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Modeling of annular two-phase flow using a unified CFD approach

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HIGHLIGHTS

- Annular two-phase flow has been modeled using a unified CFD approach.
- Liquid film was modeled based on a two-dimensional thin film assumption.
- Both Eulerian and Lagrangian methods were employed for the gas core flow modeling.

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ABSTRACT

A mechanistic model of annular flow with evaporating liquid film has been developed using computational fluid dynamics (CFD). The model is employing a separate solver with two-dimensional conservation equations to predict propagation of a thin boiling liquid film on solid walls. The liquid film model is coupled to a solver of three-dimensional conservation equations describing the gas core, which is assumed to contain a saturated mixture of vapor and liquid droplets. Both the Eulerian–Eulerian and the Eulerian–Lagrangian approach are used to describe the droplet and vapor motion in the gas core. All the major interaction phenomena between the liquid film and the gas core flow have been accounted for, including the liquid film evaporation as well as the droplet deposition and entrainment.

The resultant unified framework for annular flow has been applied to the steam-water flow with conditions typical for a Boiling Water Reactor (BWR). The simulation results for the liquid film flow rate show good agreement with the experimental data, with the potential to predict the dryout occurrence based on criteria of critical film thickness or critical film flow rate.

1. Introduction

A crucial issue still to be resolved in the prediction of the occurrence of dryout in heated channels is to establish a mechanistic, multi-dimensional model of annular two-phase flow that accounts for the propagation of the liquid film along the walls. With such a model, the dryout prediction will be possible based on the accurate local value of the liquid film flow rate. However, this conceptually simple approach requires formulation of several closure relationships that describe the transfer of mass, momentum and energy between the liquid film and the gas core. Due to complexity of the governing phenomena, such closure relationships are still not well established and their generic formulations have to be sought.

The present paper describes a new mechanistic model of annular flow with evaporating liquid film that has been developed using computational fluid dynamics (CFD). The main objective of the model is to provide a computational tool to predict the liquid film behavior in annular flow, and in particular, to predict the disappearance of the film and the onset of a dry patch. An access to such an analytical tool could be used for studies and predictions of dryout in complex geometries, such as fuel assemblies of Boiling Water Reactors (BWRs).

In nuclear reactor safety applications, the dryout occurrence is still predominantly evaluated by employing empirical correlations, which are based on expensive experiments and apparently are limited to the specific range of geometries and operational conditions (Tong and Tang, 1997). The extrapolation of these correlations to systems and conditions much outside of the range for which they were developed is of doubtful validity. To resolve theses limitations, several phenomenological and mechanistic approaches for dryout prediction have been proposed.

In the past, the phenomenological modeling of annular flow was proposed to calculate the liquid film flow based on the rate of evaporation, and droplet deposition and entrainment (Hewitt and Govan, 1990; Okawa et al., 2003). In these types of approaches, the dryout is assumed to occur when the liquid film flow rate or corresponding film thickness decreases to zero or below a critical value (Zuber and Staub, 1966; Anglart, 2011; Anglart, 2013).

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The phenomenological models are basically one-dimensional, with possible extensions to be coupled with a subchannel code. However, they fail in the application of complex geometries and channels with obstacles, e.g. grid spacers (Kataoka et al., 2000; Adamsson and Le Corre, 2011).

More recently, mechanistic approaches employing the computational multi-phase fluid dynamics (CMFD) have been developed to simulate the annular flow (Lahey, 2005; Rodriguez, 2009; Li and Anglart, 2015). To accurately capture the detailed phenomena, e.g. the gas–liquid interface in annular flow, however, CMFD is still expensive. This is particularly true when the Eulerian–Lagrangian approach is used to treat the droplet motion in the gas core.

Damsohn (2011) provided an extensive literature study on the annular flow simulation, especially the liquid film modeling, among which a two-dimensional treatment is of concern. Bai and Gosman (1996) proposed a two-dimensional liquid film model, which can be coupled with the gas core flow into a unified framework for annular flow simulation (Adechy and Issa, 2004; Meredith et al., 2011). In these approaches the liquid film model includes mass, momentum and energy interactions (e.g. the droplet deposition and entrainment) with the gas core flow, which can be represented using Eulerian–Eulerian or Eulerian–Lagrangian techniques.

In a unified framework for annular flow, the liquid film modeling should be coupled to simultaneous calculation of the gas core flow including gas and dispersed liquid droplets. The gas core flow can be described using either the Eulerian–Eulerian or the Eulerian–Lagrangian methods, both of which have been proven to be capable to capture the governing phenomena.

The gas core flow simulation using the Eulerian–Eulerian approach is based on the two-fluid two-phase model, assuming that both phases are interpenetrating continua (Mimouni et al., 2008; Ishii and Hibiki, 2011). On the other hand, in the Eulerian–Lagrangian approach, the gas phase is simulated based on the single phase fluid flow, and the droplets are tracked using the Lagrangian Particle Tracking (LPT) (Yamamoto and Okawa, 2010; Caraghiaur and Anglart, 2013; Li and Anglart, 2015).

In the current work, the previously developed two-dimensional liquid film model (Li and Anglart, 2015) has been coupled to the gas core flow with both the Eulerian–Lagrangian and the Eulerian–Eulerian approaches to form a unified framework for annular two-phase flow. The test results for diabatic upward annular flow with phase change were presented to demonstrate the potential capability for dryout prediction.

2. Method

2.1. Liquid film modeling

The previously developed liquid film model (Li and Anglart, 2015) is shortly described in this section. In diabatic annular two-phase flow, e.g. a vertical pipe as shown in Fig. 1, the liquid phase flows partly as a thin liquid film on the heated wall and partly as droplets in the gas core. The liquid film, especially that in the upstream of the dryout point, is sufficiently thin to safely make the following major thin-film assumptions:

- the flow in the wall normal direction can be reasonably assumed to be negligible
- the spatial gradients of the dependent variables tangential to the wall surface are negligible compared to those in the wall normal direction.

These assumptions imply that the advection can be treated in the wall tangential direction and diffusion in the wall normal direction, as shown in Fig. 2. As a result, the transport equations for the liquid film can be integrated in the wall normal direction to obtain the two-dimensional equations. All the liquid film properties, which vary across the film thickness, appear as depth-averaged quantities and are in general defined as

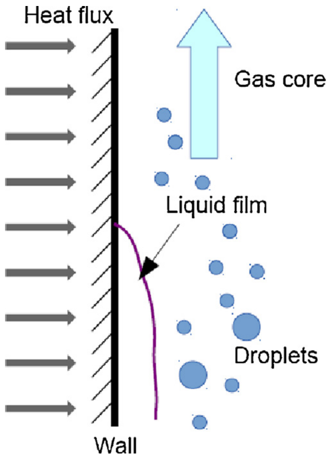

Fig. 1. Schematic of the depleting liquid film in an annular flow.

$$\overline{\varphi} = \frac{1}{\delta}\int_0^{\delta} \varphi dz \tag{1}$$

where δ is the film thickness, φ is any liquid film property variable, and z is the coordinate for wall normal direction. For simplicity, the bar is omitted for all the depth-averaged liquid film properties used in the following description. Then the mass, momentum, and energy equations are integrated in the wall normal direction as

$$\frac{\partial(\rho\delta)}{\partial t} + \nabla_s \cdot (\rho\delta\mathbf{U}) = S_\delta \tag{2}$$

$$\frac{\partial(\rho\delta\mathbf{U})}{\partial t} + \nabla_s \cdot (\rho\delta\mathbf{U}\mathbf{U}) = -\delta\nabla_s p + S_{\mathbf{U}} \tag{3}$$

$$\frac{\partial(\rho\delta h)}{\partial t} + \nabla_s \cdot (\rho\delta h\mathbf{U}) = S_h \tag{4}$$

where $\mathbf{U}$ is the mean film velocity, h is the mean film enthalpy, ∇_s is the nabla operator tangential to the surface, ρ is the density, p is the total pressure, and S_δ, $S_{\mathbf{U}}$ and S_h are the source terms. The corresponding source terms could come from the interface between the gas core and the liquid film, e.g. the interfacial shear stress, and from the wall surface, e.g. the wall shear stress. This means that all the source terms are considered in the boundary cells facing the wall and the liquid film surface. It is noted that the advection for all the equations are explicitly described, however, the diffusion and the external sources are modeled as source terms. The liquid film has complex interaction with the gas core flow, which means that corresponding models should be included as source terms to consider all the phenomena of concern.

2.1.1. Mass source terms

Fig. 3(a) depicts the main mechanisms of mass transfer considered in the present model. As indicated, the sources and sinks of

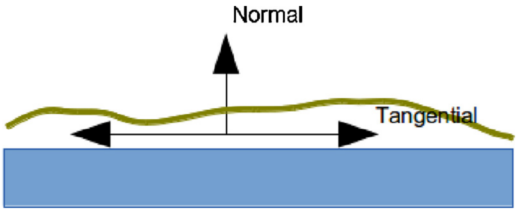

Fig. 2. Coordinate system used in the liquid film model.