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A critical heat flux model for saturated flow boiling on the downward curved heated surface

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ABSTRACT

The critical heat flux (CHF) distribution on the outer surface of the lower head is a crucial parameter to assess the coolability limits of the in-vessel retention strategy through external reactor vessel cooling. Several CHF correlations concerning the orientation angle of heated wall have been proposed while the theoretical analysis is relatively insufficient. Based on the liquid microlayer dryout mechanism, a theoretical CHF model for the saturated flow boiling on the downward curved heated surface has been proposed in this work. With a thorough analysis of the vapor blanket behavior in the near-wall region, the effects of the mass velocity and orientation angle of the heated wall on the CHF are considered in present model. The well agreement between the predicted CHF and the experimental data suggests the validity and applicability of present CHF model to assess the CHF limits on the outer surface of the lower head under in-vessel retention.

1. Introduction

The in-vessel retention (IVR) through external reactor vessel cooling (ERVC) under the core degradation condition is considered as an effective severe accident management strategy, which has been adopted in several advanced reactors (Rempe et al., 2008), i.e. AP1000, Hualong One, APR1400 etc. The CHF distribution on the outer surface of the lower head of reactor pressure vessel (RPV) is the crucial parameter to assess the coolability limits of the ERVC under the in-vessel retention condition.

Dinh et al. (2003) conducted a series of experiments to investigate CHF limits along the outer surface of hemispherical vessel to support the IVR design of AP600/1000 for certification. A two-dimensional full-scale facility was established and several modifications of the flow path were proposed during the experiments. The effect of mass flow rate on CHF limits on the top region of lower head of RPV considered as the most severe position under the core degradation condition were studied by Yong et al. (2005), Park et al. (2013) There were also some experiments performed by Cheung et al. (1999), Yang et al. (2005) Noh and Suh (2013) to investigate the CHF distribution on the outer surface of hemispherical vessel on the scaled three-dimensional facility. In general, the results from those experiments indicated that CHF would increase with the increasing orientation angle of the heated surface. Some CHF correlations concerning the orientation angle have been proposed while a theoretical analysis suitable for the flow boiling crisis in this situation is insufficient.

Haramura and Katto (1983) proposed a hydrodynamic CHF model for the nucleate boiling considering the liquid layer between the vapor blanket and heated wall. The CHF would occur when the liquid layer evaporates away during the hovering time of vapor blanket. Haramura and Katto (1983) pointed out that liquid sublayer dryout mechanism in this model is suitable for both the pooling boiling and forced flow boiling. Recent experimental studies by Theofanous et al. (2002); Ono and Sakashita (2009) strongly proved that a liquid microlayer would exist between the heated wall and vapor blanket in the high heat flux nucleate boiling. The rupture of the liquid microlayer would leads to a sudden rise of the wall temperature and the occurrence of boiling crisis.

Based on the liquid sublayer dryout mechanism Lee and Mudawar (1988) developed a mechanistic CHF model for the vertical subcooled flow at high pressure and high mass velocity. The parametric trends of CHF were explored with respect to mass velocity, pressure etc. Following the same principle Katto (1992) developed a physical CHF model for the subcooled flow boiling in the vertical channel covering the range of pressure from 0.1 to 20 MPa. The velocity coefficient to link the vapor blanket velocity with that of two-phase flow was derived from CHF database containing various kinds of fluids. Celata et al. (1995) proposed an ana-

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Nomenclature

m	Mass flow rate (kg/s)
A	Area (m^2)
U	Velocity (m/s)
U_m	Liquid supplement Velocity (m/s)
U_{bml}	Velocity at central line of vapor (m/s)
q	Heat flux (kW/m^2)
h_{fg}	Latent heat (kJ/kg)
D	Diameter (m)
L_b	Length of vapor blanket (m)
F	Force (N)
g	Gravity (N/(m^{2}s))
C_D	Drag coefficient
y	Distance from wall (m)
G	Mass velocity (kg/(m^{2}s))
f	Frictional coefficient
Re	Reynolds

Greek symbols

δ	Thickness (m)
θ	Orientation angle
ρ	Density (m^3/s)
τ_w	Shear stress (Pa)
μ	Dynamic viscosity (Pa/s)
λ	Wavelength (m)
v	Velocity (m/s)
σ	Surface tension (N/m)

Subscript

l	Liquid
g	Steam
w	Wall
b	Bubble

lytical model where the thickness of liquid sublayer could be derived by subtracting the vapor blanket diameter from the thickness of the superheated layer with the hypothesis that the vapor blanket existed in the superheated layer in the near-wall region. Liu et al. (2000) pointed out that the two waves of the vapor blanket in the radial direction should be the same wavelength. Then the velocity of the vapor blanket could be derived from the expression of the two wavelengths.

For the saturated pool boiling on the outer surface of the hemispherical vessel Cheung and Haddad (1997) proposed a hydrodynamic CHF model considering the local dryout of microlayer beneath an elongated vapor blanket. The variation of CHF with the orientation angle of the heated surface has been well explained accounting for the accelerating vapor velocity in the direction parallel to the curved surface. In the flow boiling the behavior of vapor blanket and liquid microlayer would deeply influenced by the orientation angle of heated surface and mass velocity in flow channel. Since the liquid microlayer dryout model was mostly developed for the flow boiling in vertically channel, the necessary modification must be made to accommodate the downward curved heated surface.

In this work a theoretical model based on the liquid microlayer dryout mechanism for the CHF on the downward curved surface in saturated flow condition has been developed. The effects of the mass velocity and orientation angle of the heated wall are considered. The well agreement of the prediction results with the several sources of experimental CHF data suggests the validity of the CHF model.

2. Theoretical model of CHF

2.1. Description

The visual records from the subscale boundary layer boiling experiments by Haddad et al. (1995) revealed that a two-phase boundary layer would be induced on the outer surface of heated hemispherical vessel in the high heat flux boiling process. The vapor blanket beneath the heated wall in the two-phase boundary layer would prevent the direct cooling of the liquid from the bulk region. As shown in the Fig. 1, the presence of the liquid microlayer between the heated wall and vapor blanket could ensure an effective cooling and prevent the occurrence of the local dryout on the heated wall. When the liquid replenishment from the two-phase boundary layer could not make up the liquid film in microlayer consumed by evaporating, boiling crisis occurs and the wall heat flux would be the CHF limits Fig. 2.

From the vapor-liquid interface configuration shown in Fig. 1, the liquid replenishment rate to the liquid film in microlayer could be expressed as:

$$m_l = \rho_l \cdot A_l \cdot U_m \tag{1}$$

where m_l is the liquid replenishment rate, kg/s; ρ_l is the liquid density, kg/m^3; A_l is the cross section area of the liquid supplement path to microlayer, m^2; U_m is the liquid supplement velocity, m/s.

The evaporation rate of the liquid film in microlayer under saturated condition could be expressed as:

$$m_l = \frac{q_w \cdot A_w}{h_{fg}} \tag{2}$$

where m_l is the evaporation rate of the liquid film, kg/s; q_w is the wall heat flux, kw/m^2; A_w is the heated wall area covered by vapor blanket, m^2; h_{fg} is the latent heat of the liquid, kJ/kg.

As described earlier the wall heat flux would be the local CHF limits when the evaporation rate of the liquid film in microlayer exceeds the liquid supplement from two-phase region. Combined Eqs. (1) and (2), we can obtain the CHF expression as follows:

$$q_{CHF} = \frac{\rho_l h_{fg} \cdot A_l \cdot U_m}{A_w} \tag{3}$$

where q_{CHF} is the critical heat flux, kw/m^2.

As shown in Fig. 1, by setting the axial length of the vapor blanket to be L_b, the diameter of the vapor blanket to be D_b, the thickness of the liquid microlayer to be δ_l, the A_l and A_w could be further expressed as:

$$A_l = \delta_l \cdot D_b \tag{4}$$

$$A_w = L_b \cdot D_b \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (3), the CHF correlation could be expressed as:

$$q_{CHF} = \frac{\rho_l h_{fg} \cdot \delta_l \cdot U_m}{L_b} \tag{6}$$

From Eq. (6) it is clearly that in present model the thickness of liquid microlayer, liquid supplement velocity and axial length of the vapor blanket are the key variables to determine the CHF lim-