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A one-dimensional semi-empirical model considering transition boiling effect for dispersed flow film boiling

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HIGHLIGHTS

- Seven heat transfer mechanisms are studied numerically by the model.
- A semi-empirical method is proposed to account for the transition boiling effect.
- The parametric effects on the heat transfer mechanisms are investigated.
- The thermal non-equilibrium phenomenon between vapor and droplets is investigated.

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ABSTRACT

The objective of this paper is to develop a one-dimensional semi-empirical model for the dispersed flow film boiling considering transition boiling effects. The proposed model consists of conservation equations, i.e., vapor mass, vapor energy, droplet mass and droplet momentum conservation, and a set of closure relations to address the interactions among wall, vapor and droplets. The results show that the transition boiling effect is of vital importance in the dispersed flow film boiling regime, since the flowing situation in the downstream would be influenced by the conditions in the upstream. In addition, the present paper, through evaluating the vapor temperature and the amount of heat transferred to droplets, investigates the thermal non-equilibrium phenomenon under different flowing conditions. Comparison of the wall temperature predictions with the 1394 experimental data in the literature, the present model ranging from system pressure of 30–140 bar, heat flux of 204–1837 kW/m^2 and mass flux of 380–5180 $kg/m^2 s$, shows very good agreement with RMS of 8.80% and standard deviation of 8.81%. Moreover, the model well depicts the thermal non-equilibrium phenomenon for the dispersed flow film boiling.

1. Introduction

Dispersed flow film boiling (DFFB), characterized with the liquid droplets dispersed in continuous vapor flow, is a specific heat transfer regime downstream of the dryout of liquid film of annular flow. The heat transfer in this regime is deteriorated as the liquid no longer covers the wall continuously. This leads to an increase of the wall temperature, which may damage the heating element. Therefore, the dispersed flow film boiling is of crucial importance for the safety of nuclear power plants. It may also be crucial for the design of a heat exchanger or in cryogenic process.

In this flow regime, the liquid droplets generated before dryout are dispersed in the vapor flow, and under certain circumstances, most of the heat diffused from the wall is first transferred to the vapor, then to the droplets. This may cause the thermal non-equilibrium phenomenon; that is, the heat transferred from vapor to droplets may be ineffective that most of the heat is used to increase the vapor temperature instead of evaporating the droplets. The wall temperature in the this region is bounded by two limiting cases: complete thermal equilibrium and complete thermal non-equilibrium (Collier and Thome, 1994). If the flow is in High Degree of Thermal Non-equilibrium (HDTN), that is, most of heat is absorbed by the vapor without transferring to the droplets, the vapor temperature will keep increasing; on the contrary, if the flow is in Low Degree of Thermal Non-equilibrium (LDTN), in which the heat can be easily transferred to the droplets, the vapor

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Nomenclature

DFFB	dispersed flow film boiling
HDTN	high degree of thermal non-equilibrium
LDTN	low degree of thermal non-equilibrium
Bo	Boiling number $\frac{q''}{i_{lv}G}$
Cp	specific heat, J/kg K
D	tube diameter, m
G	mass flux, kg/m^2 s
g	gravitational constant, m/s^2
h	heat transfer coefficient, W/m^2 K
i_{lv}	heat of vaporization, J/kg
N	droplet number density, 1/m^3
$\dot{N}$	droplet flux ($\dot{N} = N \times u_d$), 1/m^2 s
Nu	Nusselt number $= \frac{hk}{D}$
P	pressure, bar
Pr	Prandtl number = $\frac{Cp\mu}{k}$
q	total heat transfer rate, W
q'	heat transfer rate per unit length, W/m
q''	heat flux, W/m^2
Re	Reynolds number = $\frac{\rho u D}{\mu}$
r	average radius
s	slip ratio
T	temperature, K
u	velocity, m/s
W	characteristic parameter of Gaussian distribution
We	Weber number, $We = \frac{\rho_v (u_v - u_d)^2 2r_d}{\sigma}$
x	quality
z	axial location, m

Greek symbols

α	void fraction
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscript

0	dryout
a	actual
BU	droplet break-up
cr	critical
conv	convection
cond	conduction
d	droplet
dry	dry contact
l	saturation liquid
max	the minimum film boiling location
v	vapor
w	wall
wd	wall to droplet
wv	wall to vapor
wet	wet contact
rad	radiation

temperature will remains at the same temperature. About a half century ago, Parker and Grosh (1961) reported the existence of dispersed droplets after the theoretical quality reaches unity, suggesting the possibility of vapor being superheated, while the droplets still remained in the tube without being fully-evaporated. Subsequently, Forslund and Rohsenow (1968) verified this phenomenon through comparison of the experimental data with the calculated results considering vapor superheat.

The dispersed flow film boiling can be further divided into two main heat transfer regimes: transition boiling and stable film boiling (Tong and Tang, 1997). Immediately after the dryout location is the transition boiling region, which is characterized by the intermittent contact of liquid droplets and intensive evaporation at the wall, resulting in mild increase in the wall temperature. Further downstream, as the wall temperature rises, the droplets no longer contact with the wall directly, the flow regime transits to the stable film boiling regime. With the presence of droplets, the wall temperature will decrease after it reaches a maximum value. It is because that, in the downstream, the increase in the vapor quality will lead to the increase in vapor velocity and, therefore, the increase in heat transfer coefficient.

Numerous methods for the prediction of dispersed flow film boiling heat transfer have been proposed. There are various empirical correlations in the literature, which used experimental data to correlate the heat transfer coefficient with the local flowing conditions (Groeneveld, 1975). Moreover, phenomenological models have also been proposed to estimate the vapor superheat and actual quality by simplify the interactions between vapor and droplets using an empirical vapor generation rate (Webb and Chen, 1982; Saha, 1980). However, due to the empiricism in the above mentioned methods, the validity of those methods are limited in the narrow range of the experimental data and may not be extrapolated. Another methodology, table look-up (Groeneveld et al., 2003; Nguyen and Moon, 2015), tabulates the heat transfer coefficient in the post-dryout region as a function of pressure, mass flux, quality and tube diameter for a wide range of flowing conditions. Nevertheless, the table look-up methods do not provide the detailed information such as droplet density or the interfacial heat transfer rate in the dispersed flow. Another method, the so-called mechanistic models, employs conservation equations to consider different heat transfer paths and the interactions between vapor and droplets, giving the physical interpretation of the dispersed flow film boiling including the droplet velocity, vapor quality and vapor superheat, etc. The method is first proposed by several reports published at Massachusetts Institute of Technology in 1960s. The most quoted model was proposed by Forslund and Rohsenow (1968). The follow-up studies presented detailed analysis focusing on the existence of dispersed droplets in the vapor flow (Varone and Rohsenow, 1986; Andreani and Yadigaroglu, 1994; Guo and Mishima, 2002; Meholic et al., 2015a,b; Iloeje, 1975; Jayanti and Valette, 2004).

Since the heat transfer mechanism in transition boiling region is quite different from that in stable film boiling region, the prediction method for transition boiling should be treated differently. Webb and Chen (1982) divided the post-dryout heat transfer into near-field and far field effects, and used the phenomenological method to estimate the vapor generation rate. However, the study only presented the predicted results in the stable film boiling region. Nguyen and Moon (2015) employed a correction factor, which is a function of Graetz number, wall superheat and vapor quality, expressed in the form of Gaussian density function to obtain the modified heat transfer coefficient for the developing regime from the fully-developed film boiling look-up tables. This method was able to estimate the wall temperature correctly. However, the methods can only provide the estimation of wall temperature without giving the detailed flowing information in the dispersed flow film boiling regime. As for the mechanistic model, Iloeje (1975) proposed a theoretical model considering two