the size of the microchannel also affecting the transition from one flow regime to another.

CONCLUSION

The single-phase forced convective heat transfer characteristics of water flowing through microchannels with a rectangular cross-section were investigated experimentally. The experimental results indicate that the liquid convection characteristics are quite different from those observed in conventionally sized channels. The conversions of flow modes and heat transfer regimes are initiated at much lower *Re* than for the conventional situation. The transition from the laminar flow regime occurs at *Re* of approximately 300, and the transition to the fully turbulent flow regime at about $Re = 1000$. The transitions are influenced by liquid temperature, velocity and microchannel size.

Transition and laminar heat transfer in microchannels are significantly different from those of liquid flowing through conventionally sized channels, and are considerably more complicated. The range of the transition zone, and the heat transfer characteristics of both the transition and laminar flow regimes, are strongly affected by the liquid temperature, liquid velocity and microchannel size, and, hence, are not only determined by *Re*. Evidence was presented to support the existence of an optimum channel size in terms of the forced convective flow heat transfer of a single-phase liquid flowing in a rectangular microchannel.

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Pergamon

Int. J. Heat Mass Transfer. Vol. 38, No. 4, pp. 758–760, 1995

0017-9310/95 $9.50+0.00

Boiling curve correlation for subcooled flow boiling

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(*Received* 2 *July* 1993 *and in final form* 25 *May* 1994)

1. INTRODUCTION

A precise knowledge of the subcooled flow boiling curve is essential in many engineering applications, which include research fission and fusion reactor components, high-power synchrotron and optical components, and advanced electronic components. Such examples are characterized as high heat flux (HHF) applications, which can be accommodated by few other means except subcooled flow boiling. Accurate subcooled flow boiling conditions are usually represented by the boiling curve, which describes the relationship between the applied heat flux and the wall temperature or wall superheat, and hence the heat transfer coefficient for the given flow conditions. Complete and accurate representation of this curve for HHF applications requires the identification and characterization of various flow regimes and transition boundaries. Although much work in characterizing the boiling curve at low heat flux levels has been completed, there are still many uncertainties and inaccuracies in HHF applications.

The objective of this work is to improve the present ability to predict local (axial) heat transfer in the subcooled flow

NOMENCLATURE

Bo	boiling number, q''/Gi_{fg}	q''	heat flux [W m^{-2}]
D	inside diameter [m]	St	Stanton number [$Nu\ Re^{-1}\ Pr^{-1}$]
G	mass velocity [kg m^{-2} s^{-1}]	$T_b(Z)$	local bulk temperature [°C]
h	heat transfer coefficient [W m^{-2} °C^{-1}]	T_{sat}	saturation temperature [°C]
h_{sp}	single-phase heat transfer coefficient [W m^{-2} °C^{-1}]	$T_w(Z)$	local wall temperature [°C]
		ΔT_{sat}	wall superheat, $(T_w - T_{sat})$ [°C]
i_{fg}	latent heat of vaporization [J kg^{-1}]	ΔT_{sub}	subcooling, $(T_{sat} - T_b)$ [°C]
L	heated length of channel [m]	x	quality
Nu	Nusselt number	x^*	quality at the location where $T_w = T_{sat}$ [5]
P_{exit}	exit pressure [MPa]	Z	axial coordinate [m].
Pr	Prandtl number		

boiling regime for the case of uniformly heated coolant channels operating anywhere between the single phase (SP) to the fully developed boiling (FDB) regimes. The present results will be useful for both heat transfer research and industrial design. For example, the composite subcooled flow boiling correlation discussed below may be applicable to any subcooled flow and any fluid, as long as graviational effects are not important; i.e. when the Froude number, $Fr = G^2/g\rho_l^2 D$, is greater than 50.0. Later refinements may result in the application of the results to non-uniformly heated geometries.

2. MODEL DEVELOPMENT

There have been many investigations of subcooled boiling [1–16], and there have been many correlations given for each regime in the subcooled nucleate boiling region. Using selections from this previous work, an *initial* composite nucleate subcooled boiling model [10] was proposed. Petuhkov's [15], Shah's [16], and Kandlikar's [5] correlations were essential in the development of the initial model.

The present work focuses on an approach to improve the initial model. The present model is called the modified model and is based on modification of the "initial" model. Both models are based on improved predictions in the partial nucleate boiling (PB) regime by using the following commonly used (e.g. Kandlikar [5]) interpolation function between the SP and FDB regimes:

$$q''_{PB} = a + b\Delta T^m_{sat} \tag{1}$$

where q'' is the heat flux and ΔT_{sat} is the wall superheat. The conditions for determining a, b, and m are

$$\text{(i)}\quad q''_{PB} = q''_{SP} \quad \text{when} \quad T_W = T_{sat} \tag{2}$$

$$\text{(ii)}\quad q''_{PB} = q''_{OFDB} \quad \text{when} \quad \Delta T_{sat,PB} = \Delta T_{sat,OFDB} \tag{3}$$

and

$$\text{(iii)}\quad \frac{\partial q''_{PB}}{\partial \Delta T_{sat}} = \frac{\partial q''_{OFDB}}{\partial \Delta T_{sat}} \quad \text{at OFDB} \tag{4}$$

where OFDB represents the onset of fully developed boiling.

These conditions, when applied to equation (1), result in the following new forms, as compared to the form given in refs. [5, 10], for the parameters a, b, and m:

$$a = h_{SP}(T_W = T_{sat})\Delta T_{sub} \tag{5}$$

$$b = \frac{q''_{OFDB} - a}{\Delta T^m_{sat,OFDB}} \tag{6}$$

$$m = \frac{\varepsilon \Delta T_{sat,OFDB}}{q''_{OFDB} - a} \tag{7}$$

$$\varepsilon = \left(\frac{h_{SP}}{F}\right)_{OFDB}\left[1 - h_{SP}\frac{(T_W - T_b)g_1}{F^2 f_1^2}\right]^{-1}_{OFDB} \tag{8}$$

$$F = \left[\frac{1}{f_1(B_0)} + X\right], \quad X = \frac{x}{x^*} \tag{9}$$

$$x^* = -\frac{q''\,c_{pc}}{h_{sp} i_{lg}} = -\frac{Bo}{St} \tag{10}$$

$$g_1 = \frac{\partial f_1}{\partial q''} = \begin{cases} 115 Bo^{0.5}_{OFDB}\dfrac{1}{q''_{OFDB}} & \text{for} \quad Bo > 3.0\times 10^{-5} \\ 23 Bo^{0.5}_{OFDB}\dfrac{1}{q''_{OFDB}} & \text{for} \quad Bo \leqslant 3.0\times 10^{-5} \end{cases} \tag{11}$$

and f_1 was given by Shah [16]. Notice again from the above that m, a, and b are functions of q'' but no assumptions or curve fits were needed to adjust these parameters for an optimal data fit. In the above, all thermophysical properties should be evaluated at the local film temperature. This correlation was intended to increase the magnitude of the heat transfer coefficient relative to the values predicted by the "initial" model [10]. In addition, this modified correlation provides a better approximation for the asymptotic limit for the partial nucleate boiling region as ΔT_{sat} decreases, and does not require prediction of the onset of nucleate boiling. The onset of fully developed boiling was evaluated in the usual manner, as suggested by Forster and Grief [13], and requires $q''_{OFDB} = 1.4q''_D$, where q''_D is the heat flux at the intersection of single-phase and fully developed boiling curves.

3. RESULTS

Flow boiling predictions were made of the local (axial) heat transfer coefficient for water data taken from Boyd [11, 12]. The range of flow parameters and the comparison between the predicted and measured local (axial) heat transfer coefficient are shown in Fig. 1.

Figure 1 shows comparisons of predictions with the data near the heated channel exit (Z = 28.66 cm), the heated midsection (Z = 14.59 cm), and the inlet (Z = 0.317 cm) for exit pressures of 1.66 and 0.77 MPa. In each case, comparisons with the data are encouraging. Using 185 data points, the "modified" model had the best predictions at P_{exit} = 1.66 MPa, with an overall percent standard deviation of 12.5% compared to 13.7% for the "initial" model. However, at a 0.77 MPa exit pressure, the overall percent standard deviation increased to 19.0% for the "modified" model, and that for the "initial" model increased to 18.6% for 169 data points. For most cases, the predictions were best at the channel exit (i.e. $Z = Z3$ = 28.66 cm), and worse at other locations. The increased scatter in the comparison at

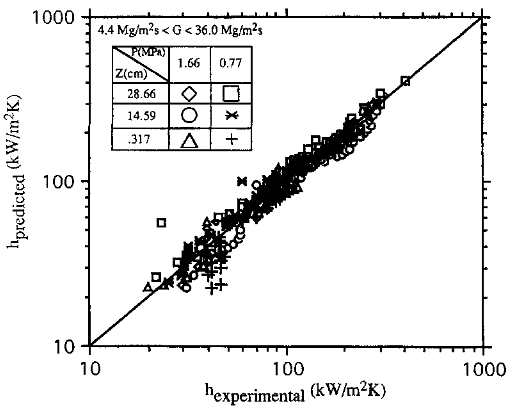

Fig. 1. Local (axial) subcooled flow boiling curve heat transfer coefficient comparisons between the modified correlation and Boyd's [11, 12] water data for a flow channel diameter of 3.0 mm, and a heated length-to-diameter ratio of 96.6.

low values of Z is clearly evident in the figure. As shown for upstream locations, the predictions were below the experimental data. This is due primarily to: (1) the heat transfer being thermally developing at upstream locations; and (2) the fact that the limiting condition used to match the single-phase and the partial boiling regions must be replaced with a better estimate for the asymptotic limit. An examination of whether a better estimate for the asymptotic limit will result in better predictions of the wall temperature at a given heat flux was made by comparing the "initial" and "modified" models with data in terms of the power (or heat flux) as a function of the wall temperature (or superheat). The results revealed that the "modified" model shifts the predictions upwards towards the data in all cases. This demonstrates that a more accurate asymptotic limit would improve the predictions in the partial nucleate boiling region. This improved correlation results in both the slope and the shape of the boiling curve changing, not only with the power level and flow regime, but also with the local bulk temperature, local quality, and mass velocity. When more of these local characteristics are included, the accuracy improves.

4. CONCLUSIONS

Like many previous correlations, the present model is an interpolation correlation. However, unlike many previous correlations, the present correlation requires no data fitting empirical parameters, which must be adjusted for an accurate data fit. Hence, no *a priori* assumptions were used for the value of parameters a, b, and m, whose form appears to be fluid-independent, but direct functions of q'', G, T_{sat}, D, L, and the thermophysical fluid properties. For the 365 data points used in the comparison, the percent standard deviations were 12.5% at 1.66 MPa and 19% at 0.77 MPa, respectively. This work will be expanded to include: (a) comparisons of the correlation with an expanded data base for different fluids (e.g. refs. [7, 9]); and (b) adapting the correlation to circumferential predictions for single-side heat flux boundary conditions.

Acknowledgements—This study was partially supported by the U.S. Nuclear Regulatory Commission and the Department of Energy under contracts NRC-04-91-364, and DE-FGO3-93ER54189, respectively. The authors are also appreciative to Shannon Holloway and Vivian Pope for graphics and typing support, respectively.

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