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An improved phenomenological model of annular two-phase flow with high-accuracy dryout prediction capability

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ABSTRACT

This paper presents a new phenomenological model of annular two-phase flow with dryout prediction capability, implemented in the CATHARE-3 system code. The model comprises existing correlations for entrainment and deposition rates and a new equation to determine the initial entrained fraction (IEF) of the liquid phase at the onset of annular two-phase flow. The proposed new model allows for a significant reduction of mean error variations with pressure and mass flux, when compared with measured dryout in pipes with internal diameter from 8 to 14.9 mm, system pressure from 3 to 10 MPa, mass flux from 500 to 6000 kg/m^{2}s, test section length from 1 to 7 m, inlet subcooling form 10 to 100 K, and critical heat flux from 0.15 to 3.90 MW/m^2. It has been also shown that, at certain conditions, the phenomenological model is unable to provide an accurate prediction, irrespective of the chosen value for the IEF parameter. Such behavior is thoroughly investigated in this paper and seldom addressed in the literature, even though it sets limits on the applicability of the model to dryout predictions.

1. Introduction

In order to assure safe operation of any boiling system its design must satisfy the safety margins which originate from many uncertainties. Water cooled reactors are no exception to this rule. One of the many limiting factors as far as nuclear power plant's design is concerned is the upper limit to the possible power production. This is governed by the phenomenon which is called critical heat flux (CHF). In case of boiling water reactors (BWR) whose flow conditions are classified as high quality flows, this phenomenon is termed as dryout. Its occurrence is correlated with disappearance of a thin liquid film from the heater rods which is consequently followed by a sudden temperature rise of the rod due to exposure to the vapour phase.

In spite of the fact that the mechanism behind dryout is known and the phenomena leading to film disappearance have been investigated for almost 50 years, empirical correlations still have to be used if high and well determined accuracy of predictions is required. Such correlation can be highly accurate within regions of their development, however, their reliability beyond these regions is questionable. Additionally, there are other parameters which influence the CHF and cannot be described by a single number (such as the axial power distribution), which impose another degree of freedom and empirical correlation fails to capture the physics and ultimately the correct value of CHF.

CHF prediction has been realized using various approaches. In experimental investigations — such as Becker et al. (1983) and Söderquist et al. (1994) — a great effort has been exercised to measure CHF values within wide range of operating conditions. This approach allowed development of the Look-Up Table (LUT - i.e. Groeneveld et al. (1996)). This solution covers a wide range of applications, is widely accepted and provides an analyst with general trends of the CHF values. Nevertheless, the need for new methods which are more accurate and as broadly applicable still is very high.

2. Computational methods and models

2.1. CATHARE-3

This paper covers work performed using the CATHARE-3 system code which solves the mass balance equation, the momentum equation and the energy equation for three fields of the flow, namely the continuous liquid, the continuous gas and the dispersed liquid. This model has been previously described and assessed for vertical two-phase flows in tubes and rod bundles by Jayanti and Valette (2004) and Jayanti and

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Nomenclature

C	concentration of droplets, (kg/m^3)
D_h	Hydraulic diameter, (m)
f	friction factor, (–)
g	gravity acceleration, (m/s^2)
G	mass flux, (kg/m^2 s)
h_{fg}	latent heat of evaporation, (m/s)
J	superficial velocity, (m/s)
J^*	dimensionless superficial velocity, (–)
k_E	entrainment coefficient, (kJ/kg)
Ku	Kutateladze number, (–)
L_b	boiling length, (m)
m	mass flow per wetted area, (kg/(m^2 s))
q''	heat flux, (W/m^2)
Q	critical power, (W)
V	velocity, (m/s)
x	flow quality, (–)
z	axial elevation, (m)

Greek

α	void fraction
	film thickness, (m)
π_E	dimensionless entrainment number
μ	dynamic viscosity ($kg/m/s$)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ξ	prediction accuracy, (–)
$\bar{\xi}$	mean prediction accuracy, (–)
Ξ	prediction error, (–)

subscripts

calc	referring to calculation
d	referring to droplets
D	referring to deposition
E	referring to entrainment
exp	referring to experiment
f	referring to liquid film
g	referring to vapour
HG	referring to Hewitt-Govan
i	referring to the interface
l	referring to liquid
lfc	referring to critical liquid film
Okawa	referring to Okawa et al.
tr	referring to transition to annular flow
w	referring to wall

Valette (2005). In these papers the entrainment and deposition terms have been validated on experimental database which included adiabatic and diabatic conditions. The first set of closure laws for LBLOCA (Large Break Loss of Coolant Accident) application has also been assessed against reflooding separate effect tests (PERICLES and RBHT) and against the reflooding phase of a postulated accident simulated on BETHSY facility Valette et al. (2011).

Currently, the CATHARE-3 code simulates the following phenomena: the transition to annular flow, the entrainment-deposition rates due to momentum exchange, the boiling induced entrainment, and the deposition inhibition. These phenomena are included using models proposed by Kutateladze (1972), Hewitt and Govan (1990), Ueda et al. (1981) and Hoyer (1998), respectively.

For the annular flow transition, apart from the Kutateladze number that needs to be greater than 3.2, a condition of void fraction higher than 0.5 must be fulfilled as well. Additionally, in order to satisfy the smoothness of the transition a spline function is implemented for both conditions.

2.2. Initial entrained fraction

An evolution of the Initial Entrained Fraction (IEF) modelling can be observed in the literature. In the first models of the entrainment and deposition phenomena it was assumed that, upon analysing the initial distribution of liquid between the film and droplets with current entrainment/deposition models, this parameter's influence was negligible — Hewitt and Govan (1990), Sugawara (1990). Later models of Okawa et al. (2002), Okawa et al. (2002), Okawa and Kataoka (2005), Okawa and Kataoka (2005) assume IEF to be calculated for the equilibrium conditions between the entrainment and the deposition rates:

$$m_E \sim m_D. \tag{2.1}$$

Even though Okawa et al. (2003) showed in their publication that this approach yielded satisfactory results, Barbosa et al. (2002) have shown that the equilibrium assumption does not agree with the experimental measurements. Moreover, the authors suggested a correlation for calculation of the IEF, however, it was derived from the air-–water data which covered pressures ranging from 1.7 to 5 bars. For this reason such correlation cannot be readily applied to high pressure water-vapour analysis. On the other hand, Azzopardi (1996) has shown that not only the position of burnout depends on the IEF, but for different operating condition different IEF values are required. Additionally the author claimed that it is difficult to optimize this parameter. Using the Azzopardi's findings Ahmad et al. (2013) and Gimeno et al. (2015) decided to employ constant IEF value (0.7 in their case) in their calculations. In the benchmark results presented by Gimeno et al. (2015) authors showed very good agreement with the experimental data which contained critical heat flux values. They compared three codes which employed the Hewitt-Govan model and IEF = 0.7 with two high pressure experiments and showed that RMS error for three codes was around 6%. At the same time the authors of the benchmark were aware of the fact that the single value of IEF is not sufficient to completely capture the considered phenomena. This statement was then extended to the real case scenario of a BWR application, where a single value of IEF is even less likely to be realistic.

Anglart (2013) presented a correlation for the film fraction which was based on the liquid Reynolds number and the Boiling number. The correlation was coupled with the Hewitt-Govan model and showed a good agreement with experimental data on liquid film flow rates in pipes with various axial power distribution (Adamsson and Anglart, 2006).

Dasgupta et al. (2015) presented their methodology of IEF modelling employing a triangular relationship between the film flow rate, film thickness and two-phase pressure drop. The authors postulate that knowledge of any of these two quantities allows calculating the third one. In the proposed methodology the pressure drop is calculated with two different formulas, one that is independent on IEF and one that takes the influence of IEF into consideration. Additionally, this methodology provides a criterion for cases which take low and high values of IEF.

Oh et al. (2015) presented a correlation which is based on the experimental data acquired by Wurtz (1978) for adiabatic and boiling water flows with pressures ranging from 3 to 9 MPa. Also these authors claimed that their correlation, due to its dimensionless nature, can be applied to a wider range of conditions. Lastly, Spirzewski et al. (2017) used experimental data of Adamsson and Anglart (2006) and developed an empirical correlation for IEF which was later validated on the