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A uniform correlation for predicting pool boiling heat transfer on plane surface with surface characteristics effect

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ABSTRACT

Based on analyzing a semi-analytical heat transfer model with both contact angle and surface roughness effects in the pool boiling, the present paper concluded that the heat transfer coefficient (HTC) could be expressed as a uniform function of wall superheat, solid–liquid contact angle, surface roughness, influence parameter of heating surface material and the fluid thermophysical properties. The comprehensive effects of surface characteristics are expressed for the first time in one correlation, and they are thoroughly discussed. An improved correlation which is similar to Rohsenow's correlation are proposed by the induction using the experimental data of 7 kinds of fluids (water, ethanol, CCl_4, acetone, *n*-hexane, R113, R141b). It is verified that the proposed correlation for predicting pool boiling heat transfer can be widely applied on the common plain surfaces without capillary structures under various pressures. These surfaces include ordinary metal, metal with coating and high thermal conductive nonmetal. It has a uniform correlation factor and fixed dimensionless parameter exponent, which will not vary with changing the surface–fluid combination. Its accuracy has satisfied the general engineering application requirements, which will offer a calculating basis for heat transfer engineering application.

1. Introduction

Nucleate pool boiling heat transfer is an important process in industrial and technical fields of power, metallurgy, petroleum, chemical and refrigeration. This heat transfer process can achieve a high heat transfer coefficient (HTC) while maintaining a low temperature difference. Previous studies mainly put forward the theoretical models, empirical and semi-empirical correlations for the boiling HTC and critical heat flux (CHF) [1–3] on some especial metal heated surfaces. The main influencing factors for HTC include saturation pressure, fluid physical properties, heat transfer surface properties (physical properties, size, thickness, surface treatment, micro-structure, etc.) and the interaction between the fluid, vapor and heat transfer surface (static solid–liquid contact angle (CA)) [4]. The comprehensive effect of these factors and the lack of experimental data make it difficult to establish a widely applicable model for predicting the HTC. If taking all these factors into consideration, the accuracy of the available correlations will be slightly inadequate.

Among the various influencing factors, the aspect of heat transfer surface causes four kinds of effects on the HTC; (1) material properties, especially the material thermal conductivity plays an important role on the unsteady-state heat transfer in nucleate boiling. However, this factor has less effect for the common industrial metal surface under steady-state heat transfer; (2) surface size, which may be ignored for common surfaces except for some extreme cases; (3) surface morphology, which mainly affects the active nucleation site density, and it can be expressed as a function of arithmetic mean roughness ($R_a < 10$ μm) for the common plain surface without special capillary structures [5]; (4) CA, which mainly affects the bubble departure frequency and the solid–liquid contact area. What's more, the general studies about the effect of surface characteristics on the CHF tend to mix the effects of roughness and CA together. However, increasing the roughness will reduce the CA, and their effects on HTC are opposite. Increasing roughness always enhances HTC, while reducing the CA always deteriorates HTC. Systematic theoretical and experimental research for the CA effect are still inadequate, thus a widely applicable correlation to predict the effect of CA on HTC does not exist yet. The present authors [6] previously proposed a predictive heat transfer model with both CA and surface roughness effects on the heated hydrophilic surfaces. Wherein, the microlayer area under the bubble is taken as a function of CA, so that the model can be applied to hydrophilic surfaces. Based on the above semi-theoretical model, the CA, the surface roughness as well as the

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Nomenclature

Ar	Archimedes number (–)
C_s	comprehensive effect parameter of heating surface (–)
C_f	correlation factor (–)
C_{sf}	surface–fluid combination factor (–)
c_p	specific heat capacity (J/kg/K)
D	diameter (m)
f	bubble departure frequency (1/s)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2/K)
h_{lv}	latent heat of evaporation (J/kg)
Ja	Jacob number (–)
k	thermal conductivity (W/m/K)
MAX	maximum
N_a	active nucleation site density (sites/m^2)
P	pressure (Pa)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
R_a	arithmetic mean roughness (μm)
R_{nd}	non-dimensional surface roughness parameter (–)
t	time (s)
T	temperature (K)
ΔT_{sat}	wall superheat, $\Delta T_{sat} = T_s - T_{sat}$ (K)

Greek symbol

α	thermal diffusivity (m^2/s)
γ	influence parameter of heating surface material (–)
θ	solid–liquid contact angle (°)
ν	kinematic viscosity of liquid (m^2/s)
ρ	density (kg/m^3)
$\Delta\rho$	$\Delta\rho = \rho_l - \rho_v$ (kg/m^3)
σ	surface tension (N/m)
ϕ	the proportion of microlayer area accounted for the projection area of bubble (–)
δ	maximum relative deviation

Subscripts

b	bubble
d	dryout
me	microlayer evaporation
r	re-formation
nc	natural convection
g	growth
w	wall
wi	waiting
s	solid surface
l	liquid
v	vapor
sat	saturation state

surface material are considered in this paper. In addition, thorough studies are carried out on the separate effect of these three factors. Common plain surfaces without capillary structures are taken as the study objects and used all over this article. These surfaces include ordinary metal, metal with coating and high thermal conductive nonmetal. Meanwhile, their surface roughnesses are generally below 3 μm and their capillary effect can be ignored. Through the unified induction of the saturated pool boiling data for 7 kinds of pure fluids under various saturated pressures, a uniform correlation for predicting pool boiling heat transfer on plane surface with surface characteristics effect is expected to be proposed. Moreover, it will offer a calculating basis for heat transfer engineering application.

2. Introduction and discussion of the semi-analytical pool boiling heat transfer model with surface characteristics effect

2.1. Introduction of the semi-analytical pool boiling heat transfer model [6]

Based on the semi-analytical model framework of Benjamin and Balakrishnan [7], the present authors previously proposed a predictive heat transfer model with both CA and surface roughness effects in the pool boiling [6]. Fig. 1 shows the schematic diagram of a growing bubble on heated common plain surface in this model. The bottom of the bubble consists of dryout region and microlayer region. After the bubble appears at the active nucleation site, the evaporating microlayer under the bubble will continually supply vapor for the bubble growth. The dryout region is the area delimited by the retreating contact line of the microlayer. The diameter of the dryout region increases with the bubble growth until the moment of bubble departure. Wherein, as already described in the reference [6,7], the total wall heat flux is shown as correlation (1), which is the sum of bubble growth heat flux and the turbulent natural convection heat flux. According to correlation (1), its three composition parts are shown as follows: (1) the latent heat q_{me} supplied for evaporating microlayer during bubble growth; (2) the heat q_r expended in re-formation of the thermal boundary layer after bubble departure; (3) the heat q_{nc} transferred by turbulent natural convection on the fraction of the heating surface which is not influenced by bubble departure. Where, t_g is the bubble growth time and t_{wi} is the waiting time for re-formation of the thermal boundary layer.

$$q_w = \frac{q_{me}t_g + q_r t_{wi}}{t_g + t_{wi}} + q_{nc} \qquad (1)$$

The latent heat q_{me} supplied for evaporating microlayer during bubble growth is shown in correlation (2) [6]. Where in, ϕ is the proportion of microlayer area accounted for the projection area of the bubble. For small CA (hydrophilic surface), ϕ is a function of θ as shown in correlation (3a) [8]. For the normal metal surface

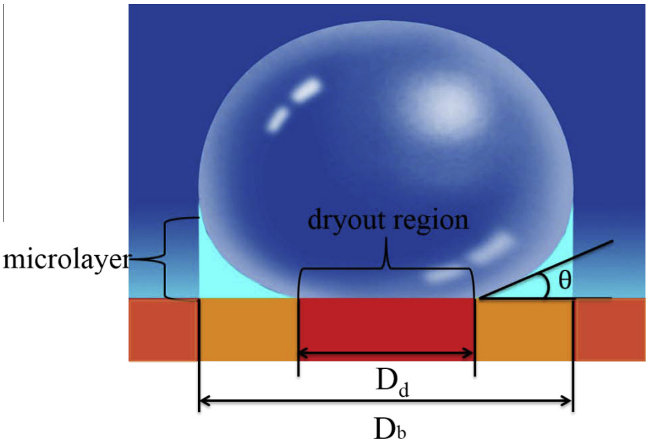

Fig. 1. Schematic diagram of a growing bubble on heated common plain surfaces.