Influence of Channel Orientation on the Subchannel Analysis of Two-Phase Flow

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1. Introduction

In water-cooled SMRs for ship applications, it is required to predict the coolant flow conditions in inclined subchannels for evaluating the thermal margin. Subchannel analysis codes are practically useful for local CHF predictions in rod bundles which provide compromise between the microscopic thermal hydraulic field and lumped parameter results. The key features of subchannel codes for accurate prediction of subchannel flow distributions in vertical rod bundles are the modelling for inter-channel exchange mechanisms such as the diversion cross flow, turbulent mixing, and void drift phenomena [1]. Two-phase flow distributions in horizontal fuel channels such as those of the CANDU reactors are further complicated due to the effect of gravity separation [2-4].

In this study, the influence of channel orientation on the subchannel flow and void distributions were examined by employing a subchannel analysis code MATRA. The buoyancy drift effect caused by gravity-induced local drift velocity was considered in the mixture energy equation of MATRA code through an additional energy transfer term between adjacent subchannels.

2. Model Description

2.1 Influence of Gravity-Induced Phase Separation

In the inclined channel conditions, the gravity induced phase separation phenomenon results in non-uniform two-phase flow distributions in subchannels due to the tendency of upward movement of the vapor phase. For the subchannel analysis codes based on mixture balance equations, an appropriate constitutive model is required to account for the relative movement of the vapor phase caused by the gravity effect. According to the drift-flux model, the vapor velocity can be expressed as [2]

$$\vec{V}_g = C_0\vec{j} + \overrightarrow{V_{gj}^*} - \frac{\varepsilon}{\alpha}\vec{\nabla}\left(\alpha - \alpha_{eq}\right) \qquad (1)$$

The terms in the R.H.S. of eq. (1) accounts for the mixture volumetric flux, local drift velocity and the turbulent void diffusion. In the inclined channels, the local drift velocity caused by gravity is related to the bubble rise velocity in stagnant fluid. The subchannel gap geometry as well as the counter-current flow through the gap may interfere the terminal rise velocity in the inclined channels. The turbulent void diffusion term accounts for the diffusion due to void gradient between subchannels and a tendency of void migration toward an equilibrium distribution. The equilibrium void distribution may depends on the subchannel geometry as well as the mass flux distribution. Experimental observation of an equilibrium distribution in horizontal channel was explained as a balance between the gravity force and the turbulent diffusion [4].

Since the local drift velocity is not considered in the homogeneous mixture equations as used in MATRA, an appropriate constitutive relation is required to consider the buoyancy drift effect. In vertical rod bundles the turbulent void diffusion effect is reflected in the two-phase turbulent mixing models such as EVVD [1]. In the inclined rod bundles, it was assumed that the gravity-induced vapor movement does not cause a net mass transfer between subchannels. Moreover, the axial momentum transfer by the buoyancy drift was neglected. Consequently, the buoyancy drift effect was considered in the mixture energy equation of MATRA code by employing additional energy transfer due to gravity-induced vapor movement.

2.2 Implementation in the MATRA code

The inclined channel implies two kinds of angle information as shown in Fig. 1. The orientation of axial flow direction to the gravity (θ) and the orientation of the alignment of adjacent channels to the lateral gravity (β_{ij}).

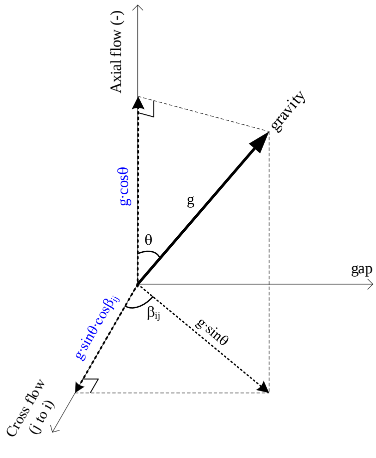

Fig. 1. Orientation angles for inclined subchannels

The lateral momentum equation of MATRA code considers the gravitational force due to channel orientation. It is expressed as

$$\frac{\partial W_{ij}}{\partial t} + \frac{\partial W_{ij} u_{ij}^*}{\partial x} = \frac{s}{l} \Delta P_{ij} - F_{f,ij} - s\rho_i g \sin\theta \cos\beta_{ij} \quad (2)$$

Where the source term $F_{f,ij}$ implies lateral frictional loss due to cross flow. The lateral momentum flux and heat conduction effects were neglected.

The energy transfer due to gravity-induced vapor movement was considered in the mixture energy equation as

$$\frac{\partial (A\rho h)_i}{\partial t} + \frac{\partial (AGh)_i}{\partial x} + \sum_j W_{ij} h = Q - w'_{ij,g} h_{fg} \quad (3)$$

The source term Q implies heat addition due to external heat source, fluid heat conduction, and turbulent mixing between adjacent channels. The last term in the R.H.S. of eq. (3) represents energy transfer from channel-*i* to *j* by vapor movement. Since the vapor moves with the bubble rise velocity, the vapor mass flow rate per unit axial length through the gap can be expressed as

$$w'_{ij,g} = s \cdot \alpha^* \cdot \rho_g^* \cdot V_{rise} \quad (4)$$

where * means the donor channel properties. The bubble rise velocity model was adopted from the constitutive relations used in the ASSERT-4 subchannel code [5] that is written as

$$V_{rise} = 1.5 \cdot \mathrm{F} \cdot \alpha^{0.1} \left[\frac{\Delta\rho\sigma g}{\rho_l^2}\right]^{0.25} |\sin\theta| \cos\beta_{ij} \quad (5)$$

where F is the correction factor accounting for the asymptotic behavior of the bubble rise velocity.

3. Analysis Results

3.1 Two Channel Analysis

Parametric effects of channel orientation on the behavior of subchannel mass flux and void distributions were examined for a simple 2-channel geometry which comprises square (channel-1) and triangular (channel-2) subchannels. The ratios of the hydraulic diameter and the isolated enthalpy rise for channels 1 and 2 are 1.36 and 0.37, respectively. The channel gap spacing is 4 mm and the heated length is 1000 mm with uniformly located four spacer grids. Analysis conditions are pressure of 10 MPa, mass flux of 1000 kg/m^{2}s, inlet quality of -0.13, and average exit void fraction of 0.51.

Fig. 2 shows axial distributions of subchannel mass flux and void fraction for various orientations. They are compared with the results for vertical orientation ($\theta = 0^o$). Results for horizontal is classified into 3 cases. In case-1 ($\theta = 90^o/\beta_{ij} = 90^o$) the buoyancy drift effect as well as the gravitational force in the lateral momentum equation do not influence two-phase flow distributions. As shown in Fig. 2-(a), the mass flux in channel-2 (hotter channel) reduces further in horizontal inclination. This is mainly due to the fact that the frictional loss becomes more dominant in the axial pressure drop under horizontal orientation. This results in the increase of channel-2 void fraction in comparison with that of vertical orientation as shown in Fig. 2-(b). Channel arrangement for case-2 and 3 is shown in Fig. 2 ($\theta = 90^o/\beta_{ij} = 180^o$). The buoyancy drift effect was intentionally neglected in case-2 analysis. Since the two-phase distributions for case-2 are very close to those for case-1, it was concluded that the influence of gravitational force in the lateral momentum equation is not significant for this sample problem. Case-3 analysis considered buoyancy drift effect in the energy balance equation. The decrease of channel-2 (lower channel) void fraction due to energy transfer by buoyancy drift was remarkable as shown in Fig. 2-(b). It tends to mitigate the channel orientation effects on the axial momentum balance, and reduces the difference of mass fluxes between the two subchannels in comparison with that for case-2.

3.2 7-Rod Bundle Analysis

Subchannel flow and void distributions in a 7-rod bundle have been examined. The hydraulic diameter in corner, side, and central subchannels are 4.8 mm, 8.7 mm, and 11.5 mm, respectively. Analysis results show that the void in lower subchannels tend to migrate upward by the gravity-induced phase separation effect. The increased channel pressure drop due to higher void fraction results in the reduction of mass fluxes in the upper subchannels as shown in Fig. 3-(a). Increase of void fraction was remarkable in the upper subchannel connected by a horizontal gap orientation (channel-2) in comparison with those in the vertical orientation as shown in Fig. 3-(b).

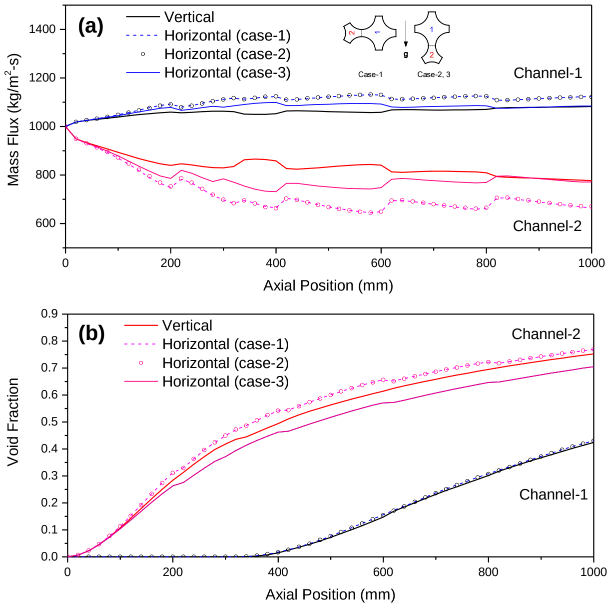

Fig. 2. Comparison of subchannel mass flux and void fraction distributions between vertical and horizontal inclination of two interconnected channels

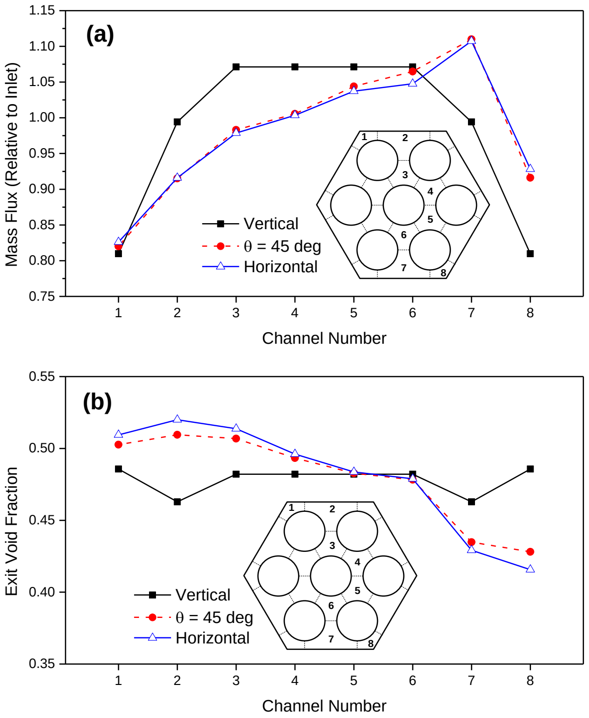

Fig. 3. Subchannel mass flux and void distributions in 7-rod bundle with various channel inclinations

4. Conclusions

The influence of channel orientation on the subchannel mass flux and void distributions were examined by employing a subchannel analysis code MATRA. A constitutive model for the energy transfer due to gravity-induced vapor movement as well as the gravitational force term in lateral momentum equation were implemented in the MATRA code with the channel and gap orientation information. A parametric study for the selected sample problems, it was revealed that the energy transfer due to the buoyancy drift effect was remarkable in comparison with the gravitational force effect in lateral momentum.

For further studies, it is required to improve the gravity-induced mass, energy, and momentum transfer models. In addition, validation/optimization of the models by comparing with appropriate experimental data is essential for design applications.

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