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Influence of wettability due to laser-texturing on critical heat flux in vertical flow boiling

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ABSTRACT

The critical heat flux (CHF) marks the upper limit of safe operation of heat transfer systems that utilize two-phase boiling heat transfer. In a heat-flux-controlled system, exceeding the CHF results in rapid temperature excursions which can be catastrophic for system components. Recent studies have focused on the influence of surface wettability on the departure from nucleate boiling (DNB) through surface modifications and coatings, though many of these studies are limited to pool boiling systems. In this study, the surface wettability influence is studied on the boiling curves and specifically the point of DNB. A femtosecond laser is used to texture the surface to change the wettability from hydrophilic to hydrophobic. A parametric study is performed with mass flux, pressure, and inlet subcooling in a vertical rectangular channel that is heated from one side. CHF excursions are triggered under various system conditions and are compared with existing models. For the experimental conditions considered, the hydrophobic surface showed delayed onset of nucleate boiling compared to the hydrophilic surface, shifting the boiling curves to higher wall superheat. The hydrophobic surface also showed significantly lower CHF for the same system conditions and less sensitivity to changes in subcooling.

1. Introduction

Boiling heat transfer is an effective cooling mechanism whereby large amounts of heat are removed from critical system components through the heating and vaporization of coolant, either driven by a pump or through buoyant forces. Boiling heat transfer offers high heat transfer coefficients due to both the sensible heating and the latent heating of the coolant, enabling high steady-state cooling rates with minimal surface superheats. The greatest concern of boiling heat transfer is the transition to poor heat transfer regimes, particularly the departure from nucleate boiling (DNB) to film boiling in low-quality flows and the dryout of the annular film in high-quality flows. These transitions are characterized by sudden temperature excursions which risk damage to components. For this reason, the critical heat flux (CHF) is a major safety concern in boiling heat transfer as well as a limitation for effective heat removal in many engineering applications. In addition, the sensitivity of wettability on the critical heat flux is an ongoing research effort for accident-tolerant fuels in nuclear power plants [1]. Due to the complexity of the phenomenon, the accurate prediction of CHF remains a concern [2–10].

Many studies have been conducted to experimentally measure and improve prediction of the critical heat flux in conditions relevant to commercial power generation, particularly in the nuclear industry where temperature excursions can lead to catastrophic system failures [11–14]. Experimental and modeling efforts [15–19] have led to understanding of triggering mechanisms for CHF, including bubble overcrowding, wetting fronts, Taylor instabilities, liquid sublayer dryout, and others. Particular attention has been given to addressing difficulties under low-pressure, low-flow conditions [2–9]. Mishima and Nishihara [2] analyzed the effect different geometries had on the CHF phenomenon, studying annuli, pipes, and square channels. For low-flow conditions, the CHF was found to approach the flooding limit due to the countercurrent-flow limitation proposed by Wallis [20] where the flow geometry was captured by a single constant. Chun et al. [3] and Schoesse et al. [4] also observed that the lower limit of CHF was captured by the flooding condition and that subcooling and pressure were less influential on the CHF in this low-flow regime. El-Genk et al. [5], Park et al. [6], and Kim et al. [7] all observed that, beyond the flooding limit (i.e., flow rates greater than 100–150 kg/m^2-s), the CHF increased with increasing pressure, mass flux, and subcooling. This effect was also observed by Chun et al. [3] which considers a wide range of pressures for CHF under low flow, observing that the peak in CHF occurred between

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Nomenclature

G	mass flux (kg/m^2-s)
P	pressure (kPa)
q''	heat flux (kW/m^2)
Re	Reynolds number (–)
ΔT	superheat or subcooling (°C)
t	time (s)

Greek

ε	error (–)

Subscripts

exp	experimental
mod	model
phil	hydrophilic
phob	hydrophobic
sub	subcooling
w	wall

2 and 3 MPa. Park et al. [6] and Kim et al. [7] both observed that the CHF also increased with increasing channel diameter and with decreasing heated length at constant mass flux. Lu et al. [8] and Mayer et al. [9] observed that the critical equilibrium quality decreased with increasing mass flux and decreasing pressure. Many studies that compare CHF data with existing models conclude that more research on CHF under low-pressure, low-flow conditions is required [2–5,8,9].

In addition to system parameters such as flow rate, pressure, diameter, and inlet subcooling, much effort [21–34] has been devoted in recent years to surface influences on boiling heat transfer and critical heat flux. Frost and Kippenhan [21] first showed the influence of surface tension on boiling heat transfer by adding surface active agents to the bulk fluid in order to reduce surface tension at the heater surface, yielding an enhancement of the heat transfer. Kandlikar [22] developed a pool boiling model that incorporated the influence of surface wettability using data on vertical pool boiling with multiple wettability surfaces and working fluids. The developed model is an adaptation of Zuber's [15] model with coefficients involving contact angle. However, the predicted value for CHF decreases to zero as the contact angle approaches 180°. Hsu and Chen [23] studied the effect wettability had on boiling heat transfer with nano-silica particle coatings on a copper surface in a horizontal pool boiling system. The CHF was observed to decrease with increasing contact angle, and pool boiling curves shifted to greater wall superheat with increasing contact angle, thus degrading the heat transfer in the nucleate boiling regime. Large differences were also observed in the wall nucleation phenomenon between the different wettability surfaces. Li et al. [24] performed a theoretical analysis and an experimental study on the influence of wettability on boiling properties in pool conditions for hydrophilic surfaces. A semi-analytical model employing correlations involving wettability for the departure frequency, diameter, and site density were used to calculate the latent heating of the heater surface, and the model was shown to predict the heat flux within 30% for several hydrophilic surfaces with varying wettabilities in pool boiling. Bourdon et al. [25] also studied the influence of wettability on boiling heat transfer and onset of nucleate boiling, performing horizontal pool boiling studies on smooth glass surfaces. The wettability was controlled with chemical grafting, thereby not modifying the surface topography, obtaining two surfaces: hydrophilic and hydrophobic. The less wetted (hydrophobic) surface was found to have an earlier ONB point compared with the other surface, and the pool boiling curve was found to be shifted to lower wall superheat, though CHF was not investigated. Betz et al. [26] studied the heat transfer and wall nucleation from superhydrophobic, superhydrophilic, biphilic, and superbiphilic surfaces under pool boiling. The surfaces were prepared using silicon wafers and oxygen plasma to make the surfaces superhydrophilic. A thin layer of Teflon fluoropolymer was then spun onto select surfaces to create a superhydrophobic finish. It was observed that the nucleation site density increased with decreasing wettability (increasing contact angle) for the same wall superheat, which indicated an enhancement of the heat transfer coefficient for hydrophobic and superhydrophobic surfaces, a finding confirmed by the reported pool boiling curves. Jo et al. [27] also observed a similar effect on the pool boiling curves with a higher heat transfer coefficient for hydrophobic surfaces at low wall superheat and a higher heat transfer coefficient for hydrophilic surfaces at high wall superheat. The surfaces were prepared in a similar manner to those by Betz et al. [26] using a silicon dioxide surface for the hydrophilic surface and a Teflon surface for the hydrophobic surface. Both Betz et al. [26] and Jo et al. [27] observed lower CHF values for hydrophobic surfaces compared with hydrophilic surfaces and an enhancement of the CHF for biphilic or mixed-wettability surfaces. Marcel et al. [28] modeled the effect wettability has on the boiling characteristics through contact angle and the departure diameter using a stochastic-automata model in pool boiling. The nucleation site density is greater at the same wall superheat for less wetting surfaces which causes the heat flux to be greater. Kim et al. [29] studied the effect of surfaces with temperature varying wettabilities on the boiling heat transfer in vertical flow. Surfaces became more hydrophilic at higher temperatures, and boiling curves were shifted to lower wall superheat as the wettability increased. Kumar et al. [30] observed the opposite trend, decreasing wettability shifts boiling curves to lower wall superheat using copper surfaces coated with diamond or carbon nanotubes, thus changing the wettability. The CHF increased with increasing flow rate, but also increased with the carbon nanotube surface, which has a lower wettability than the plain copper surface, an effect also not observed by previous studies.

From a review of literature, although some effort has been made in pool conditions, few studies have systematically analyzed the effect of wettability on heat transfer and CHF in flow boiling. The objectives of this paper are to meet the data needs for improved understanding of the influence of surface characteristics on heat transfer and CHF in flow boiling and to evaluate the prediction capability of existing CHF models.

2. Experimental approach

A closed-loop facility described in Ooi et al. [35] is modified slightly to measure boiling heat transfer and CHF and is shown in Fig. 1. A positive-displacement pump is used to drive distilled water through the test section at a constant rate. A bypass is connected in parallel with the rest of the section to decrease pressure oscillations and to keep the flow steady through the test section. Water driven by the pump passes through a 5 kW preheater which is used to heat the water to the appropriate inlet temperature to the test section. Water is then driven into the vertical test section, a schematic of which is shown in Fig. 1(b). The assembly is made of