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Heat transfer correlation for film boiling in vertical upward flow

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ABSTRACT

There is no heat transfer correlation available in the Inverted Slug Film Boiling (ISFB) regime. In this study, a new correlation for film boiling in a vertical channel is proposed using a semi-empirical model. This correlation is applicable in the Inverted Annular Film Boiling (IAFB) heat transfer regime as well as ISFB heat transfer regime. A semi-empirical model is developed to establish the functional dependence of the Nusselt number on various controlling parameters. Test data obtained from the transient reflood tests carried out in a full length 7 × 7 vertical Rod Bundle Heat Transfer (RBHT) facility are used to develop the correlation. The predicted Nusselt number agrees within 15% with the RBHT data set and other data set available in the literature. This heat transfer correlation is applicable up to a void fraction of 90%, i.e., both in the IAFB and ISFB regimes. The proposed correlation is also applicable to a tube geometry using a modified coefficient in the correlation with an error less than 10%.

1. Introduction

Film boiling heat transfer occurs in the post critical heat flux (CHF) regime. In film boiling, the vapor envelopes the heating surface completely, thus preventing direct liquid contact with the heating surface. When film boiling occurs in the presence of forced convective flow in tubes or channels, it is referred to as flow film boiling. The latter is further categorized into two different flow regimes, namely, Inverted Annular Film Boiling (IAFB) and Dispersed Flow Film Boiling (DFFB) depending upon the void fraction. When the void fraction is less than 0.5 or so [1–3], the flow regime is known as IAFB, and known as DFFB when the void fraction is larger than 0.9 [4,2]. In DFFB, the void fraction can be close to unity and liquid is present in the form of dispersed droplets. When the void fraction range is between 0.5 and 0.9, the heat transfer regime is called Inverted Slug Film Boiling (ISFB).

The IAFB heat transfer is characterized by a continuous liquid core enveloped by a vapor film separating it from the heated wall downstream of the quench front. The heat transfer takes place from the wall to the vapor and then to the interface by convection, also some heat is transferred from wall to interface by radiation. As a result of continuous vaporization of liquid in the IAFB regime, higher void fraction and higher vapor flow cause breakup of the liquid core into slugs thus resulting in the transition region known as Inverted Slug Film Boiling (ISFB) regime. This regime contains liquid slugs along with droplets. Further downstream, liquid slugs breakup into droplets and the void fraction increases significantly, leading to a droplet flow regime known as DFFB.

The IAFB regime finds importance in safety analysis of nuclear reactors during Loss-of-Coolant Accidents (LOCA) for Pressurized Water Reactors and during the transient operation of Boiling Water Reactors. This flow regime is also observed in other areas of engineering such as cooling of rocket engines, hydrogen-fueled automobiles, quenching of metals, and cryogenic applications.

1.1. Film boiling models

Film boiling has been extensively studied by many researchers in the past. Bromley [5] presented one of the earliest models for pool film boiling on external surfaces based on Nusselt's film condensation theory and using experimental data on horizontal tubes. The heat transfer coefficient was expressed as

$$h = C\left[\frac{\tilde{h}_{fg} g \rho_g k_g^3 (\rho_l - \rho_g)}{\Delta T \mu_g D}\right]^{1/4}, \tag{1}$$

where $\tilde{h}_{fg}$ is the modified latent heat of vaporization given by

$$\tilde{h}_{fg} = h_{fg} + 0.5 c_{p,g} (T_W - T_{sat}). \tag{2}$$

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Nomenclature

A	constant
c_p	specific heat
C	constant
D	diameter
D_h	hydraulic diameter
f	friction coefficient
g	acceleration due to gravity
G	mass flux
h	heat transfer coefficient
$\hbar$	enthalpy
$\hbar_{fg}$	latent heat of vaporization
Ja	Jakob number
k	thermal conductivity
L	length
L_c	characteristic length scale
m	exponent
$\dot{m}$	mass flow rate
n	exponent
Nu	Nusselt number
p	pressure
P	perimeter
Pr	Prandtl number
q	exponent
q''	heat flux
Re	Reynolds number
T	temperature
u	velocity
y^+	non-dimensional distance
v	specific volume
z	length in flow direction

Greek letters

α	void fraction
δ	vapor film thickness
δ^*, δ^+	non-dimensional vapor film thickness
$\Delta()$	difference of ()
ϵ	emissivity
Φ	two-phase friction multiplier
λ_c	critical wave length
μ	dynamic viscosity
ν	kinematic viscosity
ν_t	turbulent viscosity
ρ	density
σ	Stefan–Boltzmann constant
τ	shear stress

Subscripts

g	gas or vapor phase
exp	experimental
i	interface
l	liquid phase
QF	quench front
r	radiation
sat	saturation
sub	subcooling
sup	superheat
v	vapor
w	wall

Bromley [5] model which is applicable for saturated film boiling in a liquid pool, does not account for liquid subcooling. Bromley et. al. [6] also studied film boiling with forced upward convection over horizontal tubes. The effect of convection was found to be important for Froude number $\left(u/\sqrt{gD}\right) > 2$.

Since then many analytical and experimental work has been carried out for film boiling on flat plate for both horizontal as well as vertical orientation. A boundary layer type analysis was carried out by Koh [7] for film boiling on an isothermal vertical surface in a liquid pool using the similarity method. Frederking [8] presented an integral analysis for natural convection film boiling. The effect of subcooling on laminar film boiling has been discussed by Sparrow and Cess [9]. The process of saturated film boiling on a vertical surface was studied experimentally by Suryanarayana and Merte [10]. The heat transfer coefficient was found to decrease immediately downstream of the leading edge of the film due to film growth, but further downstream the heat transfer coefficient increases due to interfacial disturbances. Bui and Dhir [11] theoretically and experimentally investigated the natural convection saturated film boiling on a vertical surface. Vijaykumar and Dhir [12] studied subcooled pool film boiling on a vertical surface. The heat transfer coefficient was found to decrease from the leading edge and found to be dependent on the degree of subcooling. Results obtained from their analysis were found to compare well with the experimental data for a vertical surface but under-predicted the experimental results for a vertical cylinder. All of the studies mentioned above assumed a smooth interface between liquid and vapor and their results only agreed near the quench front.

Cess and Sparrow [13] analyzed the film boiling in a forced convection boundary layer flow on a horizontal flat plate. Meduri et al. [14] experimentally investigated wall heat flux partitioning and interfacial heat transfer during the subcooled flow film boiling in a vertical surface. They proposed a correlation for the Nusselt number for the wavy interface region. Their model accounts for the subcooling in the flow as well as the liquid flow effects. However, it cannot be applied near the quench front when the interface is smooth. This model fails to predict film boiling in a cylindrical geometry [15].

The works discussed so far are for flat plate geometries. Furthermore, researchers have investigated film boiling in tube and annulus outside the cylindrical rods. Dougall and Rohsenow [16] theoretically and experimentally investigated film boiling in a vertical tube. Their analyses using turbulent integral method yielded the following expression for the Nusselt number

$$Nu = \frac{0.794\left[\frac{\rho_g(\rho_l-\rho_g)gD^3}{\mu_g^2}\right]^{\frac{1}{3}}(\delta^+)^{\frac{1}{3}}}{\int_0^{\delta^+}\frac{dy^+}{1+Pr\frac{\nu_t}{\nu_g}}}. \tag{3}$$

Dougall and Rohsenow's analysis was restricted to saturated liquid inlet temperatures. They assumed that interfacial shear was equal to wall shear stress. Due to this approximation, the effect of liquid flow is not accounted for in the model.

Greitzer and Abernathy [17] studied the film and transition boiling in a vertical tube using methanol flow. They identified the effect of vapor bulge at interface. Experimental work showed the effects of liquid velocity and subcooling in the flow, but they did not present any quantitative analysis. Using a scaling analysis, they proposed a relation for the heat transfer coefficient. However, this model is restricted to natural convection saturated film boiling. Sudo [18] investigated film boiling in a single rod experiment