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A fractal analysis of subcooled flow boiling heat transfer

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Abstract

A fractal model for the subcooled flow boiling heat transfer is proposed in this paper. The analytical expressions for the subcooled flow boiling heat transfer are derived based on the fractal distribution of nucleation sites on boiling surfaces. The proposed fractal model for the subcooled flow boiling heat transfer is found to be a function of wall superheat, liquid subcooling, bulk velocity of fluid (or Reynolds number), fractal dimension, the minimum and maximum active cavity size, the contact angle and physical properties of fluid. No additional/new empirical constant is introduced, and the proposed model contains less empirical constants than the conventional models. The proposed model takes into account all the possible mechanisms for subcooled flow boiling heat transfer. The model predictions are compared with the existing experimental data, and fair agreement between the model predictions and experimental data is found for different bulk flow rates.

Keywords: Subcooled flow boiling; Fractal; Heat transfer

1. Introduction

The subcooled flow boiling is widely applied in engineering and technology. In the development of modern cooling systems such as internal combustion engines, power engineering, nuclear reactors and microprocessors, the increasing output of specific power combined with a most compact space and weight saving design leads to high thermal loads on heating surfaces. For such devices, a high coolant power is to be required with limitations on the available surface area and the mass flux of liquid coolant as well as the acceptable wall temperature, and a controlled operating mode to the boiling regime is desirable.

In subcooled flow boiling heat transfer it is generally recognized that there are three main mechanisms contributing to the wall heat flux (q_W): single-phase heat transfer (q_{sp}), micro-layer evaporation (q_{ev}), and the

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sensible heat of fluid that occupies the volume evacuated by a departing bubble (q_b). Thus the wall heat flux can be expressed as

$$q_W = q_{sp} + q_{ev} + q_b \tag{1}$$

Bowring (1962) obtained the relation between q_{ev} and q_b as

$$\varepsilon = q_b/q_{ev} \tag{2}$$

The evaporation heat flux (q_{ev}) was given by

$$q_{ev} = \rho_G h_L V_b f N_a \tag{3}$$

where V_b is the volume of single bubble at departure, f is the bubble departure frequency, N_a is the number of active sites per unit area of heated surfaces, h_L is latent heat of evaporation of liquid, and ρ_G is the vapor density. The ratio ε is found empirically, which was given by the following expression:

$$\varepsilon = 1 + 3.2\frac{\rho c_p \Delta T_{sub}}{\rho_G h_L} \quad 1 \times 10^5 \text{ Pa} \leqslant p \leqslant 9.5 \times 10^5 \text{ Pa} \tag{4a}$$

$$\varepsilon = 2.3 \quad 9.5 \times 10^5 \text{ Pa} \leqslant p \leqslant 50 \times 10^5 \text{ Pa} \tag{4b}$$

$$\varepsilon = 2.6 \quad p \geqslant 50 \times 10^5 \text{ Pa} \tag{4c}$$

where p is pressure, ρ is the liquid density, c_p is specific heat at constant pressure, ΔT_{sub} is the subcooling ($T_S - T_L$) of liquid, and T_S is the saturation temperature of liquid, T_L is the bulk temperature of liquid.

The single-phase heat transfer (q_{sp}) is given by Mikic and Rohsenow (1969) as

$$q_{sp} = (1 - KN_a\pi D_b^2)h(T_W - T_L) \tag{5}$$

where K is the proportional constant for bubble diameter of influence, which is taken to be 1.8 by Judd and Hwang (1976), D_b is bubble departure diameter, T_W is the wall temperature, and h is the single-phase heat transfer coefficient for forced convection, which can be calculated using the Dittus–Boelter equation (1930)

$$h = 0.023Re^{0.8}Pr^{0.4}\left(\frac{k_L}{D}\right) \tag{6}$$

where D is the inner diameter of flow channel, k_L is thermal conductivity of liquid, Pr is the Prandtl number of fluid defined by $Pr = v/\alpha$, Re is the Reynolds number defined by $Re = uD/v$, and v is kinematic viscosity of fluid, α is thermal diffusivity of fluid, u is the bulk velocity of fluid.

As discussed by Basu et al. (2002, 2005a,b), a quantitative prediction of subcooled flow boiling heat flux from a superheated wall based on Eqs. (1)–(6) requires the knowledge of several additional empirical constants because each of the quantities D_b (or V_b), f and N_a contains several empirical constants, which usually have no physical meanings. On the other hand, the calculation of subcooled flow boiling heat transfer so far lacks the consensus as to which set of empirical constants is to be used since different authors used different correlations. Until now no united mechanistic model is available because boiling is a very complex and elusive process. From the earlier literature review of the available models for prediction of wall heat flux in flow boiling, it is evident that in most cases not all the mechanisms have been taken into account. Some studies ignored the contribution of heat transfer due to liquid circulation caused by bubbles disrupting the boundary layer and only considered q_{sp} and q_{ev} as the sum of the wall heat flux. The models by Larsen and Tong (1969), Ahmad (1970), Hancox and Nicol (1971), Maroti (1977), Lahey (1978), Chatoorgoon et al. (1992), Zeitoun (1994) fall into the above category. Most of them do not calculate q_{ev} directly, but indirectly by knowing q_W and calculating q_{sp}. In most studies some models were developed as a part of the modeling for void fraction, the independent validation of q_W partitioning has never been carried out though the overall model validation for void fraction prediction has been justified. Since most of these correlations were developed at high pressures and high velocity conditions, at low pressures the comparison on the above models with experimental data shows great discrepancies.

From the above brief review it is seen that a mechanistic model has not yet been developed, in which every component of wall heat flux should be determined independently. The modeling should be such that the