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Experimental and theoretical studies of critical heat flux of flow boiling in microchannels with microbubble-excited high-frequency two-phase oscillations

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ABSTRACT

Critical heat flux (*CHF*) during flow boiling in silicon microchannels ($H = 250\ \mu m$, $W = 200\ \mu m$, $L = 10$ mm) using self-excited and self-sustained high frequency two-phase oscillations is studied both experimentally and theoretically. Tests are performed on deionized water over a mass flux range of 200–1350 kg/m^2 s. An enhanced *CHF* of 1020 W/cm^2 is achieved experimentally at a mass flux of 1350 kg/m^2 s in the present study. Since no existing *CHF* models and correlations on parallel mini/microchannels considered high frequency two-phase oscillations, hence are not applicable to predict *CHF* in the present microchannel configuration. Adopting Helmholtz and Rayleigh instability theories and based on experimental study of liquid thin film dry-out phenomena in two-phase oscillations, a semi-theoretical *CHF* model is proposed. The proposed theoretical predictions show satisfactory agreement with experimental data with a reasonable low mean absolute error (*MAE*) of 25–32%.

1. Introduction

Critical heat flux (*CHF*) of flow boiling refers to the maximum heat flux just before the boiling crisis where a drastic decrease of heat transfer rate or a sudden increase of surface temperature occurs. Hence, this is one of the critical thermal limits in electronics cooling systems, heat exchangers and thermal–hydraulic system of nuclear power plants. Achieving an ultra-high *CHF* is desirable to increase the heat flux safety margin of thermal system. Additionally, high power electronics cooling becomes even more challenging as the transistor size keeps shrinking with an increasing power density. Therefore, it is of great interest to improve *CHF* of these miniature electronic devices. *CHF* can be triggered by boundary layer separation [1], bubble crowding [2] and sub-layer dryout on heated surface [3]. Many flow boiling enhancement techniques have been developed to enhance *CHF* in last decades. The main enhancement mechanisms are: regulating bubble slugs, suppressing flow instability, modifying surface characteristics, improving surface to volume ratio, and promoting liquid rewetting. For example, to suppress flow instability, inlet/outlet restrictors [4,5] and reentrant cavity [6,7] were introduced. Recently, nanofluid (e.g., Al_2O_3 nanoparticle in DI-water [8]) and nano/microscale coating (e.g., nanowire [9–11], nanotube [12] and nanoporous surface [13]) were developed to improve wettability. Meanwhile, surfactant can enhance *CHF* by reducing surface tension of fluids [14]. In addition, techniques, such as micro/mini-jets [15,16], tapered manifod [17], micromixer [18] and solution (e.g., aqueous *n*-butanol, TSP and boric acid solutions) [19,20] can enhance *CHF* as well. However, some enhancement techniques are at the cost of pressure drop. For example, inlet restrictors are considered as one of the most effective ways to improve *CHF*. However, significant additional pumping power is required for this technique. Furthermore, nano/microscale coating technique can drastically enhance *CHF* with penalty of pressure drop [9,21] as well. Pros and cons of existing *CHF* enhancement techniques are listed in Table 1.

Ultra high *CHF* (>30,000 W/cm^2) was achieved at high mass fluxes (>38,111 kg/m^2 s) in microchannel flow boiling [28]. However, much more pumping power was required. Most recently, in our previous studies, a microbubble-excited actuation mechanism has been established to create intense mixing in the microchannels [16,29]. This new enhancement mechanism can effectively suppress flow boiling instabilities and significantly improve liquid rewetting without adding additional pressure drops [16]. In the present study, *CHF* of flow boiling in a multiple microchannel array with self-excited and self-sustained high frequency two-phase oscillations is experimentally studied. Experimental results show that an ultra-high *CHF* (up to 1020 W/cm^2) can be achieved at a modest mass flux of 1350 kg/m^2 s on DI water.

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Nomenclature

A_{cr}	cross sectional area of counter flow, m^2
A_s	cross sectional area of auxiliary channel, m^2
A_v	contact area between bubble and subcooled fluids, m^2
A_w	heated surface area of auxiliary channel, m^2
C_p	heat capacity at atmospheric pressure, J/kg K
d	width of auxiliary channel, m
D_h	hydraulic diameter of auxiliary channel, m
Fo	Fourier number
G	mass flux, kg/m^2 s
h	heat transfer coefficient at vapor/liquid interface, W/m^2 K
H	channel height, m
h_{fg}	latent heat of vaporization, kJ/kg
Ja	Jacob number
k_l	thermal conductivity of subcooled liquid, W/m K
l	length of vapor column entering subcooled liquid, m
L	length of auxiliary channel, m
M	number of experimental data
MAE	mean absolute error
$\dot{m}_l$	mass flow rate of liquid, kg/s
$\dot{m}_v$	Mass flow rate of vapor, kg/s
n	constant number
Nu	Nusselt number
Pr	Prantl number
q_l	heat transfer rate of liquid, W
q_v	heat transfer rate from vapor interface to liquid, W
q''	heat flux, W/m^2
q''_{CHF}	critical heat flux, W/cm^2
R	radius of vapor column, m
Re	Reynolds number
ΔT	increased temperature of subcooled liquid (T_{sub}–T_{in}), K
T_{in}	inlet temperature of liquid, °C
T_{sat}	saturated temperature of vapor, °C
T_{sub}	temperature of incoming subcooled liquid, °C
ΔT_{sub}	temperature difference between saturated vapor and incoming subcooled liquid (T_{sat}–T_{sub}), K
U_c	Helmholtz critical velocity, m/s
U_v	velocity of vapor, m/s
U_l	velocity of liquid, m/s
ρ_v	density of vapor, kg/m^3
μ_l	dynamic viscosity of liquid, Pa s

Greek symbols

λ	Rayleigh critical wavelength, m
σ	surface tension, N/m
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s

Subscripts

CHF	critical heat flux
in	inlet
l	liquid
rel	relative
sub	subcooled liquid
v	vapor

Table 1
Existing *CHF* enhancement techniques for flow boiling in microchannels [22].

Techniques	Pros*	Cons*
Inlet restriction [4,5]	*CHF*+ and HTC+	ΔP+
Reentrant cavity [6,7]	*CHF*+	ΔP∼ and HTC∼
Tapered manifod [17]	*CHF*+, HTC+ and ΔP−	
Micro/minijet [15,16,23]	*CHF*+, HTC+ and ΔP−	
Micromixer [18]	*CHF*+ and HTC+	ΔP+
Nanofluid [8,24,25]	*CHF*+	ΔP+ and HTC∼
Surfactant [14]	*CHF*+ and HTC+	ΔP∼
Solution [19,20]	*CHF*+ and HTC+	ΔP∼
Surface modification		
Nano/microscale coating [9,10,12,13,21]	*CHF*+	ΔP+ and HTC∼
Surface roughness [26,27]	*CHF*+ and HTC+	ΔP+

* + increase; − decrease; ∼ little effect or unknown.

Owing to the complexity of *CHF* mechanisms during flow boiling in microchannels, most of the existing *CHF* models or correlations are empirical and semi-empirical [30–32]. According to the recent review on *CHF* in mini/microchannels conducted by Roday and Jensen [33], experimental *CHF* results are inconsistent with existing models. For instance, there are disagreements with the influence of inlet subcooling degree, pressure, exit quality, and diameter on *CHF* in existing models [30,34,35]. Additionally, only a few theoretical *CHF* models are available for flow boiling in microchannels, for example, a theoretical *CHF* model based on interfacial waves [3,36], or local liquid thin film dryout [37]. However, none of these models considered two-phase oscillations; hence these models are not applicable to the present microchannel configuration.

To better understand this *CHF* enhancement mechanism, a semi-theoretical study in conjunction with experimental investigation is conducted based on fundamental thermal/fluid physics. To develop a semi-theoretical *CHF* model for flow boiling in microchannels with high frequency self-sustained two-phase oscillations, all essential thermo-physical properties, for example, thermal conductivity, specific heat, and latent heat of evaporation should be considered. In addition, the mass flux of subcooled liquid is critical to the direct condensation heat transfer at the vapor/liquid interface, which primarily determined bubble dynamics in the inlet manifold and *CHF* condition of subcooling flow boiling [38,39]. Especially, as the *CHF* is approaching, vigorous vapor generation resulting from thin film evaporation leads to reversal vapor flow, which is governed by the Helmholtz and Rayleigh instabilities. Therefore, it is critical to take account of the interfacial condensation [40].

It is challenging to couple the Helmholtz and Rayleigh instabilities [41] in a flow boiling *CHF* model. The Helmholtz critical velocity of the reversal vapor flow is determined by surface tension and hydraulic diameter of the auxiliary channel. The establishment of stable vapor columns in the auxiliary channel blocks the liquid supply to the heating areas, then results in the *CHF* conditions. The major challenges to develop theoretical *CHF* model are two-fold: (a) the length of vapor columns varies with the subcooling liquid flow rate; and (b) the interfacial condensation heat transfer rate is difficult to determine. Visualization study of bubble dynamics at *CHF* conditions is conducted to address the former challenge. Additionally, three different interfacial heat transfer coefficient (h) correlations have been used to adopt the best suitable interfacial heat transfer coefficient model for this present condition. All related influences arising from local subcooling near vapor/liquid interface, conjugate heating, and mass flux are taken account into the model. Pressure and temperature oscillations have been discussed in our previous studies [16,29].