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Proposal of a new type of two-phase interchannel mixing model for application to subchannel analysis of PWR conditions

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ABSTRACT

Prediction accuracy of a subchannel analysis depends strongly on modeling of the interchannel mixing effect. In the present paper, we proposed a new phenomenological two-phase interchannel mixing model in the subchannel code MATRA (Yoo et al., 1999) for application to the bubbly flow regime under PWR pressure level. The three elemental natural interchannel mixing effects (Lahey et al., 1977; Sadatomi et al., 1994), i.e., turbulent mixing (TM), diversion cross flow (DC) and void drift (VD), were separately considered in the proposed interchannel mixing model. The key constitutive relation of the new mixing model is the modeling of void drift, for which the concept of Lahey et al. (1977) that a two-phase flow approaching an equilibrium state was adopted. Based on systematic CFD simulations, correlations were proposed to describe both the void fraction distribution at equilibrium state and the effective mixing velocity due to void drift. In order to investigate the driving force of void drift, detailed examinations of the lift force acting on bubbles were conducted. We found out a close relationship between the lift force and the interchannel mixing effect of void drift. Finally, the new interchannel mixing model along with the proposed void drift model were implemented in MATRA for validation calculation with selected test cases of the ISPRA rod bundle benchmark (Herkenrath et al., 1981).

1. Introduction

The main challenge arising in a subchannel analysis is the modeling of flow interactions in the lateral direction between adjacent subchannels. Disregarding the forced lateral interchannel exchange effects caused by extra constructive elements, such as grid spacers, mixing vanes or wire wrap, the natural interchannel mixing of a vertical upward two-phase flow in a rod bundle can be normally decomposed into three elemental components (Lahey and Moody, 1977; Sadatomi et al., 1994): i.e., turbulent mixing (TM) that occurs from the stochastic flow fluctuations, diversion cross flow (DC) induced by the lateral mean pressure gradient between adjacent subchannels and void drift (VD) that occurs only under two-phase flow conditions. In a subchannel analysis, the effect of diversion cross flow is directly solved with a lateral momentum equation. Constitutive equations are required for modeling the mixing effect of turbulent mixing and void drift. Lahey and Moody (1977) refer void drift to as a phenomenon resulting from the tendency of a two-phase system approaching a fully developed, equilibrium state. The two-phase interchannel mixing model proposed by Lahey and Moody (1977) combines the mixing effect due to turbulent mixing and void drift, based on the assumption that fluid globs of the same volume but different densities are exchanged between adjacent subchannels. Hence, this interchannel mixing model is referred to as the equal-volume-exchange turbulent mixing and void drift (EVVD) model. It hypothesizes that the net two-phase interchannel mixing flow rate per axial length due to turbulent mixing and void drift from subchannel i to its adjacent subchannel j (denoted with w_{itoj}^{EVVD}) is proportional to the non-equilibrium void fraction gradient. This yields:

$$w_{itoj}^{\mathrm{EVVD}} \propto \left[(\alpha_j - \alpha_i) - (\alpha_j - \alpha_i)_{EQ}\right] \quad (1)$$

with α_i and α_j stand for void fraction of the subchannel i and j, respectively. By adopting a simple model proposed by Levy (1963), Lahey and Moody (1977) relate the void fraction distribution at equilibrium state $(\alpha_j - \alpha_i)_{EQ}$ with the mass flux distribution in the two interacting subchannels. This yields:

$$\frac{(\alpha_j - \alpha_i)_{EQ}}{\alpha_{avg}} = \frac{(G_j - G_i)}{G_{avg}} \quad (2)$$

with G_i and G_j denote the mass flux (of the main streamwise direction) in the subchannel i and j, respectively. The subscript *avg* stands for the average flow properties of the two interacting

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subchannels. Since Levy's assumption is not well validated and has been disapproved by the measurement of Sadatomi et al. (1994, 2004), an empirically determined dimensionless void drift correction factor K_{VD} is introduced. This yields:

$$(\alpha_j - \alpha_i)_{EQ} = K_{VD}\frac{(G_j - G_i)}{G_{avg}} \tag{3}$$

Accordingly, w_{itoj}^{EVVD} is expressed as:

$$w_{itoj}^{\mathrm{EVVD}} = (\beta_{SP}\cdot S\cdot G_{avg})\cdot\theta\cdot\left[(\alpha_j - \alpha_i) - K_{VD}\frac{(G_j - G_i)}{G_{avg}}\right] \tag{4}$$

with S the gap distance of the two interacting subchannels, β_{SP} the single phase turbulent mixing coefficient and θ a flow regime dependent two-phase turbulent mixing multiplier proposed by Beus (1971). It is clearly seen that the key parameter to describe the mixing effect of turbulent mixing and void drift is the void drift correction factor K_{VD}, which as given in Eq. (3) characterizes the void fraction distribution at equilibrium state. Although Lahey's EVVD model was developed in the 1970s, it is widely adopted in state-of-the-art subchannel analysis codes. In THERMIT-2 code, Kelly et al. (1981) adopt the EVVD model and assume $K_{VD} = 1.4$. In the subchannel code MATRA (Yoo et al., 1999), Hwang et al. (2000) propose an optimized model of K_{VD} in dependence on system pressure and flow regime derived from assessment of experimental results obtained in rod bundle benchmarks under both BWR and PWR pressure levels. Accordingly, K_{VD} is expressed for bubbly-slug regime ($x_{avg} < x_C$ with x_{avg} the average quality of two interacting subchannels and x_C the transition quality from slug to annular flow regime) as:

$$K_{VD} = a_1\left(\frac{x_{avg} - x_{OSV}}{x_C - x_{OSV}}\right) \tag{5}$$

and for annular regime ($x_{avg} > x_C$) as:

$$K_{VD} = a_1 + a_2\left(\frac{x_{avg} - x_{OSV}}{x_C - x_{OSV}} - 1\right) \tag{6}$$

where the parameters a_1 and a_2 are:

$$a_1 = 0.72\left(\frac{1 - p_r}{p_r}\right)^{1.33} \tag{7}$$

$$a_2 = 10 \tag{8}$$

and x_{OSV} is the quality, at which bubble departure from heated wall begins, i.e. onset of significant void fraction (Levy, 1967). p_r stands for the reduced pressure, which is defined as system pressure divided by the critical pressure.

However, one noticeable drawback of the EVVD model should be pointed out. In the EVVD model, see Eq. (4), mixing effects due to turbulent mixing and void drift are modeled in a combined manner. The same effective mixing velocity, interpreted with the single phase turbulent mixing coefficient β_{SP} and the two-phase turbulent mixing multiplier θ, is used for both turbulent mixing and void drift. However, these two mixing effects are induced by different physical mechanisms. Due to the irregular nature of turbulent fluctuations, turbulent mixing is regarded as a non-directional mixing effect, while void drift is a directional mixing effect with a prevailing direction as found in diverse measurements (Schraub et al., 1969; Sterner et al., 1983; Sadatomi et al., 2006) that the gaseous phase (void) has a strong affinity towards certain types of subchannel. The use of the same effective mixing velocity for two different mixing effects in the EVVD model is rather questionable. Turbulent mixing and void drift are not clearly separated in the EVVD model.

In the present paper, we proposed a new phenomenological two-phase interchannel mixing model, with which the three elemental natural interchannel mixing effects are separately considered. The key constitutive equation is the modeling of void drift, for which the concept proposed by Lahey and Moody (1977) of a two-phase flow approaching an equilibrium state of void fraction distribution was adopted. Different to the EVVD model, an individual effective mixing velocity due to void drift needs to be specified, as well as the void fraction distribution at equilibrium state. To determine these two key parameters of void drift, CFD approach with the commercial software package Ansys CFX (CFX Solver Theory Guide, 2009) was employed to simulate the two-phase interchannel mixing in rod bundle geometry. Based on systematic CFD simulations covering PWR conditions (bubbly flow regime with void fraction <30%), correlations were proposed to describe both the void fraction distribution at equilibrium state and the effective mixing velocity due to void drift.

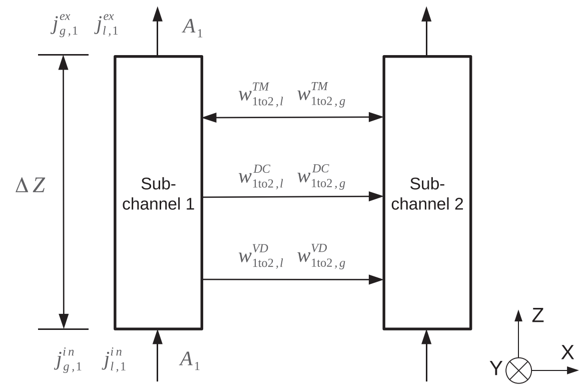

Fig. 1. Axial and lateral interchannel mass flows between two interacting subchannels 1 and 2. Z direction is the main streamwise direction.

2. Phenomenological description of the two-phase interchannel mixing

Considering two subchannels 1 and 2 with a finite axial height of ΔZ laterally connected with a gap distance of S, the axial and lateral interchannel mixing mass flows are illustrated in Fig. 1.[1]

For the subchannel 1, mass conservations[2] of the gaseous and the liquid phase could be established as:

$$\left(j_{g,1}^{in} - j_{g,1}^{ex}\right)\cdot\rho_g\cdot A_1 = w_{1to2,g}\cdot\Delta Z \tag{9}$$

$$\left(j_{l,1}^{in} - j_{l,1}^{ex}\right)\cdot\rho_l\cdot A_1 = w_{1to2,l}\cdot\Delta Z \tag{10}$$

where j, ρ and A stand for the superficial velocity, density and cross-sectional area, respectively. The subscripts g and l denote the physical properties of the single gaseous and liquid phase, respectively. The inlet and outlet flow properties are then denoted with the superscripts *in* and *ex*, respectively. In both equations, the right hand side is the sum of the net interchannel mixing mass flow rate of the gaseous and liquid phase. For studying the interchannel mixing phenomena, it is essential to decompose the sum of the net mixing mass flow rate into the individual mixing effects.

$$w_{1to2,g} = w_{1to2,g}^{TM} + w_{1to2,g}^{DC} + w_{1to2,g}^{VD} \tag{11}$$

$$w_{1to2,l} = w_{1to2,l}^{TM} + w_{1to2,l}^{DC} + w_{1to2,l}^{VD} \tag{12}$$

For this purpose, appropriate assumptions must be taken. Imaging the case of a non-equilibrium state with differences in mean static

[1] The arrows of the individual mixing components denote that turbulent mixing (TM) has no prevailing direction, whereas diversion cross flow (DC) and void drift (VD) are both directional mixing effect.

[2] The two-phase flow was treated as isothermal in the present study, hence no interphase mass exchange terms are specified in the mass conservation equations.