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TECHNICAL NOTES

Critical heat flux and heat transfer for high heat flux applications*

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1. INTRODUCTION

HIGH HEAT flux research is important in: (1) fusion component heat removal, (2) state-of-the-art electronic cooling, (3) neutral particle beam design for cancer therapy and materials testing, and (4) high temperature gas turbine blade heat removal. For the former application, there is practically no low pressure flow boiling data for large values of coolant channel length-to-diameter ratio ($L/D \approx 150$) and medium to high flux levels (i.e. 100–2000 W cm^{-2}). The present work is intended to provide a first step in filling these data voids.

There has been a significant amount of work done on flow boiling, critical heat flux (CHF), and the effects of flow channel orientation (i.e. horizontal vs vertical flow). Leontiev *et al.* [1] measured CHF (100–700 W cm^{-2}) at high pressures (6.9 and 13 MPa) and with an L/D of 69 (inside diameter, D = 0.6 cm). Jensen and Bergles [2] used a mixed convection parameter and found buoyancy effects important when $Gr/Re_l^2 \geqslant 0.0127$, where Gr and Re_l are the Grashof and liquid Reynolds numbers, respectively. In cases where orientation is important, the CHF for horizontal flow is usually (but not always) less than that for vertical flow. In this case, the heat transfer coefficient can vary by as much as a factor of 20 from the top to the bottom of the channel.

All evidence (see e.g. [2–4]) indicates that above a threshold mass velocity (G) there is little difference between horizontal and vertical flows. Merilo [3], Groeneveld [5] and Zeigarnik *et al.* [6] noted that this mass velocity limit was between 3.0 and 4.5 Mg m^{-2} s^{-1}. Merilo also measured CHF (50–200 W cm^{-2}) at high pressure (6.7–9.7 MPa) for an L/D ranging from 193 to 387. Yucel and Kakac [7] studied variations of CHF at low inlet subcooling (5–45°C) for rectangular channels with both horizontal (bottom- and top-heated) and vertical (up and down) flows. Based on the literature, there does not appear to exist moderately high CHF data ($\sim$ 500 W cm^{-2}) for moderate to large L/D ($\sim$ 100) and low pressures (0.5–2.0 MPa).

2. HIGH HEAT FLUX REQUIREMENTS

Initial emphasis has been placed on *limiters*, which are one of many high heat flux fusion reactor components. Limiters have three main functions in fusion reactors: (1) prevent the plasma from touching the walls of the confinement vessel, (2) control the plasma edge conditions, and (3) remove helium ash and impurities from the plasma. In most cases, the coolant channels in limiters are horizontal. Limiters will have coolant channels with lengths between 1.0 and 2.0 m, and will be subjected to steady-state heat fluxes of about 500 W cm^{-2}. The coolant channel's L/D is expected to range from 100 to 200 for near-term fusion components. Other components will be required to have smooth surfaces and/or irregular channel cross-sections. For the latter case, heat fluxes will be between 100 and 2000 W cm^{-2} s^{-1}, and the L/D between 50 and 200. In addition, most near-term fusion components will have thin wall coolant channels and will be used in low pressure facilities.

To meet these demands, a high heat flux flow boiling laboratory was developed. The flow loop is a quasi-automated facility developed to systematically extend previous subcooled flow boiling studies on: (1) CHF, (2) heat transfer, (3) pressure drop, and (4) heat transfer enhancement techniques. This experimental study, which is the first phase of a broader study, was intended to: (1) measure flow boiling CHF in the mid to low heat flux range at low pressure, (2) identify the CHF transition between subcooled and annular flow boiling regimes at 1.6 MPa, (3) produce unconditionally stable CHF data, and (4) make comparisons between the data and selected existing CHF correlations. The flow loop was developed to minimize the difficulties in measuring the CHF and inaccuracies resulting from unanticipated phenomena such as flow instabilities, fouling and large increments in the flow parameter varied as CHF was approached. A description of the flow loop, test-section and experimental procedure is given in ref. [8].

3. RESULTS

Local (axial) heat transfer and CHF were examined in horizontal, resistively-heated test-sections as a function of axial location and mass velocity, respectively. Both the inlet water temperature (20°C) and exit pressure of (1.6 MPa) were constant. Measurements were made for flow in resistively-heated copper tubes of uniform thickness for the following conditions: G = 0.63–3.5 Mg m^{-2} s^{-1}, L/D = 115.56 and D = 1.02 cm. Deionized, degassed water was the coolant.

3.1. *Heat transfer*

An indication of the rate of heat removed from the test-section, at any given instant, is directly related to the difference between the inlet and exit bulk temperatures. This was used as a secondary check on the measured power generation and was found to agree within less than 3.0% using constant temperature properties. At any given power level, the radiative and convective heat losses from the test-section were less than 0.3%. Axial temperature measurements were made on the outside of the test-section. In all cases, the thermocouples were electrically isolated from the test-section. Since the circumferential temperature variations around the heated channel were found to be small ($\leqslant$ 2°C for $G \geqslant 0.63$ Mg m^{-2} s^{-1}), the measured wall temperature data were used to determine the heat transfer coefficients (h_i) by accounting only for the radial and axial temperature variations.

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Using the measurements of the outside wall temperature, the local (axial) heat transfer coefficient was computed based on the local film temperature (see Fig. 1; $G = 1.7\ \mathrm{Mg\,m^{-2}\,s^{-1}}$). The CHF occurred near the exit (axial location, $z = 113.7$ cm downstream of entrance) and caused an instantaneous drop in h_l. This drop occurred before any change in h_l at the other upstream locations. Observations using a video recorder indicated that the time rise to burnout was approx. 200 ms. For the case shown in Fig. 1, there was more than a factor of four increase in the Nusselt number (from 120 to 500) from the entrance to the exit of the test-section. This demonstrates the significance of the axial variations in h_l for low and moderate levels of mass velocity.

3.2. *Critical heat flux (CHF) data*

Since the CHF forms a practical upper limit for the heat flux in flow boiling, its characterization and predictibility are fundamental to any high heat flux application. The objectives of the CHF measurements were to produce unconditionally stable data for: (1) further characterizing the transition region between subcooled and annular regimes, (2) use by designers, and (3) flow boiling correlation and data-base selection. An equally important concern was data repeatability. The CHF measurements are shown in Fig. 2 as a function of the mass velocity.

Figure 2 has been divided into three flow boiling regimes: (1) subcooled, (2) transition and (3) annular. These divisions are based on CHF measurements which are described below. The subcooled and annular flow regimes differ most strikingly by the actual distribution of the vapor and liquid in the flow channels. Briefly, the subcooled regime exists when nucleation occurs upstream of the location where zero thermodynamic quality occurs. The annular regime exists when nucleation occurs downstream of the zero quality location. Although much detail has been omitted, these definitions suffice for the present discussion. Also shown in Fig. 2 is the curve corresponding to a zero thermodynamic (equilibrium) quality, x_{eq}. The zero quality line provides a qualitative condition for the boundary between the annular and subcooled regimes. The transition regime will be denoted here as a 'narrow' region bounding the zero quality line.

At constant exit pressure and inlet temperature, the CHF in the subcooled regime decreased with decreasing mass velocity (G) and was greater than the CHF in the annular flow boiling regime until the transition regime was reached. As the

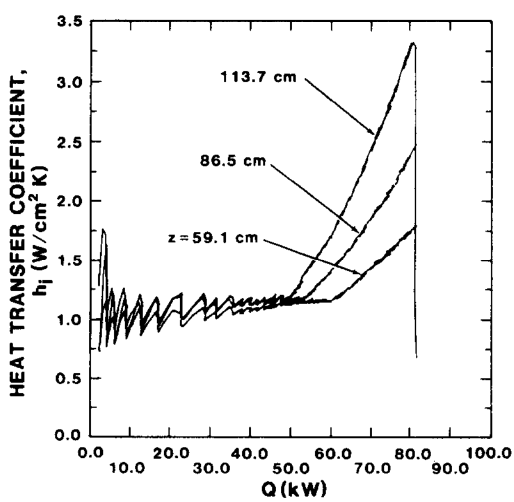

FIG. 1. Heat transfer coefficient as functions of the power generation and z for: $D = 1.02$ cm, $L/D = 115.6$, exit pressure = 1.6 MPa, inlet temperature = 20°C, and $G = 1.7$ Mg $\mathrm{m^{-2}\,s^{-1}}$. The fluid was deionized, degassed water.

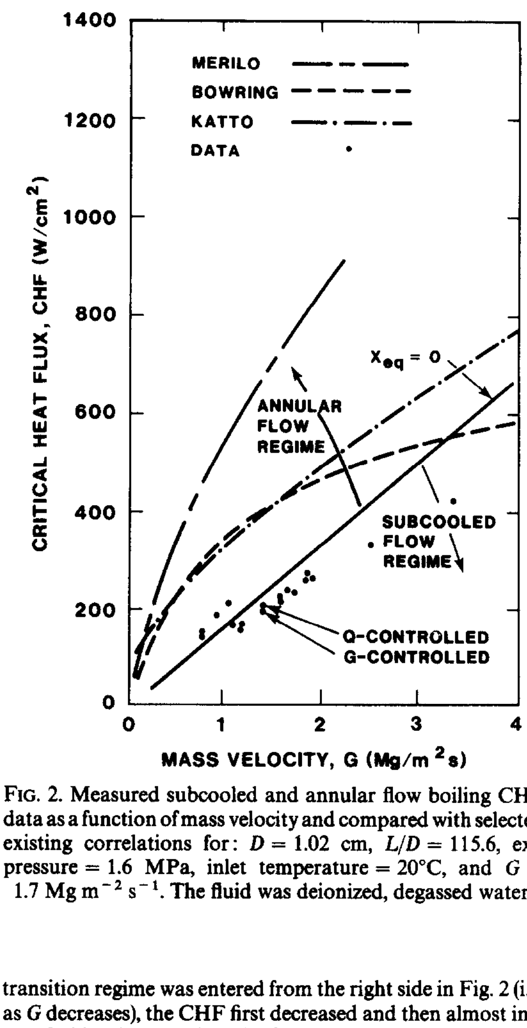

FIG. 2. Measured subcooled and annular flow boiling CHF data as a function of mass velocity and compared with selected existing correlations for: $D = 1.02$ cm, $L/D = 115.6$, exit pressure = 1.6 MPa, inlet temperature = 20°C, and $G =$ 1.7 Mg $\mathrm{m^{-2}\,s^{-1}}$. The fluid was deionized, degassed water.

transition regime was entered from the right side in Fig. 2 (i.e. as G decreases), the CHF first decreased and then almost in a step fashion increased as the flow structure approached the annular configuration. At an exit pressure of 1.6 MPa and inlet temperature of 20°C, the boundaries characterizing the transition from the subcooled regime to the annular regime were measured to be 1.03 and 1.26 Mg $\mathrm{m^{-2}\,s^{-1}}$. The left boundary was identified by approaching CHF (with Q varying) at successive lower values of mass velocity. The left boundary was located at the value of G where a decrease in CHF occurred following its increase (mentioned above). To verify this result, redundant tests were conducted with and without the dampener for $G = 1.03$ Mg $\mathrm{m^{-2}\,s^{-1}}$. The same value of CHF was obtained to within $\sim \pm 2.5\%$. The right-most boundary was located less rigorously. As G was decreased below 1.3 Mg $\mathrm{m^{-2}\,s^{-1}}$, larger differences in the measured value of CHF occurred. The right-most boundary was located at a value of G, 1.26 Mg $\mathrm{m^{-2}\,s^{-1}}$, where this difference became of the order of the accuracy of the CHF measurements.

As indicated previously, one objective of this experiment was to produce unconditionally stable and repeatable data. The term 'unconditionally stable' implies that the slope of the pressure-drop/flow-rate curve for the pump is infinite, which was nearly the case with the positive displacement pump used in the flow loop. This means that the likelihood of the occurrence of flow instabilities was reduced. This was verified using an approach established over 20 years ago; i.e. some tests were run with a dampener (to reduce pressure oscillations) while progressively increasing the pressure-drop (using the throttling valve) upstream of the test-section as the power generation was increased. The results compared well with other tests without the dampener.

Redundant experiments were also performed at 1.6 Mg m^{-2} s^{-1} to determine whether or not the value of CHF would change if the CHF was approached using different control-parameters (i.e. the parameter varied as CHF was approached). This was necessary in order to establish additional confidence in the data and the flow loop. The CHF was approached, in most tests, with all other parameters constant except the applied power generation, i.e. Q-controlled. The measured value of CHF is shown in Fig. 2. In another case, all parameters were maintained constant (including Q) except the mass velocity. The mass velocity was decreased (i.e. G-controlled) until CHF was attained. This measured value of CHF is also shown in Fig. 2 and compares very well with the previously measured value using Q as the control parameter.

3.3. *CHF data and correlation comparisons*

The CHF correlations developed by Merilo [4], Bowring [9] and Katto [10] were selected for comparisons with the CHF data. The latter two correlations were developed for vertical flow and the former for horizontal flow. There were at least four reasons for selecting these correlations. First, a portion of the data is in the annular flow (and lower subcooled) regime(s), where these correlations have been applied to a large amount of CHF data. Although not based on first principles, these correlations have been developed to account for the dependence of CHF on a significant number of dimensional and dimensionless flow parameters. Further, since Merilo's correlation was developed for high pressures (low density ratios as well as different fluids) and specifically for horizontal flows, comparisons with it will give an indication of its applicability at lower pressures. Finally, in the absence of the necessary data, the correlations by Bowring and Katto were recommended for fusion reactor limiter design (see [8]); an evaluation of this recommendation will be useful for the design of future fusion components.

As is shown in Fig. 2, the data are below the three CHF correlations. As the mass velocity increases, the data show that the slope of the CHF vs the mass velocity curve decreases. Although a similar trend was displayed by the Bowring correlation, the reduction in slope of that correlation appeared to be larger than that of data. This will result in Bowring's correlation underpredicting the CHF for a mass velocity above 5.0 Mg m^{-2} s^{-1}. Since the slope of Katto's correlation is slightly above that of the data, it will apparently overpredict the CHF at all values of mass velocity. Therefore, below 5 Mg m^{-2} s^{-1}, the correlations will overpredict the CHF. However, above 5 Mg m^{-2} s^{-1}, the CHF will be bounded from below and above by Bowring's and Katto's correlations, respectively. Since the CHF is bounded by Bowring's and Katto's correlations for mass velocities above 5 Mg m^{-3}, the recommendations made previously [8] regarding these CHF correlations for limiter design appear to be reasonable. However, these comparisons clearly demonstrate the need for additional fundamental work on CHF correlation development.

Merilo's correlation predicted CHF significantly above the present data. The differences between the CHFs are due to the large differences in the pressure of the data used by Merilo in developing his correlation (density ratio, $\rho_l/\rho_g \leqslant 20$) and the pressure for the present data ($\rho_l/\rho_g \sim 100$). The closer agreement between the data and the correlations by Katto and Bowring, as compared with Merilo's correlation, can be explained. Their correlations account, to some extent, for both the high and low pressure influences on CHF. Since these pressure influences are quite different, their inclusion in correlations used for all high heat flux applications are essential. Because of the low pressure used in the present experiments, Merilo's correlation could not be used to assess the importance of channel orientation effects.

The effect of orientation (i.e. horizontal vs vertical flow) on CHF was found to be negligible. Merilo [3], Groeneveld [5] and Zeigarnik [6] noted that the limit, above which the effect of orientation on CHF is negligible, is between 3.0 and 4.5 Mg m^{-2} s^{-1}. However, the present data indicate that this limit is no more than 0.63 Mg m^{-2} s^{-1} at 1.6 MPa. The differences in the above mass velocity limits imply that it may be dependent on flow parameters such as the exit pressure and subcooling. Two experimental observations demonstrated the negligible influence of orientation effects: (1) the CHF occurred simultaneously around the periphery of the test section; and (2) the circumferential wall temperature variations were small. The small influence of orientation effects on the present data appear to be due to: (1) high Re_l (10^5), (2) high inlet subcooling (> 180°C), (3) moderate (as compared to that in ref. [4]) L/D (115), (4) increased effects of surface tension when compared to buoyancy and viscous forces (Bond number = 23.7 and the Ohnesorge number = 2.3×10^{-4}) at higher pressures, and (5) the low value of the mixed convection parameter (or high Froude number), Gr/Re_l^2 ($\leqslant 1.5 \times 10^{-5}$).

4. CONCLUSIONS

Flow boiling experiments were performed using horizontal, uniformly-heated, copper tubes. A flow loop was developed and used to produce flow boiling heat transfer and CHF data, which can be used for high heat flux removal applications. In the present experiments, the mass velocity varied from 0.63 to 3.5 Mg m^{-2} s^{-1}, and the resulting CHF (for both annular and subcooled flows) varied from 150 to 425 W cm^{-2}. Axial variations in the Nusselt number were measured at several values of mass velocity. At 1.7 Mg m^{-2} s^{-1}, Nu was found to vary from approx. 120 (h_i = 0.7 W cm^{-2} K^{-1}) at the inlet of the coolant channel to 500 (3.2 W cm^{-2} K^{-1}) at the exit. For an exit pressure of 1.6 MPa and inlet temperature of 20°C, the limits of the transition from annular to subcooled CHF were measured and found to be 1.03 and 1.26 Mg m^{-2} s^{-1}.

The flow boiling CHF data were compared with three correlations (developed by Bowring, Katto and Merilo) for L/D = 115.6, and D = 1.02 cm. Above 5 Mg m^{-2} s^{-1}, the CHF is bounded below and above by Bowring's and Katto's correlations, respectively. Below 5 Mg m^{-2} s^{-1}, all the correlations overpredicted the CHF. For an exit pressure of 1.6 MPa, the effect of channel orientation was negligible for a mass velocity greater than 0.6 Mg m^{-2} s^{-1}. This limit on the mass velocity was below previous observations [5, 6].

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Transient conduction in a three-dimensional composite slab

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INTRODUCTION

IN A RECENT issue of this journal, Salt [1, 2] examined in two consecutive papers the eigenvalues and eigenfunctions of the eigenvalue problem associated with the solution of transient heat conduction in a two-dimensional composite slab having three of its boundaries insulated with the fourth boundary parallel to the layers subjected to a uniform temperature. By considering the physical significance of the eigenvalues it was concluded that:

> while it is possible to have a temperature variation across a fully insulated composite slab with no temperature variation along it, it is impossible to have temperature variation along the slab without having temperature variation across it.

In the present brief note we analyze the three-dimensional version of the problem considered by Salt [1, 2] and show that similar results and conclusions are readily obtainable as a very special case of the general solutions given in refs. [3, 4]. Furthermore, the recently developed sign-count method [4–6] is applicable for the solution of the two- or three-dimensional eigenvalue problems associated with heat conduction in multilayer slabs.

STATEMENT OF THE PROBLEM

We consider three-dimensional transient conduction in a nonhomogeneous finite medium in which the thermal and physical properties vary only in the z-direction. The mathematical formulation of the problem is taken as

$$w(z)\frac{\partial T(x,y,z)}{\partial t} = k(z)\frac{\partial^2 T}{\partial x^2} + k(z)\frac{\partial^2 T}{\partial y^2} + \frac{\partial}{\partial z}\left\{k(z)\frac{\partial T}{\partial z}\right\}, \quad \text{in} \quad 0 < x < a,$$

$$0 < y < b, \quad 0 < z < c, \quad \text{for} \quad t > 0 \quad \text{(1a)}$$

subject to the boundary conditions

$$\frac{\partial T(0,y,z,t)}{\partial x} = 0, \quad \frac{\partial T(a,y,z,t)}{\partial x} = 0 \quad \text{(1b, c)}$$

$$\frac{\partial T(x,0,z,t)}{\partial y} = 0, \quad \frac{\partial T(x,b,z,t)}{\partial y} = 0 \quad \text{(1d, e)}$$

$$\frac{\partial T(x,y,0,t)}{\partial z} = 0, \quad T(x,y,c,t) = 0 \quad \text{(1f, g)}$$

and the initial condition

$$T(x,y,z,0) = f(x,y,z), \quad \text{(1h)}$$

where $w(z) = c(z)\rho(z)$, the specific heat $c(z)$, the density $\rho(z)$ and the thermal conductivity $k(z)$ are known function of the z coordinate.

Clearly, the problem (1) describes as a special case a multilayer composite slab when $w(z)$ and $k(z)$ are chosen as stepwise functions in the z-direction, that is

$$k(z) = k_k, \quad w(z) = w_k \quad \text{for}$$

$$z_{k-1} < z < z_k, \quad k = 1, 2, \ldots, n. \quad (2)$$

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NOMENCLATURE

a, b, c	width, length and thickness of the slab
$f(x, y, z)$	initial temperature distribution
$k(z)$	known function of the z coordinate
l, m, n	integers
t	time
$T(x, y, z, t)$	temperature in the slab
x, y	positions along the slab
z	position across the slab
X, Y, Z	eigenfunctions defined by equations (5), (6) and (7)
$w(z)$	known function of the z coordinate.

Greek symbols

λ_l, ν_m	longitudinal eigenvalues
μ_{lmn}	eigenvalues
$\psi(x, y, z)$	eigenfunctions.