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A modified force-balance model for prediction of bubble departure diameter in subcooled flow boiling

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HIGHLIGHTS

- Existing bubble departure models were tested against various experimental databases.
- General experimental trends were captured correctly but give large average errors.
- A modified bubble departure model is proposed and tested against these databases.

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ABSTRACT

Experimental data by Sugrue et al., Klausner et al., Zeng et al., Prodanovic et al., and Situ et al. for bubble departure diameter in subcooled flow boiling in a wide range of orientation angle, subcooling, heat flux, mass flux, and pressure conditions were used to assess the predictive accuracy of the mechanistic force-balance models of Klausner et al. and Yun et al. The results suggested that both models capture the experimental trends correctly, but exhibit large average errors and standard deviations, i.e. 85.5% (σ = 49.7%) and 43.9% (σ = 23.1%) for Klausner's and Yun's models, respectively. Since the cube of the bubble departure diameter is used in subcooled flow boiling heat transfer models, such errors are unacceptable, and underscore the need for greater accuracy in predictions. Therefore, the databases were used to (i) identify the dominant forces determining bubble departure at various operating conditions, and (ii) optimize the empirical coefficients describing those forces in Klausner's model. The modified model considerably lowers prediction error to 22.4% (σ = 19.9%) for all data considered. Application of the modified model is demonstrated for the subcooled flow boiling conditions present in the hot channel of a typical Pressurized Water Reactor (PWR).

1. Introduction

Understanding and predicting the complex phenomena involved in two-phase flow and boiling heat transfer is necessary for the efficient operation, safety, and development of light-water cooled reactors. In U.S. Pressurized Water Reactor (PWR) plants, subcooled flow boiling occurs in the hot fuel assemblies under normal operating conditions, and determines the margin to Critical Heat Flux (CHF) Kazimi and Todreas, 1990. Subcooled flow boiling also determines the rate at which corrosion products in solution in the coolant deposit on the surface of the zircaloy cladding, which can lead to localized corrosion and neutronic distortions (axial offset), and ultimately cladding failure.

The state-of-the-art simulation approach for nuclear systems with two-phase flow and heat transfer relies on CFD simulations implementing the Eulerian–Eulerian, two-fluid, six-equation model (Bestion and et al., 2009; In and Chun, 2009; Lo et al., 2011; Michta et al., 2011) with or without an interfacial area transport model (Ishii and Hibiki, 2006). Such approaches require closure relations for the phase-to-phase and wall-to-flow mass, momentum, and energy terms in the governing equations. Subcooled boiling heat transfer is captured by the wall-to-flow constitutive relation for energy. Examples of boiling heat transfer constitutive relations are the heat flux partitioning model of Kurul and Podowski (Kurul and Podowski, 1990), Kolev's bubble interaction model (Kolev, 2002), and the more recent hybrid numerical-empirical model of Sanna et al. Sanna et al. (2009).

All of these models require accurate knowledge of the bubble departure diameter. For example, in the partitioning heat flux model, heat removal by the boiling fluid is assumed to be through

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Nomenclature

D_b	bubble departure diameter
f_b	frequency of bubble departure
h_{fg}	latent heat of evaporation
n''	nucleation site density
q_c	condensation heat flux
q_e	evaporation heat flux
q_q	quenching heat flux
q_{tot}	total heat flux
ρ	density
θ	contact angle

Subscripts

A	advancing
R	receding
l	liquid phase
v	vapor phase

three contributions, (i) the latent heat of evaporation to form the bubbles (q''_e), (ii) heat expended in re-formation of the thermal boundary layer following bubble departure, or the so-called quenching heat flux (q''_q), and (iii) heat transferred to the liquid phase outside the zone of influence of the bubbles by convection (q''_c). The total boiling heat flux is then obtained as the sum of the three heat fluxes:

$$q''_{tot} = q''_e + q''_q + q''_c \tag{1}$$

The latent heat flux is often the dominant term in Eq. (1), and can be written as:

$$q''_e = \frac{\pi}{6} D_b^3 \rho_v h_{fg} f_b n'' \tag{2}$$

where D_b is the bubble departure diameter, f_b is the frequency of bubble departure, n'' is the nucleation site density, ρ_v and h_{fg} are the vapor density and latent heat of evaporation, respectively. The cubic dependence in Eq. (2) suggests that small uncertainties in the bubble departure diameter are greatly magnified in the heat transfer model leading to a deterioration in the accuracy of the overall CFD simulation. Thus, utilizing robust and accurate bubble departure models is key to the successful prediction of subcooled flow boiling heat transfer.

2. Previous work and motivation

A plethora of experimental and analytical studies have investigated various fluids and channel geometries, as well as pressure, degree of subcooling, and flow rate ranges, to develop and validate models predicting bubble parameters, particularly bubble size at detachment (Yeoh and Tu, 2005; Yun et al., 2010, 2012; Wu et al., 2008; Chen et al., 2009).

The most commonly-used mechanistic bubble departure model for flow boiling in these investigations is that of Klausner et al. Klausner et al. (1993), which is based on a balance of forces for the bubble throughout its growth cycle from a single nucleation site. Klausner postulates that at the time of departure the balance is broken and the bubble can either liftoff (non-zero net force perpendicular to the wall) or slide along the wall (non-zero net force tangential to the wall). This model was originally calibrated to predict bubble departure size for horizontal flow of refrigerant R113 under atmospheric pressure conditions, for heat fluxes of 11–26 kW/m^2 and mass fluxes of 112–287 kg/m^{2}s.

Subsequently, Zeng et al. Zeng et al. (1993) modified and expanded the applicability of the Klausner's model for both horizontal and vertical channels under pool and flow boiling conditions with refrigerant R113, with pressure ranging from 20 to 280 kPa; Jakob number between 4 and 869; and gravity 1 to 0.014 g. Situ et al. Situ et al. (2005) and Yeoh et al. Yeoh and Tu (2005), Yeoh et al. (2008) extended the model to flow conditions of water for forced convective boiling. Specifically, Situ et al. proposed a model based on experimental results from a BWR-scaled vertical upward annular channel for atmospheric pressure conditions. The model by Situ et al. yielded an average relative deviation of ±35.2% with respect to these data. Yeoh et al. incorporated an improved wall heat flux partitioning model and coupled this with the mechanistic force balance model to extend its applicability to a wider range of wall heat fluxes and flow conditions.

Yun et al. improved the model's predictive capability by incorporating a bubble condensation model as well as evaluating the model for a wider range of pressure, temperature, and flow rates (Yun et al., 2010, 2012). The original model of Klausner et al. did not consider vapor condensation around the bubble heat, an effect that can limit bubble growth for subcooled boiling conditions. Yun et al. introduced a bubble condensation model to take into account the liquid subcooling effect on a growing bubble, making the model applicable to a wider range of liquid temperatures. This model also incorporated a relationship between the contact diameter of the bubble on the wall and its departure diameter, which is valid for high mass flux and high pressure steam/water flows. However, it is worth noting that the database used to calibrate Yun et al.'s model did not include any data for water, i.e. calibration was based entirely on the DEBORA (Garnier et al., 2001; Krepper and Rzehak, 2011) database, which is for refrigerant R12.

Several experimental databases also exist that could be used for validation of these bubble departure diameter models, i.e. the original database by Klausner et al. for horizontal flow of saturated refrigerant R113 (Klausner et al., 1993); the database of Zeng at al. for flow boiling of refrigerant R113 (Zeng et al., 1993); the database of Situ et al. for upward vertical flow boiling of water (Situ et al., 2005); the DEBORA database for high mass flux data of refrigerant R12 in a vertical annular channel which was used by Yun et al. for their own modification of Klausner's et al. Garnier et al. (2001), Krepper and Rzehak (2011); and the Prodanovic et al. database for vertical subcooled flow boiling of water at low pressures and low flow rates (Prodanovic et al., 2001; Bibeau and Salcudean, 1994). All of these studies looked at bubble departure for either vertical or horizontal channels.

Most recently, Sugrue et al. Sugrue et al. (2014) investigated the impact of orientation angle of the channel on bubble departure diameter. In high mass flux situations, which are typical of full-power reactor operation, the Froude number is high, and thus, the effects of buoyancy forces and channel orientation can be neglected (Celata and Mariani, 1999). However, when the mass flux is lower, buoyancy forces and channel orientation can be significant in determining the bubble departure diameter. This is the case in applications such as current reactors under off-normal operations (e.g., natural circulation following loss of flow, or decay heat removal from the vessel surface during severe accidents, the so-called in-vessel retention), in small modular reactors using natural circulation under normal operation, and in electronic cooling applications. The main novelty of Sugrue et al.'s database is the systematic investigation of the effect of orientation angle on