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Influence of channel diameter on subcooled flow boiling burnout at high heat fluxes

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INTRODUCTION

AMONG the many technical challenges that fusion technology has given rise to over the recent past, particular interest was reserved to the handling of the plasma and the heat from fusion reactions. In particular, some components of fusion reactors, such as divertors, plasma limiters, neutral beam calorimeter, ion dump and first-wall armor, are estimated to be subjected to very high heat loads. Heat fluxes to be removed range from 2 to 60 MW m^{-2}, and forced convective subcooled boiling can accommodate these very high heat fluxes. However, successful use of subcooled flow boiling for high heat fluxes removal requires the critical heat flux (CHF), which is described as a sharp reduction in the energy transfer from a heated surface, not to be reached. The occurrence of CHF, for the case of heat flux controlled systems, results in a significant increase of the wall temperature, which is usually well above that at which serious damage or 'burnout' of the heating surface occurs. A review of recent experiments and predictive aspects of burnout at very high heat fluxes was given by Celata [1]. Macroscopic parameters affecting the CHF condition in subcooled boiling, as given by Collier [2], are subcooling, mass flux, pressure, diameter, and length-to-diameter ratio. Boyd [3] reviewed experimental results of the effects of the macroscopic parameters. Generally, CHF increases with subcooling and mass flux, and most recent experiments, as reported by Celata *et al.* [1, 4], revealed almost a linear (a little less than linear) fashion for mass fluxes up to 40 Mg m^{-2} s^{-1} and exit subcooling up to 190 K. Subcooling effects tend to be greater when associated with higher values of mass flux [1]. CHF, generally, increases with pressure at low pressure, is relatively constant over an intermediate range of pressure, and decreases at high pressure [3]. Recent experiments carried out under operating conditions typical of fusion reactor thermal hydraulics (high mass flux and subcooling, pressure between 2.0 and 5.0 MPa) showed that, other conditions being equal, direct influence of the pressure is weak. None the less, a higher pressure, other conditions being equal, allows us to obtain a higher liquid subcooling, and, indirectly, contributes to the enhancement of the CHF [1]. Of the geometric parameters, diameter may be the most interesting, yet only a few investigations have been performed. Ornatskii and Kichigan [5], Bergles [6] and Vandervort *et al.* [7] noted a significant increase in the CHF for decreasing diameter. In each of these studies the effect of decreasing diameter was reduced as mass flux increased.

If the number of data points regarding the effect of diameter on CHF in subcooled flow boiling is limited, even more reduced information is available in operating ranges typical of fusion reactor thermal hydraulics (high liquid velocity and subcooling, i.e. high heat fluxes). The aim of this technical note is to provide a critical status of the art of experiments carried out so far under the above-mentioned conditions with regard to the effect of diameter.

DATA ANALYSIS

A consistent CHF data bank under fusion reactor thermal hydraulic conditions was recently collected by Celata *et al.* [8]. Experimental points reported in Table 1 are those presented by Boyd [9–11], Inasaka and Nariai [12], Nariai *et al.* [13], Achilli *et al.* [14], Celata *et al.* [15–18], Gambill and Greene [19], and Vandervort *et al.* [7], and the overall operating ranges are: $0.1 < p < 5.5$ MPa; $0.3 < D < 15.0$ mm; $0.0021 < L < 0.3$ m; $2 < G < 40.5$ Mg m^{-2} s^{-1}; $900 < \Delta T_{sub,in} < 230$ K.

A thorough analysis of a single parameter requires that other parameters are kept constant while increasing or decreasing the parameter that is the object of the analysis. In other words the exit pressure, the mass flux, the heated length and, above all in the case of subcooled flow boiling CHF, the exit quality (or the exit thermal hydraulic conditions) must be kept constant during the tests with different

Table 1. Experimental data used for present evaluation

CHF data (ref.)	No. of points	T_{in} (°C)	p (MPa)	D (mm)	L (mm)	L/D	G (Mg m^{-2} s^{-1})	q''_{CHF} (MW m^{-2})
Celata *et al.* [15]	43	18.6–54.6	0.1 ~ 2.2	2.5, 4, 5	100	20 ~ 40	2.2 ~ 32.6	4.0 ~ 42.7
Celata *et al.* [16]	88	29.8 ~ 70.5	0.6 ~ 2.6	2.5	100	25	10.1 ~ 40.0	12.1 ~ 60.6
Celata *et al.* [18]	48	29.3 ~ 71.5	0.5 ~ 2.6	4.0	100	25	5.0 ~ 40.0	10.6 ~ 54.4
Celata *et al.* [18]	7	29.3 ~ 40.7	0.8	5.0	100	20	4.1 ~ 20.0	13.0 ~ 34.7
Celata *et al.* [17]	14	29.8 ~ 75.9	2.1 ~ 5.0	6.0	100	16.6	5.0 ~ 10.0	11.8 ~ 27.8
Celata *et al.* [17]	46	29.1 ~ 80.7	0.4 ~ 5.0	8.0	100 ~ 150	12.5 ~ 18.7	2.0 ~ 10.0	7.4 ~ 29.5
Inasaka–Nariai [12]	29	25.0 ~ 78.0	0.3 ~ 1.1	3.0	100	33	4.3 ~ 30.0	7.3 ~ 44.5
Nariai *et al.* [13]	95	15.4 ~ 64.0	0.1	1.0 ~ 3.0	10 ~ 100	5 ~ 50	6.7 ~ 20.9	4.6 ~ 70.0
Boyd [9–11]	10	20.0	0.77 ~ 1.66	3.0	289.7	96	4.4 ~ 40.5	6.0 ~ 41.5
Achilli *et al.* [14]	35	26.4 ~ 158.2	1.0 ~ 5.5	8.0 ~ 15.0	150 ~ 300	15 ~ 20	4.6 ~ 14.9	11.0 ~ 35.6
Gambill–Greene [19]	7	4.9 ~ 35.8	0.1	7.8	47 ~ 157	6 ~ 20.3	13.0 ~ 26.0	15.8 ~ 33.0
Vandervort *et al.* [7]	78	7.8 ~ 87.9	0.6 ~ 1.2	0.3 ~ 2.2	2.1 ~ 54	2 ~ 25	10.0 ~ 40.0	17.4 ~ 95.8
Total	500	4.9 ~ 158.2	0.1 ~ 5.5	0.3 ~ 15.0	2.1 ~ 300	2 ~ 96	2.0 ~ 40.5	4.0 ~ 95.8

NOMENCLATURE

D	tube inside diameter [m]
G	mass flux [kg m^{-2} s^{-1}]
L	heated length [m]
p	pressure [MPa]
q''	heat flux [MW m^{-2}]
T, ΔT	temperature, temperature difference [°C, K]
x	steam quality.

Subscripts

CHF	pertains to the critical heat flux condition
eq	equilibrium condition
in	pertains to inlet conditions
sub	subcooled condition.

test channel diameters. Unfortunately, most of the above data points were carried out for purposes different from the evaluation of the test channel diameter influence *per se*, and therefore only a few of them are 'homogeneous' in the sense

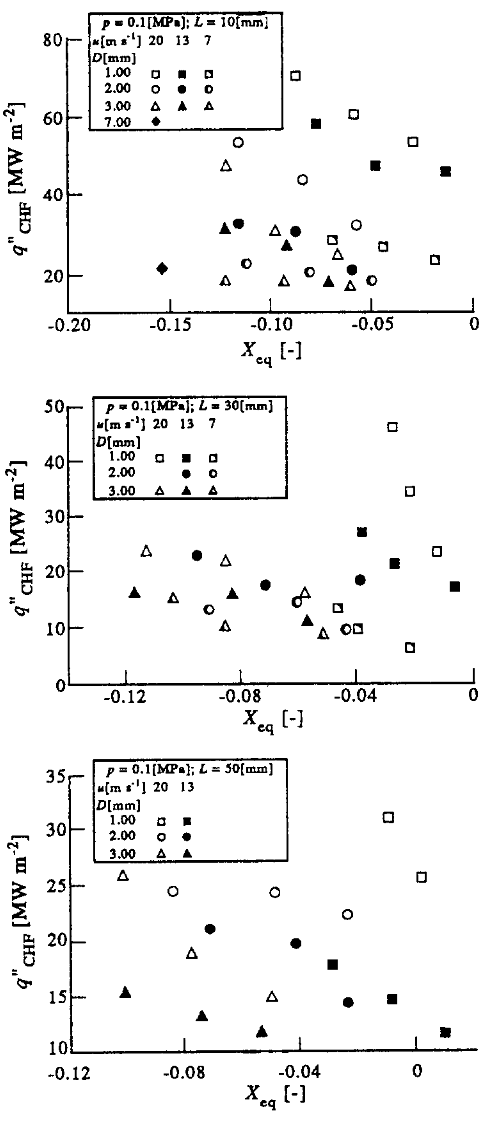

FIG. 1. Critical heat flux vs exit equilibrium quality for different tube inside diameter, liquid velocity and heated length. All data are from Nariai *et al.* [13] except one point with $D = 7.0$ mm from Gambill and Greene [19].

above described. None the less, it has been possible to find some data for an evaluation of the diameter effect on CHF in these operating ranges. Experimental data useful to this comparison were those performed by Inasaka and Nariai [12], Nariai *et al.* [13], Celata *et al.* [15–18] and Gambill and Greene [19].

Figure 1 shows three graphs reporting the critical heat flux q''_{CHF} vs the equilibrium quality at the exit, x_{eq} for different liquid velocities and channel diameters. The three graphs refer to three different heated lengths, while the exit pressure, p, is always the same, i.e. a nominal value of 0.1 MPa. All the experimental data points are from Nariai *et al.* [13] with the only exception of a point from Gambill and Greene [19] having a channel diameter of 7.0 mm.

Similarly to the previous figure, Fig. 2 reports q''_{CHF} vs x_{eq} for different channel diameters and for fixed values of liquid velocity, exit pressure and heated length of the test section. In Fig. 2 experimental data with $D = 3.0$ mm are from Inasaka and Nariai [12], while all the other data are from Celata *et al.* [15–18]. For given values of outlet thermal hydraulic conditions, heated length, liquid velocity, q''_{CHF} increases with the decrease of the tube inside diameter (Figs. 1 and 2). Other conditions being equal, q''_{CHF} increases also with the decrease of the heated length (Fig. 1). As far as the combined effect of the tube inside diameter and liquid velocity is concerned, from Fig. 1 it is possible to argue that the effect of D and L on q''_{CHF} tends to vanish as long as D and L are sufficiently large.

From data reported in Figs. 1 and 2, respectively, we derived the direct dependence of q''_{CHF} on D, other conditions being equal. Such a derivation was obtained considering a continuous, ideal curve of the data plotted in Figs. 1 and 2, and reading on these curves the values of CHF corresponding at a fixed value of x_{eq}. Figure 3 represents the before-mentioned dependence of Inasaka and Nariai [12] data in the top graph (tube inside diameter from 1 to 3 mm) and for Inasaka and Nariai data [12] ($D = 3$ mm) and Celata *et al.* [15–18] data ($D = 2.5$, 4.0, 5.0 and 6.0 mm) in the bottom graph. It is here more evident that tube inside diameter and liquid velocity are inter-related, i.e. increase of CHF with the decrease of tube inside diameter tends to be greater when associated with higher values of liquid velocity. This was in contrast with previous observations, and in agreement with recent experiments carried out by Vandervort *et al.* [7]. The threshold beyond which the effect of the tube inside diameter may be considered negligible is a function of the channel geometry and the thermal hydraulic conditions. At this stage of the research, available experimental data do not allow us to draw any systematic and quantitative conclusion, but only to have a generic qualitative information on the feature of the dependence. To explain the observed dependence of the CHF from the tube inside diameter it is worth reporting here three different reasons proposed by Bergles [6]. For a tube with a smaller inside diameter we have: (i) small bubble diameters, (ii) an increased velocity of the bubbles with respect to the liquid, and (iii) the fluid subcooled bulk is closer to the growing bubbles (collapsing in the bulk). From the analysis of experimental data of void fraction in

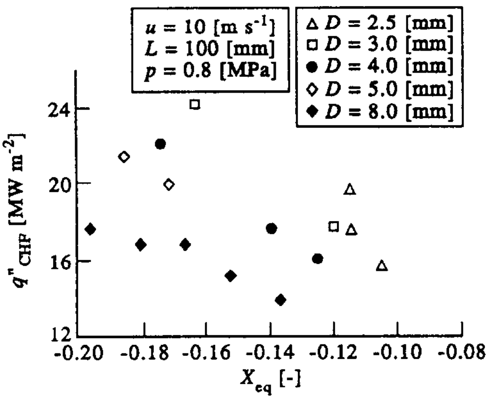

FIG. 2. Critical heat flux vs exit equilibrium quality for different tube inside diameter, liquid velocity and heated length. All data are from Celata *et al.* [15–18] except data points with $D = 3.0$ mm from Inasaka and Nariai [12].

narrow tubes, Nariai and Inasaka [20] concluded that, as tube inside diameter decreases and mass velocity increases, the diameter of generated bubbles or, better, the thickness of the two-phase boundary layer, becomes smaller due to the intense condensation effect by subcooled water at core region, and the void fraction becomes smaller, so making the CHF higher. The decrease of the diameter gives rise to an increase of the slope of the velocity profile in the two-phase boundary layer, making the detachment of growing bubbles and the consequent condensation in the core region easier. The higher the mass flux the more consistent the above-mentioned effect.

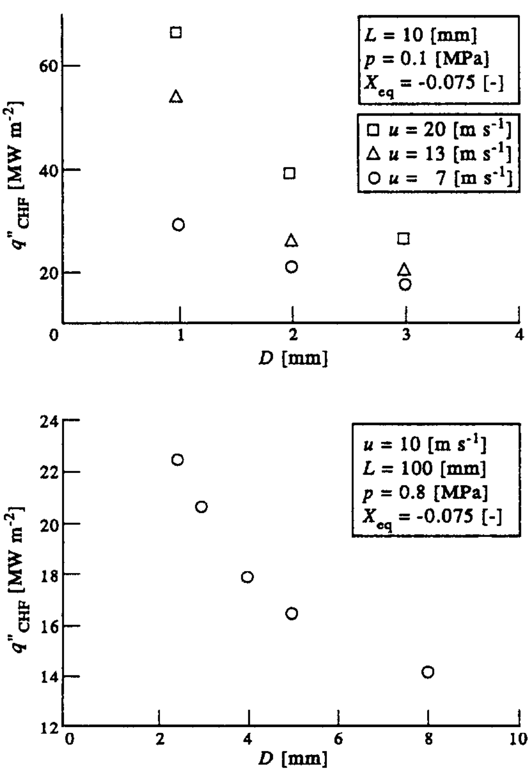

FIG. 3. Critical heat flux vs inside tube diameter for Nariai *et al.* data [13] (top graph) and for Celata *et al.* [15–18] ($D = 2.5$, 4.0, 5.0 and 8.0 mm) and Inasaka and Nariai data [12] ($D = 3.0$ mm) (bottom graph).

CONCLUSIONS

Taking advantage of a recent data bank of 500 points collected for fusion reactor thermal hydraulic application purposes, an attempt is presented to analyse the influence of tube inside diameter on the CHF. Generally speaking, with small inside tube diameter at high water velocity, the CHF may become very high and is supposed to be inversely related to the tube inside diameter. This effect could be ascribed to the reduction of the void fraction with the decrease of the channel diameter, because of smaller bubbles diameter (or thickness of the two-phase boundary layer) and stronger action of bubble entrainment effect due to the increase of the velocity profile slope in the two-phase boundary layer. Available experimental data only allow a qualitative description of the effect of diameter on the CHF, preventing the definition of quantitative features for lack of homogeneity among data points (a single parameter effect should be established, other conditions being equal). Further detailed investigation is therefore still necessary for a thorough and comprehensive understanding of the phenomenon.

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