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A new predictive tool for saturated critical heat flux in micro/mini-channels: Effect of the heated length-to-diameter ratio

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ABSTRACT

This paper verified the macro-to-mini-scale criterion $BoRe_l^{0.5} = 200$ because data points where $BoRe_l^{0.5} \leqslant 200$ and $BoRe_l^{0.5} > 200$ show very different trends for the entire database (1672 data points). Boiling number at critical heat flux (Bl_{chf}) decreases greatly with heated length-to-diameter ratio (L_h/d_{he}) when L_h/d_{he} is small while a relatively smooth trend occurs with large L_h/d_{he} values. The paper proposed a threshold value of $L_h/d_{he} = 150$, beyond which L_h/d_{he} presents negligible effect on saturated critical heat flux. The combined dimensionless number $We_mCa_l^{0.8}$ was introduced to analyze saturated critical heat flux, which represents the significance of inertia, surface tension, and viscous force, without considering gravitational force for the region where $L_h/d_{he} > 150$ and $BoRe_l^{0.5} \leqslant 200$. In addition, a new predictive tool for saturated critical heat flux in micro/mini-channels was obtained, predicting almost 95.5% of the non-aqueous data and 93.5% of the water data within a ±30% error band.

1. Introduction

The critical heat flux (CHF) is defined as the state of the system characterized by a sharp reduction of the local heat transfer coefficient which results from the replacement of liquid adjacent to the heat transfer surface by vapor, causing a sudden rise in surface temperature [1]. The CHF limiting condition forms a most important boundary when considering the performance of heat exchange equipments in which evaporation is occurring. The ability to determine CHF is therefore of vital importance to the safety of two-phase heat sinks since only with such knowledge can a heat sink be designed with an acceptable margin of safety relative to the maximum heat flux dissipation or the minimum coolant flow rate. CHF generally occurs at the channel outlet. Saturated CHF is occurred when the thermodynamic equilibrium vapor quality at the channel outlet is greater than zero but less than one, typically encountered at low mass velocities and low inlet subcoolings. The trigger mechanism for saturated CHF is widely regarded as dry-out of the liquid film near the outlet [1–3]; the corresponding flow pattern at the outlet is mostly annular with the vapor phase occupying most of the channel core while the liquid flows as a thin film along the channel wall.

There are published papers discussing saturated-flow boiling critical heat flux (CHF) in small channels, but most are only based on the authors' own experiments. Table 1 lists the experimental data of saturated CHF in small channels, which covers the fluids R134a, R123, R236fa, R245fa, nitrogen, R12, CO_2, and water at various mass fluxes, exit qualities and heat fluxes. There are two types of channel geometries: circular channels in highly conductive metal (copper, stainless steel) [4–22] and rectangular channels in silicon or metal substrate [23–33]. The latter can be heated non-uniformly. Tests were conducted for single-channel [4–19,32] or multi-channel [23–31] configurations. For channels with hydraulic diameter larger than 3 mm, the flow in channels is vertical upward flow [12–14,16–20,32,33]. A database was obtained by collecting a large number of experimental data of different fluids in small channels from the above literature.

Table 2 lists several existing empirical correlations. The Katto correlation [34] is a correlation based on forced convection boiling in vertical uniformly heated macro-channels. Qu and Mudawar [30] found that as CHF was approached, flow instabilities induced vapor backflow into the heat sink's upstream plenum, which negated the advantages of inlet subcooling, resulting in a CHF virtually independent of inlet subcooling. Their new empirical correlation is based on experimental CHF data for water and R113 in a micro/mini-channel heat sink containing 21 parallel 215×821 μm channels. Wojtan et al. [10] investigated CHF characteristics of R134a and R245fa in single 0.5 and 0.8 mm internal diameter tubes, and proposed a saturated CHF prediction method by modifying the Katto–Ohno correlation. Respective accuracies of these empirical correlations were verified by analyzing the whole database. Considering the effect of heated length-to-diameter ratio, a new predictive tool was developed, applicable for a wide range of operational conditions, different fluids and micro/mini-channel dimensions.

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Nomenclature

A_{ch}	micro/mini-channel cross-sectional area [m^2]
A_h	heated inside area [m^2]
Bl	boiling number, $q/(Gh_{lv})$ [–]
Bo	bond number, $g(\rho_l - \rho_v)d_h^2/\sigma$ [–]
Ca	capillary number, $\mu G/(\rho\sigma)$ [–]
Co	confinement number, $[\sigma/(g(\rho_l - \rho_v)\ d_h^2)]^{1/2}$ [–]
d_h	channel hydraulic diameter [m]
d_{he}	heated equivalent diameter [m]
d_{th}	macro-to-micro-scale threshold diameter proposed by Kew and Cornwell [37] [m]
e_A	average absolute error [%]
e_R	average relative error [%]
G	mass flux [kg/(m^2 s)]
g	gravitational acceleration [m/s^2]
h_{lv}	latent heat of vaporization [J/kg]
L_h	heated length [m]
P	pressure [Pa]
P_h	inside heated perimeter of channel [m]
q	heat flux [kW/m^2]
Re	Reynolds number, Gd_h/μ [–]
T	temperature [°C]
t_s	substrate thickness
We	Weber number, $G^2d_h/(\rho\sigma)$ [–]
x	thermodynamic vapor quality [–]
$Y1$	parameter used in Eq. (5) [–]

Greek symbols

λ	percentage of data within a ±30% error band [%]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
ρ_m	average density [kg/m^3]
σ	surface tension [N/m]
σ_N	standard deviation [%]
Δh_{in}	inlet subcooling enthalpy [J/kg]

Subscripts

cal	calculated
chf	critical heat flux
e	exit
exp	experimental
h	hydraulic; heated
in	inlet
l	saturated liquid
lo	liquid only
m	average
th	threshold
v	saturated vapor

2. Database description

The ranges of experimental conditions for the entire database (1672 data points from 28 different datasets, covering eight different working fluids) are presented in Table 1. In the present work, the datasets which explicitly report simultaneous values of exit quality, heat flux, mass flux, and saturation pressure are included. For the published datasets which report length-to-diameter ratio or the heated length and not quality, only the ones presenting inlet subcooling values simultaneously were considered. Therefore, the information of the CHF can be recreated with certainty. In addition, some of data points were not included because the data points immediately following them at nearly the same conditions had not yet achieved the CHF.

The distribution of the database against heated equivalent diameter (d_{he}) is shown in Fig. 1a. The heated equivalent diameter d_{he} is based on the heated perimeter only, reflecting the actual heat transfer conditions, which is defined as:

$$d_{he} = \frac{4A_{ch}}{P_h}. \tag{1}$$

A_{ch} is the micro/mini-channel cross-sectional area, and P_h is the inside heated perimeter of channel. Heated equivalent diameter covers a wide range of $0.223 \leqslant d_{he} \leqslant 6.92$ mm. About 350 data points have heated equivalent diameters smaller than 0.5 mm, and 38.6% of the data points display a heated equivalent diameter smaller than 3 mm.

Fig. 1b shows the repartition of the database against mass flux. The range of G is comprised between 23.4 and 5200 kg/m^{2}s. Almost 72% of the data points are in the region: G < 1000 kg/m^{2}s, among which 63.5% are in the region: G < 500 kg/m^{2}s. Only 41 data points have mass fluxes larger than 3000 kg/m^{2}s.

Fig. 1c presents the combined non-dimensional number $BoRe_l^{0.5}$ versus the Bond number Bo. The horizontal solid red line represents the macro-to-micro-scale transition $BoRe_l^{0.5} = 200$ [35] and verified by Li and Wu [36], which identifies the micro-scale region when $BoRe_l^{0.5} \leqslant 200$. Based on this criterion, about 51.4% of the entire database belongs to the micro/mini-scale region. Although the hydraulic diameter is as large as 6 mm, the combined non-dimensional number $BoRe_l^{0.5}$ can be smaller than 200 for water, which is the fact in experiments of Kim et al. [17]. While the vertical dashed red line corresponds to the macro-to-micro-scale transition proposed by Kew and Cornwell [37], which defines the micro-scale region when $d_h \leqslant d_{th}$, yielding $Bo \leqslant 4.0$. According to this criterion, 48.0% of the overall data points are located in the micro/mini-channel region.

Among the entire database (1672 data points), there are 462 non-aqueous (four halogenated refrigerants and nitrogen) data points, while 397 data points for water, with values of $BoRe_l^{0.5} \leqslant 200$, comprising the micro/mini-channel database.

3. Results and discussion

Data points with $BoRe_l^{0.5} > 200$ were not adopted in developing the new predictive tool because they are not located in the micro/mini-scale region as mentioned above. Heat flux is non-dimensionalized with mass flux and latent heat in boiling number Bl. Since Bl combines two important parameters, q and G, it is widely used in empirical treatment of flow boiling

$$Bl_{chf} = q_{chf}/(G \cdot h_{lv}), \tag{2}$$

q_{chf} is the internal wall heat flux at CHF conditions.

As shown in Fig. 2, boiling number at CHF (Bl_{chf}) decreases greatly with the heated length-to-diameter ratio L_h/d_{he} when L_h/d_{he} is small. A relatively smooth trend occurs with large L_h/d_{he} values. Therefore, it is common to consider that there exists a value of L_h/d_{he} beyond which it does not affect CHF significantly. Groeneveld et al. developed the 2006 look-up table [38] based on the experimental data of $L_h/d_{he} \geqslant 50$ for saturated critical heat flux in conventional channels with acceptable accuracy. While Lee et al. [39] developed a new correction method for the effect of length-to-diameter ratio on CHF by applying artificial neural networks and conventional regression techniques for water flow in uniformly-heated, vertical tubes. The threshold value was not a