Review

Critical heat flux enhancement by surface modification in a saturated pool boiling: A review

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ABSTRACT

Numerous surface modifications were proposed to enhance the critical heat flux (CHF) in a saturated pool boiling. CHF enhancement is a result of the effects of extended surface area, nucleation site density, wettability, capillary wicking, and wavelength decrease based on the modified Zuber hydrodynamic stability model. A number of combined techniques for CHF enhancement have been proposed. The objective of this paper is to review the CHF enhancement techniques by the various surface modifications and to introduce the enhancement mechanism. Moreover, recommendations are made for future studies to enhance the CHF of a saturated pool boiling.

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1. Introduction

Pool boiling has been used for cooling in numerous thermal energy dissipation systems, such as high-power electronics, heat exchangers, and nuclear reactors. The advantage of pool boiling is that a high heat flux can be removed passively while maintaining a low superheat compared with natural/forced convection without phase change. However, the heat removal capacity is limited by the upper limit of cooling, i.e., the critical heat flux (CHF), where the

heat transfer coefficient decreases dramatically because the boiling regime is changed from nucleate boiling to film boiling. Therefore, the CHF enhancement is of great interest to engineers and researchers.

Studies on CHF enhancement by surface modification in saturated pool boiling have generally considered (1) porous coatings (uniform or modulated) or/and (2) structures of various sizes fabricated/installed on the heated surface. In general, CHF enhancement in saturated pool boiling is a result of the effects of (a) extended surface area, (b) nucleation site density, (c) wettability, (d) capillary wicking, and (e) wavelength decrease based on the modified Zuber hydrodynamic stability model [1]. The exact contribution of each effect has not yet been clarified. A number of

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combined techniques for CHF enhancement have been proposed. Studies on CHF enhancement through surface modification of a flat plate are summarized in Table 1 according to the type of test fluid, i.e., water, refrigerant, or organic fluid.

Gambill and Lienhard [2] showed the theoretical upper limit of cooling for evaporation, neglecting condensation on the liquid-vapor interface. The theoretical maximum heat flux is given by

$$q''_{max} = \rho_v h_{lg} \sqrt{\frac{RT_v}{2\pi M}} \qquad (1)$$

where ρ_v, h_{lg}, R, T_v, and M are the density of the vapor, the latent heat of evaporation, the universal gas constant, the saturation temperature, and the molecular mass, respectively. Using Eq. (1), the theoretical maximum heat flux for water is 223.2 MW/m^2 and for FC-72 is 46.7 MW/m^2 under atmospheric pressure condition. In general, the achievable CHF for a plain surface without using external power is smaller than the theoretical upper limit for evaporation by one or two orders of magnitude, which indicates that CHF enhancement may be possible.

2. Uniform porous coating on a heated surface

A uniform porous coating surface can be produced via methods such as welding, sintering, or brazing of particles, electrolytic deposition, flame spraying, bonding of particles via plating, galvanizing, plasma spraying of a polymer, or metallic coating of a foam substrate, and deposition of a nanofluid. A porous layer coating of uniform thickness on a boiling surface can often increase the CHF in comparison with a plain surface.

Chang and You [3] examined pool boiling heat transfer from diamond-particle-coated surfaces immersed in saturated FC-72. Uniform porous coatings are classified into two groups, i.e., microporous coatings and porous coatings, according to the superheated liquid layer thickness, which is estimated to be 100 μm for FC-72 [3]. A significant increase in CHF was observed over the microporous surface regime. The CHF plateaus when the coating enters the thick porous coating regime. For the thick porous coating regime, Byon et al. [4] investigated the CHF of bi- and monoporous sintered copper coatings in FC-72 (see Fig. 1(a) and (b)). The effects of particle size ($45 < d < 100$ μm), cluster size ($250 < D < 675$ μm), and coating thickness ($0.7 < t < 3$ mm) on the CHF were considered. Their results revealed that the CHF for biporous coatings was significantly improved compared with that of monoporous coatings. The CHF for biporous coatings was shown to be primarily a function of the particle-size-to-cluster-size ratio (d/D) (see Fig. 1(c)). Hwang and Kaviany [5] suggested that the thin, uniform porous coating influences the hydrodynamic (macroscale) stabilities such that, statistically, the critical Rayleigh-Taylor wavelength decreases and/or the vapor area fraction increases in a manner that causes a statistically significant decrease in the dominant interfacial wavelength (Fig. 2). Li and Peterson [6] systematically investigated the effects of geometric parameters, such as the coating thickness, volumetric porosity, and mesh size of microporous coatings made from sintered woven mesh, on the CHF. The results revealed that the CHF increases with increasing coating thickness and reaches a plateau [6,7]. There is a critical coating thickness that distinguishes the CHF mechanism between thick and thin porous coatings. The CHF mechanism for thin porous coatings is considered to be governed primarily by the hydraulic instability resulting from porous coatings, while the CHF mechanism for thick porous coatings is a result of a combination of the capillary limit resulting from the capillary flow inside the coating and the hydraulic instability resulting from surface variations in the coating. They pointed out the state-of-the-art CHF models of porous coatings were not found to accurately predict the available test data. This is because

these models do not take into account the capillary fluid flow inside the porous coatings, which is clearly a major factor in the determination of CHF for these porous coatings. To fabricate a heater surface with unique features for CHF enhancement, nanowires [8–13], nanoporous structures [14–16], copper microporous surface layers [17,18], nanotube arrays [19], carbon nanotube coating [20–23] or composite porous surfaces [24], can be applied. Scanning electron microscopy images and information regarding the test fluid, the system pressure, the maximum CHF $q_{CHF,max}$, and the maximum CHF enhancement ratio $q_{CHF,max}/q_{CHF,p}$ are shown in Figs. 3–8, respectively.

The silicon nanowire-coated surface is obtained via an aqueous electroless etching method. The techniques used for large-scale nanowire synthesis (electrochemical etching and electroplating) are inexpensive and readily scalable for large-area fabrication [13]. The CHF can be enhanced by increasing the nanowire height [10,12,13]. The CHF enhancement can be attributed to some unique properties of nanowires, such as high nucleate site density, super-hydrophilicity, and an enhanced capillary pumping effect. The heat transfer coefficients of the nanowire surfaces increases proportionally as nanowire height increases. It is observed that the micro-scale cavities increase in number and size as the nanowire height increases, but it is still unclear if the cavities alone are responsible for the heat transfer enhancement.

The heat transfer performance for a copper microporous surface layer [17,18] is markedly better than those reported by various investigators for saturation boiling of PF-5060 and FC-72 dielectric liquids on a roughened plane, microporous, micro- and macro-structured surfaces, and metal foams. The alumina nanoporous structure (ANPS), which is produced using an anodic oxidation technique, has a unique hybrid pore structure, consisting of pores with a smaller diameter ($d_p = 100$ nm) and a larger diameter ($d_p = 500$ nm) (Fig. 6). Both of the CHF and the heat transfer coefficient increase with the increase of the ANPS thickness. The preorganized nanoporous surface plays an important role in the enlarged surface area, the active nucleation site densities for boiling and evaporation at menisci. The amount of liquid uptake within a porous coating can be directly quantified by the capacitance obtained from electrochemical impedance spectroscopy (EIS) [14]. Composite porous surfaces with macropores of greater than 0.2 mm in diameter, micropores of approximately 2 μm in diameter, and dendritic structures of approximately 400 nm in diameter are prepared using an electrochemical method [24]. Patil and Kandlikar [25] reviewed a variety of manufacturing techniques used to produce porous surfaces in pool boiling applications.

Polezhaev and Kovalev [26] believed that the porous structure, rather than the Taylor instability, is the decisive factor in the formation of the vapor columns for boiling on porous coatings. To maintain Helmholtz stability, a higher vapor velocity is needed, which is also the primary cause of the enhanced CHF. Based on these analyses, Polezhaev and Kovalev [26] proposed a semi-empirical CHF model of a uniform coated surface:

$$q_{CHF} = 0.52\varepsilon^{2.28}h_{fg}\sqrt{\sigma\rho_l\rho_v/(\rho_l + \rho_v)R_{br}} \qquad (2)$$

where ε is the porosity and R_{br} is the radius of the vapor jets that break through the liquid. Experimental data for water, ethanol, and Freon-113 showed good agreement with the values predicted using Eq. (2) [26].

You et al. [27] were the first to use nanofluids to enhance the CHF for saturated pool boiling. The CHF was increased dramatically by approximately three times (1.68 MW/m^2) compared to that for pure water (0.54 MW/m^2) at a lower saturation temperature of $T_{sat} = 60$ °C ($P_{sat} = 19.9$ kPa). The drastic enhancement in the CHF obtained using nanofluids is of particular interest. Nanofluids are colloidal suspensions of nanoparticles, which are typically made