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Critical heat flux prediction model for low quality flow boiling of water in vertical circular tube

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ABSTRACT

Based on the viewpoint of bubble crowding in near-wall bubble layer, a critical heat flux (CHF) prediction model was developed for low quality flow boiling of water in uniformly heated vertical circular tube under high pressure and low flow rate conditions. In this model, a CHF formula was derived from the conservation equations of mass, momentum and energy, where the transverse mass transport between the near-wall bubble layer and core is assumed to be limited. Taking account of the convective shear effect caused by the frictional drag on the wall-attached bubbles, the limiting transverse interchange of mass flux crossing the bubble layer–core interface was determined from the momentum balance equations. A new formula of bubble departure diameter considering the effect of buoyancy was put forward and used to solve the model with numerous other empirical correlations (e.g. bubble departure point, turbulence velocity profile, void fraction and so on). The model shows good agreements with the experimental data of uniformly heated circular tube. Based on this, the effects of flow variables such as pressure, mass flux and inlet subcooling on CHF prediction results were also discussed.

1. Introduction

Flow boiling in tubes and channels is one of the most complex phase-change processes encountered in industry applications. CHF phenomenon in flow boiling has attracted wide attention as it frequently occurs in many heat transfer equipments such as boilers, evaporators, water-cooled nuclear reactors, heat exchangers, and so on. Two major categories of CHF mechanisms exist for flow boiling: (a) departure from nucleate boiling (DNB) at subcooled or low quality conditions and (b) liquid film dryout (LFD) at high-quality conditions [1]. The physical mechanism of the LFD is relatively well understood and reliable theoretical models are also available, whereas the detailed aspects of the DNB mechanisms have not been fully clarified at present.

In the foretime, numerous researchers such as Galloway and Mudawar [2], Gersey and Mudawar [3], Chang et al. [4], Zhang et al. [5] and Celata et al. [6] conducted lots of experimental studies on DNB phenomena. These works evidently enhance our understanding on DNB mechanisms even though they are still insufficient and sometimes contradictory. With the continuous expansion of experimental data bases and applicable systems of interests, three kinds of empirical prediction methods have been developed: (a) empirical correlations, (b) look-up table methods, and (c) artificial neural network and other information processing techniques [1]. Some mechanism models, which seem to be dependent on flow and geometrical conditions, have been proposed based on visual observations and theoretical investigations. Among DNB mechanisms proposed so far, near-wall bubble crowding model is being considered to be one of the most promising models [1,7].

The near-wall bubble crowding model was first developed by Weisman and Pei [8] based on the existence of a bubble layer near the boiling surface at subcooled or low quality conditions. Turbulent interchange between the bubble layer and core was taken as the limiting mechanism in Weisman–Pei model, and the predicted results show good agreements with the experimental data of water under high pressure. Afterwards, the model was improved by Weisman and Ying [9] to fit in with the CHF prediction of fuel bundles in pressurized water reactor. A correction model proposed by Ying and Weisman [10] considered the radial distribution of void fraction in round tube. Chang and Lee [11] proposed a new CHF prediction model based on bubble crowding mechanism, in which momentum conservation equation was used to calculate the limiting interfacial mass flux transfer between the bubble layer and core. Lee et al. [12] modified this model by introducing some new modeling features. The above-mentioned model was further

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Nomenclature

A	cross section area, m^2
C_0	distribution parameter
c_{pf}	liquid specific heat, $J\ kg^{-1}\ K^{-1}$
D_b	bubble departure diameter, m
d_{in}	tube diameter, m
F_b	buoyancy, N
F_d	drag force, N
F_s	surface tension in flow direction, N
f	skin friction factor
G	mass flux, $kg\ m^{-2}\ s^{-1}$
G^*	limited transverse mass flux, $kg\ m^{-2}\ s^{-1}$
g	acceleration of gravity, $m^2\ s^{-1}$
h	specific enthalpy, $kJ\ kg^{-1}$
h_{fg}	latent heat, $kJ\ kg^{-1}$
k	thermal conductivity, $kW\ m^{-1}\ K^{-1}$
N_{bub}	the number of wall-attached bubbles
Pr	Prandtl number
p	pressure, MPa
q	heat flux, $kW\ m^{-2}$
Re	Reynolds number
u	velocity, $m\ s^{-1}$
u_{gj}	drift velocity, $m\ s^{-1}$
u^+	dimensionless velocity
x	quality
Y^+	dimensionless distance
z	axial location, m

Greek symbols

α	void fraction
β	blockage factor
δ_b	thickness of bubble layer, m
ξ	perimeter, m
η	fraction of cross-section
λ	skin friction coefficient (=0.25f)
μ	dynamic viscosity, $N\ s\ m^{-2}$
ρ	density, $kg\ m^{-3}$
σ	surface tension coefficient, $N\ m^{-1}$
τ	shear stress, $N\ m^{-2}$
τ_w	apparent wall shear stress, $N\ m^{-2}$
$\tau_{w,v}$	viscous shear stress on wall, $N\ m^{-2}$
Φ_{acc}	acceleration term

Subscript

avg	average
b	bubble layer
bc	from bubbly layer to core
c	core
cb	from core to bubble layer
cr	critical
d	bubble detachment point
eq	thermal equilibrium
f	saturated liquid
g	saturated vapor
i	interface between bubbly layer and core
l	liquid phase
NVG	initial point of net vapor generation
w	heated wall
2Φ	two phase

developed by Kwon and Chang [13], who compared the calculated results with the experimental data of water and freon. In the model, they take the departure diameter of single bubble as the thickness of bubble layer and the wall roughness at CHF conditions.

Accurate CHF prediction is the basis of thermal–hydraulic design for water-cooled nuclear reactors and power plant boilers, and existing CHF models are not fit for low flow rate resulting from some extreme operation conditions. Therefore, in allusion to high pressure and low flow velocity conditions, a CHF prediction model available for low quality flow boiling in uniformly heated vertical circular tubes was established based on bubble crowding mechanism in this paper, and the calculated results were compared with the experimental data of water.

2. Theoretical model

2.1. Physical mechanism and basis assumptions

In light of the viewpoint of near-wall bubble crowding, for forced convective boiling in uniformly heated vertical circular tubes, lots of bubbles are continuously generated on heated surface and form a thin bubble layer, and detach from the heated surface entering core while the bubble diameter reaches a limiting value (bubble departure diameter). With the augment of wall heat flux, the bubble generation rate is higher than the bubble detachment rate, which results in a congregation of bubbles in near-wall bubble layer. When the void fraction of the bubble layer reaches a critical value, severe bubble crowding prevents the bulk cold liquid from reaching the heated surface, which deteriorates boiling heat transfer and induces burnout in tubes. The limiting wall heat flux is defined as CHF and the heat transfer deterioration phenomenon is also called CHF phenomenon. On this basis, a mechanistic model is developed in this paper to predict the flow boiling CHF in uniformly heated vertical circular tube. The hypothetical flow boiling structure at CHF condition is considered in above-mentioned model, as shown in Fig. 1.

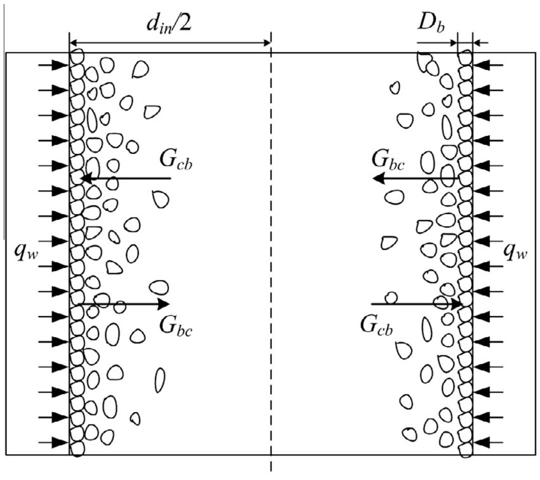

Fig. 1. Schematic representation of flow boiling structure at CHF condition.