Pergamon

*Int. J. Heat Mass Transfer.* Vol. 39, No. 8, pp. 1755–1757, 1996

0017–9310/96 $15.00+0.00

**0017–9310(95)00264–2**

# TECHNICAL NOTES

## The effect of the tube diameter on the critical heat flux in subcooled flow boiling

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(*Received* 5 *April* 1995 *and in final form* 6 *July* 1995)

### INTRODUCTION

As is known, the prediction of the CHF may be generally obtained using correlations, models or look-up tables. An excellent and very detailed review on the basic mechanisms of the CHF and predictive tools has been recently proposed by Katto [1].

CHF correlations are generally valid only within the ranges of their data bases, and cannot be extrapolated to conditions far beyond those ranges, because of incorrect asymptotic trends. Modelling of the CHF has not yet been accomplished in an exhaustive way for all the different conditions, and often, even mechanistic models rely on empirical constants, encountering similar problems as correlations.

Claiming a more accurate prediction, widest ranges of application, simplicity of use, easiness of updating, correct parametric and asymptotic trends, with regard to correlations or semi-analytical models, several authors propose the look-up methods as the most convenient tool for the prediction of the CHF [2]. Generally speaking, a look-up table provides CHF values for a given tube diameter (8 mm tube in [2]) at discrete values of pressure, mass flux and CHF quality. Linear interpolation is used to determine the CHF for conditions in between the tabulated values. A problem which has to be solved in the use of the look-up tables is the evaluation of the correction factor for CHF to account for the diameter effect and extend its validity to other values of tube diameter.

The main aim of the present note is to determine the correction factor for CHF to account for the diameter effect in a wide range of tube diameter (from 0.5 to 32 mm) and for exit subcooled conditions of the coolant (water). The basis of the study is a mechanistic model for the prediction of the CHF in subcooled flow boiling recently developed by the authors [3], and recent experimental data [4].

### CALCULATION PROCEDURE

The evaluation of the diameter effect on the CHF in subcooled flow boiling is made using a model recently proposed by the authors [3]. The model proved to be very accurate and precise in calculating the CHF in subcooled flow boiling in a very wide range of tube diameter and length, and thermal hydraulic conditions. Briefly, the model is based on the liquid sublayer dryout mechanism. A thin vapour layer or slug (called 'vapour blanket') is formed, due to accumulation and coalescence of the vapour furnished from the wall, overlying a very thin liquid sublayer adjacent to the wall. CHF is assumed to occur when the liquid sublayer is extinguished by evaporation during the passage time of the vapour blanket sliding on it. Parameters to be determined are: initial thickness of the sublayer $\delta$, vapour blanket length $L_B$, and velocity $U_B$. The evaluation of $\delta$ is obtained from the following argumentation. Vapour blanket can develop and exist only in the near-wall region where the local liquid temperature is equal to the saturation value. Considering the temperature distribution from the heated wall to the center of the channel, it will exist a distance from the wall at which the temperature is equal to the saturation value at the local pressure. This distance is defined as 'superheated layer', and indicated with $y^*$. For a distance from the wall greater than $y^*$, the blanket (and each single bubble) will collapse in the subcooled liquid bulk. Considering also that the vapour blanket is pushed toward the center of the tube by the velocity gradient, it is assumed that the vapour blanket location in the superheated layer is such to occupy the region closer to the saturation limit, i.e. as far as possible from the heated wall, but within the superheated layer, $y^*$. The liquid sublayer thickness, $\delta$, can therefore be calculated as the difference between the superheated layer, $y^*$, and the vapour blanket thickness, $D_B$. Vapour blanket length $L_B$, is postulated to be equal to the critical wavelength of Helmholtz instability of the liquid–vapour interface. Vapour blanket velocity $U_B$, is obtained by superimposing the liquid velocity, calculated using the Karman velocity distribution and the relative blanket velocity, with respect to the liquid, deduced from a forces balance applied to the vapour blanket (buoyancy and drag forces).

As is known, the CHF in subcooled flow boiling is typically a local phenomenon [5, 6]. Therefore, the evaluation of the tube diameter effect on the CHF must be accomplished under constant values of the other geometric (length) and exit thermal hydraulic conditions (velocity or mass flux, exit pressure and exit quality). Although the model can be used for either uniform or non-uniform heating of the channel, for sake of simplicity we consider here a uniform heating condition. Nonetheless, experiments have shown that for constant exit conditions (quality and pressure) the CHF is independent of the heating mode [6].

In order to provide useful information for the present look-up tables [2], we chose for the calculations a mass flux of 7500 kg $m^{-2}$ $s^{-1}$, and an exit pressure of 5.0 MPa. The variation of the tube diameter was between 0.5 and 32 mm. Regarding the tube length, two different calculations were made. In the first the $L/D$ ratio was kept constant, equal to 20, as the tube diameter was varied. In the second calculation, other conditions being equal, the tube length was maintained equal to 400 mm. In the latter case, we may have an $L/D$ ratio in the ranger of slight/no influence on the CHF for most of the tube diameters [7].

Using the Celata *et al.* model [3], we calculated for each

## NOMENCLATURE

| | |
|---|---|
| CHF | critical heat flux [MW m$^{-2}$] |
| $D$ | diameter [mm] |
| $L$ | length [m] |
| $n$ | exponent in equation (1), non-dimensional |
| $U$ | velocity [m s$^{-1}$] |
| $x$ | exit quality, non-dimensional |
| $y^*$ | superheated layer [$\mu$m]. |

Greek symbols

| | |
|---|---|
| $\delta$ | liquid sublayer [$\mu$m]. |

Subscripts

| | |
|---|---|
| B | pertains to the vapour blanket. |

diameter (14 values, from 0.5 to 32 mm) the curve CHF vs exit quality, by changing the inlet temperature of the coolant (water) from 20 to 200°C. Figure 1 shows the results of the calculation ($L/D = 20$) in terms of CHF vs exit quality, $x$, for the different diameters.

It is now necessary to establish constant exit thermal hydraulic conditions and determine the dependence of the CHF from the tube diameter. For given values of the exit quality, we calculated the curves CHF vs tube diameter. We fixed, as a reference, $x = -0.15$; $x = -0.20$; $x = -0.25$; $x = -0.30$. The CHF vs $D$ curves are reported, as an example in Fig. 2 for $L/D = 20$.

As already said, the above calculation was made for $L/D = 20$ (changing, therefore the channel length while changing the tube diameter) and for $L = 400$ mm independently of the tube diameter.

At this point we obtained CHF vs tube diameter curves, for different exit qualities, with $L/D = 20$ and $L = 400$ mm.

## RESULTS AND DATA COMPARISON

Regarding the CHF correction factor for the diameter, Doroshchuk *et al.* [8, 9] proposed to correct their tabulated CHF values with the diameter ratio:

$$\frac{(\mathrm{CHF})_D}{(\mathrm{CHF})_{D=8\,\mathrm{mm}}} = \left(\frac{D}{8}\right)^n \qquad (1)$$

where $(\mathrm{CHF})_D$ is the CHF for a diameter of interest, $(\mathrm{CHF})_{D=8\,\mathrm{mm}}$ is the CHF for an 8-mm tube (i.e. from the CHF table) and $D$ is the tube diameter value in mm. They suggested a value of $-1/2$ for the exponent $n$ in equation (1), for diameter values between 4 and 16 mm. Groeneveld *et al.* [10] examined different values of the exponent $n$ ($-1/2$, $-1/3$ and $-1/4$) and found better agreement for the value of $-1/3$ than the other two with their data base of diameter values between 4 and 20 mm. In an independent assessment, Smith [11] extended the value of $-1/3$ to tube diameter of 32 mm.

We plotted results of the above described calculations using the relationship (1), i.e. the CHF ratio vs the diameter ratio. Figure 3 shows how all the calculated points, independently of exit quality, lie on the same curve, i.e. the curve as given by equation (1), with the exponent $n$, obtained by a best-fit through the points, equal to $-0.3$ (continuous line). In the figure it is also reported the same equation (1) using the exponent $n$ as suggested by Groeneveld *et al.* [10], i.e. equal to $-1/3$ (dotted line). The two curves are practically similar and very close to the points. Besides the exit quality, also the points calculated keeping constant the $L/D$ ratio and keeping constant the channel length, $L$, do not show any

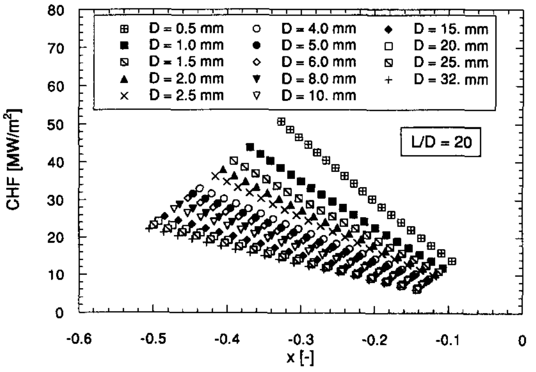

Fig. 1. Critical heat flux vs exit quality for different tube diameters and constant mass flux (mass flux 7500 kg m$^{-2}$ s$^{-1}$, exit pressure 5 MPa).

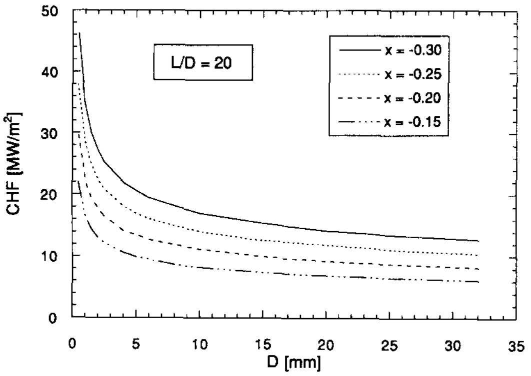

Fig. 2. Critical heat flux vs tube diameter, as a function of exit quality, for constant mass flux (mass flux 7500 kg m$^{-2}$ s$^{-1}$, exit pressure 5 MPa).

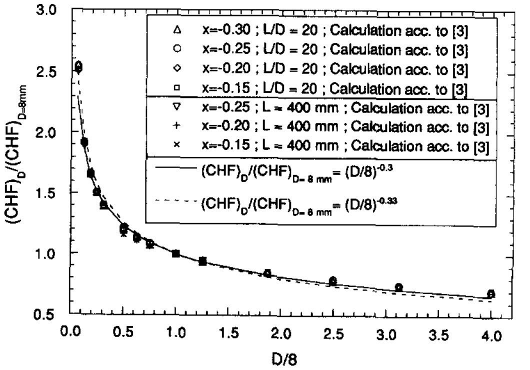

Fig. 3. Critical heat flux ratios for tubes of different diameter values, with respect to one of 8 mm: theoretical calculation.

systematic influence on the trend. Therefore, the above calculations would seem to provide an extension of the Groeneveld exponent, widening its validity in the ranges of tube diameter from 32 mm down to 0.5 mm.

At this point a comparison of equation (1) prediction against experimental data would be of interest. There are not sufficient experimental data consistent with the above procedure (i.e. different tube diameters with constant exit qualities) to accomplish a thorough experimental assessment of the above calculations [4]. Nevertheless, we tried to compare predictions provided by equation (1) with $n = -0.3$ and $n = -1/3$, against a few (five) experimental data which are somehow homogeneous. Such data have a constant exit quality, but the $L/D$ is varying from 12.5 and 40 (the channel length is equal to 100 mm for all the tests) [4]. This is in a range where the $L/D$ is still affecting the CHF, especially for the lowest $L/D$, and therefore we might expect some deviation from the theoretical curves.

The results are shown in Fig. 4, where experimental data and equation (1) are plotted reporting the CHF ratio vs the diameter ratio. The comparison between experimental data and the two curves given by equation (1) is pretty good, considering the above premises on the $L/D$ effect, the uncertainty in the experimental data, and the uncertainty associated with the model calculations.

## CONCLUDING REMARKS

Using a recently developed mechanistic model for the prediction of the CHF in subcooled flow boiling, an attempt to evaluate the influence of the channel diameter on the CHF has been pursued. From the calculations, a correction factor for the CHF to account for the diameter effect to be used in the application of look-up tables has been derived. The present study considered a wide range of tube diameters, from 0.5 to 32 mm, including the field of interest of both fission and fusion reactors.

The expression already proposed by Doroshchuk *et al.* [8, 9], i.e. equation (1), proved to be successful when using the exponent $n$ as equal to $-0.3$. Considering that Groeneveld *et al.* [10] found $n = -1/3$ to be the suitable exponent in equation (1) for tube diameter between 4 and 20 mm, and that the same value was assessed by Smith [11] for $D = 32$, we may conclude that the present work confirms the exponent $n = -1/3$ to be valid down to very low tube diameter (0.5 mm).

The comparison with the few experimental data available have shown that the above conclusions fit quite well with experimental evidence.

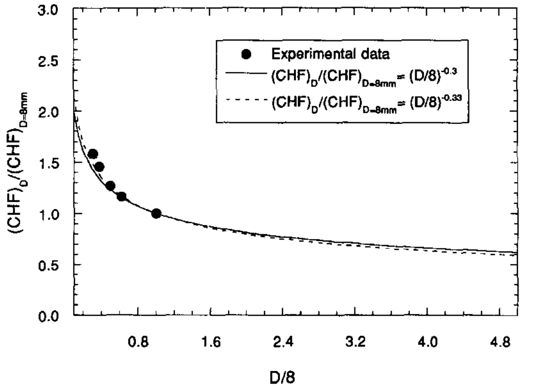

Fig. 4. Critical heat flux ratios for tubes of different diameter values, with respect to one of 8 mm: comparison between experimental data and theoretical calculation.

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