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Status of prediction methods for critical heat fluxes in mini and microchannels

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ABSTRACT

Saturated critical heat flux (CHF) is an important issue during flow boiling in mini and microchannels. To determine the best prediction method available in the literature, 2996 data points from 19 different laboratories have been collected since 1958. The database includes nine different fluids (R-134a, R-245fa, R-236fa, R-123, R-32, R-113, nitrogen, CO_2 and water) for a wide range of experimental conditions. This database has been compared to 6 different correlations and 1 theoretically based model. For predicting the non-aqueous fluids, the theoretical model by Revellin and Thome [Revellin, R., Thome, J.R., 2008. A theoretical model for the prediction of the critical heat flux in heated microchannels. Int. J. Heat Mass Transfer 51, 1216–1225] is the best method. It predicts 86% of the CHF data for non-aqueous fluids within a 30% error band. The data for water are best predicted by the correlation by Zhang et al. [Zhang, W., Hibiki, T., Mishima, K., Mi, Y., 2006. Correlation of critical heat flux for flow boiling of water in minichannels. Int. J. Heat Mass Transfer 49, 1058–1072]. This method predicts 83% of the CHF data for water within a 30% error band. Some suggestions have also been proposed in this paper for the future studies.

1. Introduction

Boiling heat transfer in so-called "microchannels" or "minichannels" holds great promise to replace air-cooling and water-cooling of microprocessor chips. The increasing demand for dissipating high heat fluxes from plasma-facing components in a nuclear fusion reactor, solid targets of a high power accelerator, etc. are also great challenges (Zhang et al., 2006). Flow boiling is a topic that has been increasingly investigated in the last decade but requires the development of reliable and accurate design tools based on extensive experimental investigations to reach its technological potential.

However, high heat flux flow boiling is limited by the critical heat flux (CHF) or burnout. When the liquid, in contact with the heated surface, is replaced with a vapor blanket, the surface heat transfer coefficient drops dramatically which results in a sudden increase of the surface temperature and possible failure of the cooled device. CHF may occur in subcooled as well as in saturated boiling conditions. In subcooled CHF, the bulk temperature at the channel outlet is subcooled and the thermodynamic equilibrium vapor quality is lower than zero, $x < 0$. These are the typical conditions for very high mass velocities, high inlet subcoolings and relative short channels compared to their hydraulic diameters. In saturated CHF, the thermodynamic equilibrium vapor quality at the channel outlet is greater or equal to zero, $x \geqslant 0$. This is typically encountered at low mass velocities, at low inlet subcoolings and in channels with a large length to diameter ratio. In this paper we will focus on the saturated CHF that are representative of computer chip cooling applications.

CHF prediction and analysis are complex. Physics explaining the phenomena is so far not well understood and most of the authors propose their own correlation. The question raised after studying the existing works is: What is the best CHF prediction method for saturated flow conditions? The aim of this paper is to answer this question. To begin with, we will present the database collected for this study. Thereafter, we will present the different prediction methods available in the literature. Finally, we will suggest some relevant issues for future CHF studies.

2. Presentation of the database

The ranges of experimental conditions for the entire database (2996 data points from 19 different laboratories) are presented in Table 1. Since the experimental parameters for water are much different from those for the non-aqueous fluids, the database is separated into two distinct groups: the non-aqueous fluids and water.

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Nomenclature

Bo	bond number (–)
Co	confinement number (–)
c_p	specific heat capacity at constant pressure (J/kg K)
CHF	critical heat flux (kW/m^2)
D	diameter (m)
Δh_{sub}	inlet enthalpy of subcooling (J/kg)
g	acceleration of gravity (m/s^2)
G	mass flux (kg/m^2 s)
H	height of the channel (m)
h_{lv}	latent heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
K	empirical inlet subcooling parameter of Katto and Ohno (–)
K'	empirical inlet subcooling parameter of Qi et al. (–)
L	length (m)
$\dot{m}$	mass flow (kg/s)
MAE	mean absolute error = $\frac{1}{N}\sum_1^N \left\lvert\frac{\text{predicted value}-\text{experimental value}}{\text{experimental value}}\right\rvert \times 100\%$
MRE	mean relative error = $\frac{1}{N}\sum_1^N \left(\frac{\text{predicted value}-\text{experimental value}}{\text{experimental value}}\right) \times 100\%$
n	exponent of Y in Shah's correlation (–)
p	pressure (Pa)
p_r	reduced pressure (–)
q	heat flux (W/cm^2)
q_{co}	saturated CHF of Katto and Ohno (kW/m^2)
R	internal radius of the tube (m)
T	temperature (°C)
ΔT_{sub}	inlet subcooling temperature (K)
u	velocity (m/s)
W	width of the channel (m)
We_D	Weber number based on the diameter (–)
We_{lo}	Weber number for liquid only (–)
x	vapor quality (–)
Y_{shah}	Shah's correlating parameter (–)

Greek letters

δ	liquid film thickness (μm)
$\Delta\delta_i$	height of the interfacial waves (μm)
λ	percentage of data within ±30% error band (%)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	shear stress (N/m^2)

Subscripts

chf	critical heat flux
do	dryout
eq	equivalent
in	inlet
l	liquid
lv	liquid to vapor
sat	saturation
sub	subcooling
v	vapor

2.1. Database for non-aqueous fluids

Fig. 1a presents the repartition of the database as a function of the fluids. The database includes 8 different non-aqueous fluids. Almost 70% of this database concern the following synthetic refrigerants: R-134a, R-245fa and R-236fa. About 8% of the data are dedicated to CO_2 and 8% to R-113. Nitrogen, R-32 and R-123 complete this database which comprises 569 experimental data coming from 12 different papers and from 10 different laboratories.

The repartition of the database as a function of the reduced pressure is shown in Fig. 1b: $0.036 \leqslant p_r \leqslant 0.688$. Most of the data display a reduced pressure less than 0.3. As expected, all CO_2 data belong to a range of p_r comprised between 0.45 and 0.7. Usually, CO_2 is evaporated at much higher reduced pressures than other refrigerants. High vapor density, a surface tension lower by one order of magnitude and a low vapor viscosity drastically influence the hydrodynamic and heat transfer characteristics of CO_2 in comparison with synthetic refrigerants. The question emerging from this observation is: "Is CO_2 a maverick fluid for the critical heat flux?" It is of importance to note here that the data for carbon dioxide were given in the original articles as dryout vapor qualities. As a result, the CHF data used in this paper have been calculated using a heat balance between the fluid and the wall and assuming that dryout occurred at the outlet of the channel without any inlet subcooling. The heat balance is given as follows:

$$x_{do} = \frac{4q_{chf}L}{Gh_{lv}D} \tag{1}$$

Fig. 1c presents the distribution of the database as a function of the diameter: $0.29 \leqslant D \leqslant 3.15$ mm. In addition, Fig. 1d shows the number of data points versus the bond number $(\text{Bo} = (\rho_l - \rho_v)gD^2/\sigma)$: $0.09 \leqslant \text{Bo} \leqslant 13.99$. The vertical line corresponds to the transition between micro/minichannel proposed by Kew and Cornwell (1997). The latter uses the confinement number, Co, which is related to the bond number, Bo, by the following relation: $\text{Bo} = \text{Co}^{-2}$. As the Kew and Cornwell criterion identifies the microscale region when $\text{Co} > 0.5$, this yields $\text{Bo} < 4.0$. This transition reflects the balance between gravitational and surface tension forces (actually it is a measure of stratification). One can see that the database includes both micro and minichannels results.

The repartition of the inlet subcooling is presented in Fig. 1e. The database display a variation of the inlet subcooling from 0 to 74.41 K, which is a large range. The highest subcooling has been measured for R-113. For very high subcoolings, we can suspect some CHF datapoints to be in the subcooled region, which is not the purpose of the present paper (saturation CHF). However, as we have no means to determine whether the datapoints are in the subcooled region or not, we will trust the results presented in the papers. For the interested readers, they should refer to the paper of Celata et al. (1992) who present data for small diameter channels in subcooled region. Fig. 1f shows the repartition of the data points as a function of the mass velocity. The range of G is comprised between 27.9 and 3736.1 kg/m^{2}s. The variation of all the experimental parameters is therefore important. In this database, different geometries may be encountered: single tube, multiple tubes and multi-rectangular microchannels. The equivalent diameter in the case of rectangular channels is given by the following relation:

$$D_{eq} = \frac{4 \cdot H \cdot W}{2 \cdot H + W} \tag{2}$$

with H the height of the rectangular channel and W its width. This equivalent diameter corresponds to the "heated" diameter of a multi-microchannel heat sink heated at the bottom. The mass velocities input into the various methods are the actual values based on the