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Critical heat flux model on a downward facing surface for application to the IVR conditions

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ABSTRACT

A mechanistic model, which is widely applicable to the flow boiling regime, is developed to predict the critical heat flux (CHF) in the In-Vessel Retention (IVR) configuration. The model is based on five general equations describing the CHF mechanism and four primary CHF variables: vapor velocity, liquid velocity, microlayer thickness and the slug length. The CHF mechanism of liquid film dryout underneath the slug is considered. Velocities of vapor and liquid are determined by the Karman velocity distribution and the force balance between buoyancy and drag force. The microlayer thickness is defined by Cheung and Haddad (Cheung and Haddad, 1997) model, based on the Helmholtz instability for the vapor stem located in the microlayer. The slug length is postulated to be the critical Helmholtz wavelength. The solution is numerically obtained starting from seven scattered input parameters: mass flux, local quality, pressure, inclination angle, gap size, working fluid and heater material. In the model, four unknown constants are used for the premature CHF due to heater deformation, the minimum length of slug and the approximation of microlayer thickness and liquid velocity. To find the best-fitted values of the unknown constants, the URANIE code, developed by Commissariat à l'Energie Atomique (CEA), is used. The CHF predicted by the new model is compared with the integrated IVR-CHF database, including experimental data from KAIST, CEA (SULTAN experiments), UCSB (ULPU experiments) and MIT. Starting from 278 experimental data points, the CHF model is affected by a root-mean-square (RMS) error of 14.8%. The CHF predicted by the model is in good agreement with the experimental IVR-CHF database, except for the condition of high mass flux conditions ($> 500\,\mathrm{kg/m^2\,s}$) and low inclination angle ($< 16^\circ$). Further improvement of the model is suggested to cover this range and reduce the RMS error based on future worldwide experimental series.

1. Introduction

In the nuclear power plant, the In-Vessel Retention (IVR) is a mitigation strategy for severe accidents. The purpose of the IVR strategy is to remove the decay heat of the molten corium and protect the integrity of the reactor vessel. The reactor vessel is submerged in a kind of water pool and the decay heat, coming from molten corium relocated in the lower plenum, is removed by the cooling water. This latter rapidly becomes saturated, and vapor is generated. It makes a natural circulation. In this circumstance, the critical heat flux (CHF) is one of the most important criteria to evaluate thermal margin and determine the success or failure of the IVR strategy.

The CHF appears when the heat transfer coefficient on the wall is suddenly decreased because of the vapor film formation between cooling water and the wall. Several works were performed in the past, trying to predict this event. Several models are found in the literature focusing on particular test conditions: a pure water and a clean surface (copper and stainless steel) with the geometry of an upward surface in the pool boiling condition (Zuber, 1959; Haramura and Katto, 1983) and a tube in the flow boiling condition (Groenveld et al., 2006). The basic behavior of the vapor considered in the existing model and correlation is consistent with that in the IVR condition. However, different flow characteristics and other local phenomena can influence the occurrence of the CHF. The CHF in the IVR conditions is observed on a downward facing and curved surface with natural circulation flow and chemical phenomena. The complexity of the CHF understanding is due

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Abbreviations: CHF, critical heat flux; IVR, In-Vessel Retention; TH, thermal hydraulic; BA, boric acid; TSP, tri-sodium phosphate; SBLB, subscale boundary layer boiling; DI, de-ionized; RMS, root-mean-square

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Nomenclature

C_D	drag coefficient
C_{pL}	specific heat of liquid [kJ/kg·K]
D_B	thickness of vapor blanket [m]
D_h	hydraulic diameter [m]
G	mass flux [kg/m^2 s]
g	acceleration of gravity [m/s^2]
h_{fg}	latent heat of vaporization [kJ/kg]
l	length of the slug [m]
P	pressure [bar]
q''_{CHF}	critical heat flux [kW/m^2]
T_{sat}	saturation temperature [K]
u_l	local liquid velocity [m/s]
u_g	local vapor velocity [m/s]
u_m	liquid micro layer velocity [m/s]
w_{heater}	width of the heated test section [m]
w_s	width of slug [m]
x	thermodynamic quality
$[BA]$	concentration of boric acid [wt%]
$[TSP]$	concentration of TSP [wt%]

Greek Letters

α	void fraction
Δh_{sub}	subcooled enthalpy [kJ/kg]
ΔT_{in}	inlet subcooling [K]
δ_m	liquid film thickness [m]
θ	inclination angle [°]
λ	Helmholtz wavelength [m]
ρ_l	liquid density [kg/m^3]
ρ_g	vapor density [kg/m^3]
σ	surface tension [N/m]
μ_l	dynamic viscosity of liquid [μPa·s]

to the influence of several parameters. These parameters are presented in four groups:

(1) Natural circulation flow and TH conditions
(2) Characteristics of the injected cooling water
(3) The material of the reactor vessel outer surface
(4) Geometry of the reactor vessel lower head

The thermal hydraulic (TH) aspect is the first essential condition to be taken into account. The pressure, mass flux and exit quality are key variables to describe the general behaviors of the natural circulation flow. For the IVR condition, the pressure during accident conditions in the containment is higher than 1 bar (the normal operation), and less than 5 bar (the accident conditions), and the mass flux is less than 500 kg/m^2 s which is low in comparison with the general data range (0–8000 kg/m^2 s). The second point is the characteristic of cooling water containing boric acid (H_3BO_3) and tri-sodium phosphate (TSP, $Na_3PO_4 \cdot 12H_2O$) that is injected into the reactor cavity to achieve the IVR strategy. The third point is the material of the heated walls that play a major role in the delayed CHF (the reactor vessel is made of SA508 Grade 3 Class 1 in the U.S. and Korean types and 18MnD5 in the French type). Corrosion of the steel surface can be changed by the environment under accident conditions. The fourth point is the geometry of the IVR condition which has a downward facing curved surface (horizontal to vertical inclination) with the flow channel between the reactor vessel and insulation structure.

To investigate and evaluate the effect of the parameters, researchers in several organizations performed the CHF experiments and developed some own empirical correlations. El-Genk and Guo (1993) measured the CHF using a downward flat surface with various inclinations. They modified the CHF model for an upward surface with the coefficient regarding the inclination angle. In Pennsylvania State University, the reactor vessel lower head was three-dimensionally simulated by using the subscale boundary layer boiling (SBLB) facility (Cheung et al., 1997). Observing the basic phenomena on the heated surface, the CHF on a downward facing curved surface was theoretically studied (Cheung and Haddad, 1997). The Commissariat à l'Energie Atomique (CEA) investigated TH and geometric aspects, proposing the SULTAN experiments (Rouge, 1997; Rouge et al., 1998). The facility simulated the IVR conditions with flat surfaces characterized by different inclination angles. Based on their experimental data, an empirical correlation was finally developed. In Korea Advanced Institute of Science and Technology (KAIST), the CHF experiments (KAIST-IVRCHF) (Jeong et al., 2005; Park et al., 2013, 2014) using a downward facing curved surface were also conducted. Their facility simulated the IVR conditions on several scales, and the effects of the heater material and the working fluid were investigated. In University of California at Santa Barbara (UCSB), the ULPU experiments (Theofanous et al., 1994; Theofanous and Syri, 2001; Dinh et al., 2003) using a downward facing curved surface were conducted, and their simple correlation was also developed. In Massachusetts Institute of Technology (MIT), some experiments (MIT-IVRCHF) (Azizian et al., 2015; Shirvan and Azizian, 2015) were recently performed to study the effect of inclination angle and heater material on the CHF.

In this study, the experimental IVR-CHF database is increased based on the experimental works conducted by CEA, KAIST, UCSB and MIT, and the influence of all variables is investigated. Considering these core studies, the main purpose of this study is to better understand the CHF phenomenon and develop a semi-empirical model with wide applicability.

2. Background

In this paragraph, related phenomena and basic parameters are investigated, based on previous experimental works. The model should explain the phenomena and parameters. Limits of the existing model and correlations are investigated focusing on the parametric aspect. The predictabilities of the existing model and correlations are investigated comparing with the experimental data.

2.1. Parametric study

According to the analysis in the previous experimental works, a parametric study is performed. Based on the four issues with the CHF mentioned above, the following parameters are considered; for the TH parameters: (1) mass flux, (2) exit quality, (3) pressure, for the geometric parameters: (4) gap size, (5) inclination angle, and for the chemical parameters: (6) working fluid and (7) heater material.

2.1.1. TH parameters

In the most of flow boiling CHF experiments, the TH parameters are commonly studied, and the effects of the TH parameters are clearly investigated. For the IVR conditions, previous experimental works (Rouge, 1997; Jeong et al., 2005; Park et al., 2013, 2014; Theofanous et al., 1994; Theofanous and Syri, 2001; Dinh et al., 2003; Azizian et al., 2015; Shirvan and Azizian, 2015), also studied the effect of mass flux, exit quality, and pressure.

In the boiling regime of the IVR conditions (Fig. 1), the mass flux affects the liquid supply rate to the heated surface and the departure of a slug, which are necessary for the CHF occurrence. The sufficient liquid supply on the surface and the swift departure of the slug make the CHF higher. Therefore, the CHF is proportional to mass flux (Rouge,