity and surface roughness, thinner coating layers to reduce thermal resistance and thermal stress and ultimately higher durability.[3]

II Nanostructure surfaces

The boiling process generally depends on and is enhanced by three factors: (1) Existence of random micro- or nano-size crevices and surface irregularities for nucleation initiation, (2) a somewhat porous surface structure that allows fluid inflow to keep nucleation sites active, and (3) surface protrusions that create more active boiling area. The nucleate pool-boiling process is described using several bubble dynamics characteristics, such as the vapor bubble diameter at the moment of departure, D_b , the vapor bubble departure frequency, f , mean velocity of vapor bubble growth, $D_b f$, and the surface characteristics. However, in practice, these characteristics are very difficult to measure owing to the stochastic nature of the boiling process. It is known from conventional theory that the average heat flux dissipated due to nucleate boiling can be related as “[1]”

$$q'' = K(\pi(k_l \sigma C_p) f)^{0.5} D_b^2 N_a \Delta T_w \quad (1)$$

Where k_l , C_p , and σ are the liquid thermal conductivity, specific heat and surface tension, respectively. K is a constant that represents the bubble diameter of influence and is independent of contact angle and physical properties of the fluid. Here, D_b and f are defined above and N_a is nucleation site density. For “bare” surfaces, the nucleation site density is estimated by the relation

$$\sqrt{N_a} = 25 \times 10^{-8} \left(\frac{h_{fg} \rho_g \Delta T}{T_s \sigma} \right) \quad (2)$$

It is believed that for nanostructured surfaces the product of $f^{0.5} D_b^2 N_a$ will increase significantly due to increased site density and concomitant increase in bubble frequency and provide boiling enhancement. The critical heat flux limit of any evaporating system depends on the mechanisms of liquid supply to and vapor escape from the phase change interface and therefore can be rationalized to be limited by the liquid and

vapor flow resistances. A theoretical CHF maximum was derived by Gambill and Lienhard [12] based on the vapor resistance dictated by the kinetic limits. For water at atmospheric conditions, the kinetic limit of evaporation is $O(10^4)$ W/cm², which is larger by two orders of magnitude than that typically observed in practice for pool boiling. But, this shows that there is much room for enhancement by co-designing effective liquid supply and evaporative zones. Nanostructured surfaces displayed hydrophilic characteristics and can be explained using the well-known Wenzel theory. For a rough surface there are typically two equilibrium states in which a wetting drop resides: the drop either wets the grooves (Wenzel state) or sits on the peaks of the rough surfaces (Cassie state). The hydrophilicity of surfaces can be explained with the Wenzel equation ($\cos\gamma = r \cos\theta$) where r is the roughness factor (ratio of total surface area to total projected surface area), and γ and θ are contact angles on the nanostructured (roughened) and completely smooth surfaces, respectively. Typically, water contact angle on a flat metal surfaces is less than 90° (and decreases with higher temperature) due to native oxides formed on the surface, so for the roughened surfaces with nano features ($r > 1$ always because of higher surface area) these surfaces become more hydrophilic as can be easily seen by Wenzel equation [13]

Effect on Critical Heat Flux

The exact mechanism and parameters affecting the boiling crisis, or CHF, remain to this day unclear. For many years, the hydrodynamic instability theory, developed by Zuber, has been widely used to predict the departure from nucleate boiling or CHF [14]

$$q_{CHF}'' = K \rho_g h_{fg} \left[\frac{g \sigma (\rho_f - \rho_g)}{\rho_g^2} \right]^{1/4} \quad (3)$$

Where, K is a constant that only depends on the geometry of the system. The hydrodynamic theory has been scrutinized in recent years because it does not account for surface characteristics such as wettability. Recent work at MIT by Kim et al. [15] among others, clearly revealed the effects of surface parameters on CHF. The hydrodynamic instability theory fails to predict the enhancement associated with modified surfaces, such as those created by the boiling deposition of nanoparticles.

Two popular theories, which do include dependence on surface characteristics such as wettability, are the macro layer dry out theory [16,17] and the hot/dry spot theory [18]. For the macro layer dry out theory, the dependence of CHF on surface wettability is tied to the thickness of a liquid macrolayer covering the surface between vapor bubbles. The equivalent thickness of the macrolayer can be calculated by:

$$\delta_e = r_b \left[\cos\theta - \frac{\pi}{12} (3 \cos\theta - \cos^3\theta) \right] \quad (4)$$

The equivalent thickness from Eq. (4) is directly proportional to the dry out time of the liquid macrolayer. CHF occurs if the liquid macrolayer vaporizes completely. As contact angle decreases, the equivalent liquid macrolayer thickness increases, so CHF will also increase proportionally. The macrolayer dryout theory qualitatively captures the wettability effect on CHF for hydrophilic surfaces.

The hot/dry spot theory predicts that CHF will occur at a nucleation site when rewetting is unable to occur at a growing hot spot. Therefore, increasing the surface wettability would allow for easier rewetting of hot spots, thereby delaying CHF. Theofanous and Dinh [18] give the following expression for the critical heat flux based off the hot/dry spot theory:

$$q_{CHF}'' = K^{-1/2} \rho_g h_{fg} \left[\frac{g \sigma (\rho_f - \rho_g)}{\rho_g^2} \right]^{1/4} \quad (5)$$

Eq. (5) is almost identical to the Zuber equation, except that the leading constant depends on surface characteristics such as wettability. Kim et al. "[5]" derived the following analytical expression for k

$$K = \left(1 - \frac{\sin\theta}{2} - \frac{\pi/2 - \theta}{2 \cos\theta} \right)^{-1/2} \quad (6)$$

Using Eqs. (5) and (6), one would also expect an increase in CHF with a reduction in contact angle. However, Eq. (6) is only applicable for θ less than 90°

Another pool boiling CHF model, proposed by Kandlikar, can be applied to both hydrophilic and hydrophobic surfaces [

$$q_{CHF}'' = \rho_g^{1/2} h_{fg} \left(\frac{1 + \cos\beta}{16} \right) \times \left[\frac{2}{\pi} + \frac{\pi}{4} (1 + \cos\beta) \cos\phi \right]^{1/2} [\sigma g (\rho_f - \rho_g)]^{1/4} \quad (7)$$

Where, β is the receding contact angle for the surface-fluid combination.

However, one incongruity arises from the results of study when compared with the CHF predictions of the hot/dry spot theory and Kandlikar's model, varying the coating thickness yields significant differences in CHF enhancement, while the measured contact angles for these coatings were virtually identical. Both the macrolayer dryout theory and the hot/dry spot theory predict a direct dependence based on surface contact angles.

Effect on Heat Transfer Coefficient

Research in the field of boiling heat transfer indicates that entrapped gas in surface cavities leads to the initial nucleation process [1]. Therefore, cavities that are not completely flooded by liquid water can promote bubble nucleation at lower wall superheats. Young and Hummel obtained higher nucleate boiling heat transfer by adding PTFE to localized regions of a boiling surface, resulting in better nucleation. Wang and Dhir predicted that surfaces with higher wettability will display poorer nucleate boiling heat transfer, whereas surfaces with reduced wettability will exhibit better nucleate boiling heat transfer, and provided a correlation to predict the nucleation site density as a function of contact angle at a fixed wall superheat

$$N_a \left(\text{sites/cm}^2 \right) \propto (1 - \cos\theta_A) D_c^{-6.0} \quad (8)$$

Where N_a is the active nucleation site density and D_c is the cavity mouth diameter. Eq. (8) predicts a higher nucleation site density and thus a higher heat transfer rate for higher contact angle. However, one cannot predict the boiling heat transfer coefficient solely from the knowledge of the nucleation site density because parameters such as bubble diameter and bubble departure frequency, which affect nucleate boiling heat transfer, are also altered by application of the thin-film coating.

METHOD OF NANOPARTICULAR DEPOSITION

- Micro reactor techniques (MAND™)
- Layer by layer assembly
- Anodizing process
- Electrical heating
- Hot-dip galvanizing/dealloying (HDGD)
- Electrophoretic deposition

Micro reactor techniques (mand™)

(MAND™) processes provide the potential to greatly reduce the costs, environmental impacts and safety risks associated with the manufacturing of nano-enabled products

Hendricks et al. [1] experimentally reported a novel approach to fabricate unique nanostructured surfaces using ZnO on Al and Cu substrates for boiling heat transfer enhancement. It has demonstrated that micro reactor techniques (MAND™) are sufficiently adaptable to fabricate tailored surfaces. It compared rigorous pool-boiling experiments on bare and nanostructured surfaces. A 10 times improvement in heat transfer coefficient was observed for nanostructured surfaces over a “bare” Al substrate. Further, an approximate 4 times improvement in critical heat flux was also measured for these nanostructured surfaces. He found that these nanostructured surfaces create very high nucleation site densities and bubble frequency at the surface that leads to the high critical boiling heat fluxes. Also demonstrated a critical heat flux dependence on surface contact angle that suggests there is necessary balance between the surface capillary fluid dynamics that brings fluid into the active nucleation sites and the surface bubble dynamics governed by bubble diameter and nucleation site density that ultimately lead to heat dissipation.

Layer by layer assembly

Forrest et al. [2] studied layer-by-layer assembly method and demonstrated thin-film coatings treated with fluorosilane displayed hydrophobicity and were found to enhance the heat transfer coefficient by about 100%. CHF enhancement was observed for all thin-film coatings tested. The enhancement ranged from 44% to 101%, with the highest enhancement observed for the thickest, calcinated coating (40 bilayers of PAH/SiO₂). The measurement results support the importance of the receding contact angle on CHF, and that a low receding contact angle yields a higher CHF. CHF enhancement increases with the super hydrophilic thin-film coating thickness. Because the coatings were calcinated to form a nanoporous structure, this implies that the total pore volume may have an effect on the CHF, in addition to the apparent contact angle.

Anodizing process

Lee et al. [3] investigated nucleate pool boiling heat transfer characteristics in saturated water, a plain aluminium alloy surface (6061, untreated) and a uniquely fabricated aluminium oxide Nanoporous Surface (NPS) sample were prepared. Generally, the NPS exhibited a lower wall superheat at the onset of nucleate boiling and a higher nucleate boiling heat transfer coefficient than the plain surface. It was also noted that the nucleate boiling heat transfer coefficient decreased by 30% on the plain surface and by 37% on the NPS after five repeated boiling tests. It was found that such performance degradation in both of the test samples was due primarily to the formation of aluminium hydroxide on the boiling surfaces.

Stutz et al. [4] has studied the effects of nanostructured surface coatings on boiling heat transfer and CHF for two different fluids: a poorly wetting fluid (water) and a highly wetting fluid (pentane). The nanoparticles coating is obtained by deposition of charged maghemite (C-Fe₂O₃) on a platinum wire by means of vigorous boiling of a maghemite aqueous solution forming a so-called nanofluid, or by means of electrophoresis in the nanofluid. The coating made of nanoparticles reduces the heat transfer coefficient by introducing a thermal resistance that becomes more and more noticeable when the layer thickness increases. The effective thermal resistance of the layer appears to decrease substantially during boiling and seems to be coupled to the bubble activity. This may indicate that vapour generation occurs inside the layer, which reduces its effective thickness. Also, capillarity probably ensures a flow of liquid into the porous layer. Observed increase in CHF is mostly due to the

increase in heat transfer area when the nanoporous layer is formed. Indeed, the first results seem to show that the nanoporous layer is sensitive to dilatation effects and, under some circumstances, to the formation of a pocket of vapour between the heater and the coating.

Saeidel et al. [5] performed nanocoating on aluminium surface specimens by anodizing and their boiling heat transfer characteristics were compared with those of bare surface of aluminium. Also, the critical heat flux and boiling heat transfer coefficients were evaluated experimentally. Chromic acid and sulphuric acid solutions were utilized as the electrolytes. Prior to anodizing, sandblasting and etching were applied as mechanical and chemical treatments of the surfaces. The coating was performed over three different durations. The maximum critical heat flux was observed to occur in samples which had been weakly etched and anodized for 30 min in the sulphuric acid solution. Critical heat flux increased by 8% compared with that of the untreated aluminium alloy surface. Also, boiling heat transfer coefficient increased by 159% in weakly etched samples. In order to investigate surface characteristics, contact angle and atomic force microscope (AFM) images were used. The surface roughness and real area were measured in six samples. The AFM images indicated that surface roughness increased with anodizing time. The change in roughness was more pronounced in surfaces treated in the chromic acid solution compared with those treated in the sulphuric acid solution.

Electrical heating

Ustinov et al. “[6]” has produced TiO₂ nanoparticle-coated nickel wires by electrical heating in various nanofluid concentrations ranging from 0.01 to 1 wt.% with various processing heat fluxes from 0 to 1000 kW/m². The experimental results demonstrated up to 82.7% enhancement on critical heat flux (CHF) in condition of coated nickel wire (processed in 1 wt. % with 1000 kW/m²) boiling in pure water. The contact angle measurement revealed that the hydrophilic porous coating formed by vigorous vaporization of TiO₂ nanofluid in nucleate boiling regime enormously modified the wettability of heating surface consequently improving the CHF. Besides, it is evident that the coverage of nanoparticle deposition tended to become more complete as concentration and processing heat flux increased based on SEM and EDS analysis. The nanoparticles dispersed in base fluid exhibited little effect on CHF enhancement and could even hinder the percentage of CHF augmentation from boosting, which demonstrated that one could enhance CHF by using only small amount of nanoparticles just adequate to form surface coatings instead of preparing working fluid with great bulk. However, according to the boiling curves in all cases of coated nickel wires, it is supposed that the nucleate boiling heat transfer coefficient deteriorates as a result of thermal resistance resulted from the occurrence of nanoparticle deposition.

Hot-dip galvanizing/dealloying (HDGD)

Tang et al. “[7]” investigated experimentally, the nucleate pool boiling heat transfer performance of a nanoporous copper surface fabricated by the facile hot-dip galvanizing/dealloying (HDGD) process with saturated deionised water. A continuous nanoporous structure of approximately 50–200 nm in pore size is formed on the copper test section. The pool-boiling heat transfer performance of the nanoporous copper surface made from this process is investigated with saturated deionised water. The experimental result implies that the pool boiling heat transfer performance is dramatically enhanced with the nanoporous surface structure particularly at low heat flux

conditions. A reduction of 63.3% in wall superheat and an increase of 172.7% in HTC were observed in this study. Also implies that thermal conductivity of nanostructure may play an important role in the boiling enhancement performance, especially at high heat fluxes.

Electrophoretic deposition

White et al. "[8]" explored the electrophoretic deposition of nanoparticles from a high particle volume fraction nanofluid as a convenient surface modification technique for enhanced boiling performance. Using a ZnO-propylene glycol based nanofluid, they demonstrate 200% improvement in the boiling heat transfer coefficient for deionized water boiled on a coated stainless steel surface under atmospheric pressure. Analysis using the Mikic-Rohsenow correlation, SEM imaging, and contact angle measurements of the surface suggests that the measured enhancement is due to an increase in the active nucleation site density.

CONCLUSION

This paper reviews the various techniques of heat transfer enhancement and increase in critical heat flux by using nanoparticle deposition. Various techniques reviewed in this paper include microreactor techniques (MAND™), Layer by layer assembly, Anodizing process, Electrical heating, Hot-dip galvanizing/dealloying (HDGD), Electrophoretic deposition. It is found that deposition of nanoparticle increase the heat transfer and CHF

More work is needed to understand the CHF enhancement by using nanoparticle deposition and their effect on base material on which it is deposited. Also the bubble dynamics study should be done clearly. The method of deposition should be fully understood and their deposition should be uniform. There is very little work on glass surface boiling behavior so more attention should be done on it.

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