Annals of Nuclear Energy 77 (2015) 415–424

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

CFD model of diabatic annular two-phase flow using the Eulerian–Lagrangian approach

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ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form 3 December 2014
Accepted 6 December 2014

Keywords:
Annular two-phase flow
Liquid film flow
Lagrangian Particle Tracking
Droplet deposition and entrainment

ABSTRACT

A computational fluid dynamics (CFD) model of annular two-phase flow with evaporating liquid film has been developed based on the Eulerian–Lagrangian approach, with the objective to predict the dryout occurrence. Due to the fact that the liquid film is sufficiently thin in the diabatic annular flow and at the pre-dryout conditions, it is assumed that the flow in the wall normal direction can be neglected, and the spatial gradients of the dependent variables tangential to the wall are negligible compared to those in the wall normal direction. Subsequently the transport equations of mass, momentum and energy for liquid film are integrated in the wall normal direction to obtain two-dimensional equations, with all the liquid film properties depth-averaged. The liquid film model is coupled to the gas core flow, which currently is represented using the Eulerian–Lagrangian technique. The mass, momentum and energy transfers between the liquid film, gas, and entrained droplets have been taken into account.

The resultant unified model 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 favorable 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

Annular two-phase flow regime plays important role in many engineering applications such as heat exchangers and boiling channels. This type of flow regime can be encountered in a wide range of pressure, mass flow rates and flow qualities. In annular flow, the liquid phase flows partly as a thin liquid film on the channel wall and partly as entrained droplets in the gas core. In a diabatic annular flow, the liquid film is depleted by both the entrainment of liquid droplets and by evaporation. When the liquid film dries out and no longer covers the wall, the heat transfer coefficient significantly deteriorates, leading to the onset of boiling crisis called dryout. Prediction of the occurrence of dryout is crucial to the optimized design and operation of industrial systems such as, Boiling Water Reactors (BWRs). As a result, research has been continually focused on better understanding of the mechanisms that govern dryout and on the accurate numerical prediction of the dryout occurrence.

Due to the complexity of the governing phenomena, 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 the range for which they were developed is of extremely doubtful validity. To resolve theses limitations, several phenomenological and mechanistic approaches for dryout prediction have been proposed.

On the one hand, 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, 2013). The phenomenological models are basically one-dimensional, with possible extensions to be coupled with a subchannel code. However, they heavily rely on the correlations for droplet deposition and entrainment (Kataoka et al., 2000; Adamsson and Le Corre, 2011).

On the other hand, mechanistic approaches employing the computational multi-phase fluid dynamics (CMFD) have been developed to simulate the annular flow (Lahey, 2005; Rodriguez, 2009). To accurately capture the detailed phenomena, e.g. the

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http://dx.doi.org/10.1016/j.anucene.2014.12.002
0306-4549/

gas–liquid interface in annular flow, however, CMFD is still expensive.

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. The droplet behavior has been successfully investigated using the Lagrangian Particle Tracking (LPT) based on the Eulerian–Lagrangian simulation (Yamamoto and Okawa, 2010), with good capability to predict the droplet deposition (Caraghiaur and Anglart, 2013).

The liquid film entrainment is mainly due to the disturbance waves developed in the gas core–liquid film interface, however, it is difficult and expensive to quantitatively capture the behavior directly based on the disturbance wave simulation (Rodriguez, 2009). As a result, the inception and rate of entrainment is still dominantly predicted using the correlations developed based on entrainment mechanism, e.g. shearing off of a roll wave crest and undercutting of a liquid film (Ishii and Grolmes, 1975).

In the current work, the two-dimensional liquid film model is coupled to the gas core flow with the Eulerian–Lagrangian method to predict the liquid film thickness in diabatic upward annular flow with phase change.

2. Method

2.1. Liquid film modeling

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:

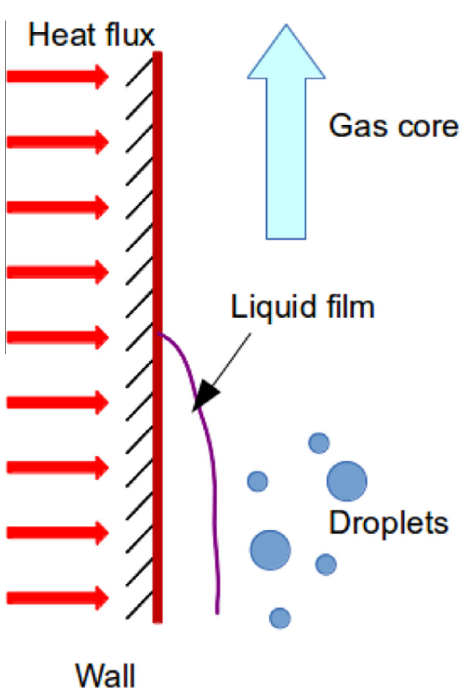

Fig. 1. Schematic of the diabatic upward annular flow with depleting liquid film.

- 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

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

where δ is the film thickness, φ is any liquid film property variable, and z is the coordinate for the 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. It is noted that the advection terms 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

In diabatic annular flow, the mass sources and sinks for the liquid film are mainly due to the phase change as well as the droplet deposition and entrainment, as shown in Fig. 3.

The phase change model considers evaporation of the liquid film, where some or all of the evaporating liquid is transferred into the gas core. This term is closely related to the energy equation and will be described in the section dealing with the energy transport phenomena.

The droplet deposition is the direct mass source from the dispersed droplets. It is formulated as the deposition rate.

The film entrainment is mainly due to the disturbance waves, and the mechanisms has been experimentally and theoretically investigated, with close relation with the liquid film-gas interfacial shear stress, boiling effect in the liquid film, and the surface tension (Ishii and Grolmes, 1975; Okawa et al., 2003). Modeling of

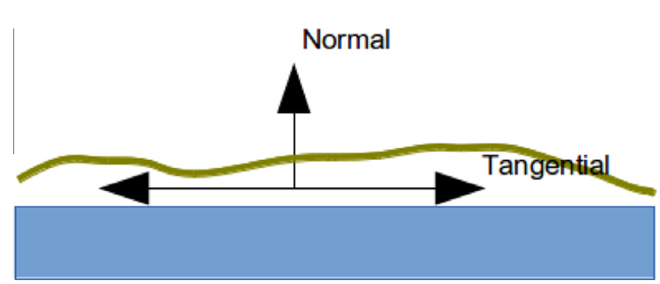

Fig. 2. Schematic of the thin film model and assumed main directions.