Implementation of the subchannel flow mixing model into the SPACE v3.0 code

Dongwi Kim, Jae Jun Jeong, Byongjo Yun*
School of Mechanical Engineering, Pusan National University (PNU)
**Corresponding author: bjyun@pusan.ac.kr*

1. Introduction

The subchannel flow mixing is an important phenomenon for the prediction of temperature and void fraction distributions in the reactor core. In subchannel analysis codes, subchannel flow mixing models, such as equal mass exchange (EM) model and equal-volume exchange and void drift (EVVD) model [1], have been adopted.

The thermal-hydraulic system code, SPACE [2], has been developed for licensing purposes of pressurized water reactors in Korea. It adopts a two-fluid three-field model for a two-phase flow. The three fields comprise a gas, continuous liquid, and droplet fields. In order to use SPACE for a subchannel analysis, a subchannel flow mixing model is needed first. In this study, we implemented the EVVD model into the SPACE v3.0 code. Then, the modified SPACE code was assessed using some subchannel experimental data. In addition, the void drift coefficient and turbulent mixing parameter in the EVVD model are discussed.

2. Description of subchannel mixing model

2.1 Subchannel mixing phenomena

Flow mixing phenomena in subchannels for a two-phase flow are composed of diversion crossflow, turbulent mixing, and void drift. Diversion crossflow occurs due to imposed transverse pressure gradients. Turbulent mixing occurs as a cause of stochastic pressure and flow fluctuations. And void drift is known to be a strong tendency of the vapor phase to drift toward the higher velocity regions.

In the SPACE code, the turbulent mixing and void drift are not considered and, the diversion crossflow is considered by solving momentum equations. In this regard, the EVVD model was implemented into the SPACE code.

2.2 EVVD model

The EVVD model was proposed by Lahey and Moody [1]. It is a simple formula based on the assumption that equal globs of fluid have the same volume, but different densities are exchanged between adjacent subchannels. The net mass flux of the EVVD model of gas and liquid phase between subchannel i and j is expressed by

$$w''_{g,i-j} = \left(\frac{\varepsilon}{l}\right)_{1\theta} \theta \left\{(\alpha\rho)_{g,i} - (\alpha\rho)_{g,j} - K_{VD}\frac{G_i - G_j}{\bar{G}_{i,j}}\rho_{g,i,j}\right\}, \quad (1)$$

$$w''_{l,i-j} = \left(\frac{\varepsilon}{l}\right)_{1\theta} \theta \left\{(\alpha\rho)_{l,i} - (\alpha\rho)_{l,j} + K_{VD}\frac{G_i - G_j}{\bar{G}_{i,j}}\rho_{l,i,j}\right\}, \quad (2)$$

$$\left(\frac{\varepsilon}{l}\right)_{1\theta} = \beta \frac{\bar{G}_{i,j}}{\bar{\rho}_{i,j}}, \quad (3)$$

where θ is a two-phase multiplier [3]. K_{VD} is a void drift coefficient, which is represented as a constant, a function of quality [4], or a function of pressure [5]. β is a turbulent mixing parameter affected by fuel assembly geometry, such as mixing vane [6]. Users determine values of β and K_{VD} to use the EVVD model. Proper selection of these variables is very important.

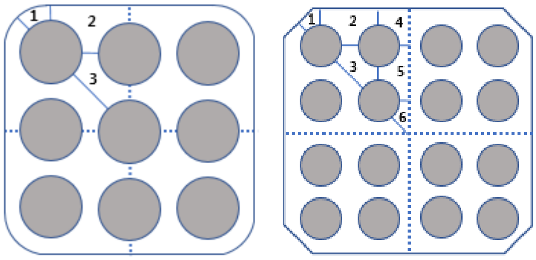
3. Assessment of subchannel mixing model

The modified SPACE code has been assessed against GE 9-rod bundle [7], ISPRA 16-rod bundle [8], and PSBT 25-rod bundle [9] experimental data. Test conditions of the three experiments are summarized in Tables 1 and 2. Fig.1 shows the SPACE nodalization for the GE, ISPRA and PSBT rod bundle experiments. A 1/8 symmetry was assumed in the GE, ISPRA rod bundle experiments.

In the GE and ISPRA rod bundle experiments, the quality and mass flux at the corner, side and inner region were measured. These experiments data can be used to find optimum the void drift coefficient used in Section 3.1. Generally, a mixing vane in spacer grid makes great turbulence. It required a large turbulent mixing parameter. To identify the effect of turbulent mixing parameter, the PSBT rod bundle experiment is used in Section 3.2. Unlike the GE and ISPRA rod bundle experiments, the PSBT rod bundle experiment is an experiment that measures the central void fraction according to the height of the test section. In Fig.4, the void fraction measured at the lower, middle, and upper positions are shown.

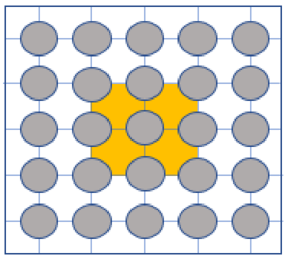
3.1 Application results of EVVD model

Figs. 2, 3 and 4 show the results of the original and the modified SPACE code. K_{VD} is set to 1.0 for general results. As shown in Figs. 2, 3 and 4, the original SPACE code mainly over-predicts the experimental data and, on the other hand, the modified code shows a better agreement with experimental data. Especially, the EVVD model has a significant effect on the prediction the quaility in the corner. For reference, RMS error is listed in the Table 3.



(a) GE (b) ISPRA

1 : corner 2 : side 3 : inner



(c) PSBT

Fig. 1. GE & ISPRA & PSBT rod bundle test bundle

Table 1 The GE & ISPRA test conditions

	GE	ISPRA
Rod array	3x3	4x4
Pressure [bar]	69	160
Power [MW]	0-1.6	1.4-2.1
Mass flux [kg/m^{2}s]	650-2050	2200-3250
Exit quality	0.03-0.36	-0.17-0.18
Number of test conditions	13	27

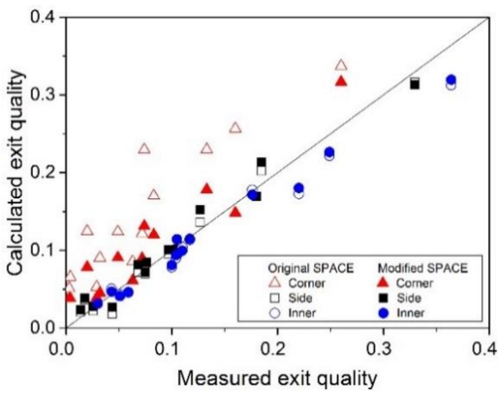


Fig. 2. Comparison of measured and calculated exit quality (GE rod bundle test)

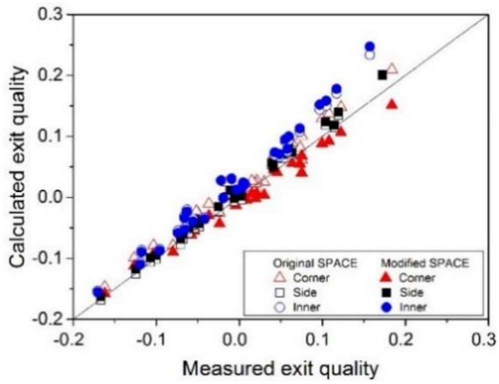


Fig. 3. Comparison of measured and calculated exit quality (ISPRA rod bundle test)

Table 2 The PSBT test conditions

	PSBT		
Assembly	B5	B6	B7
Rods array	5x5	5x5	5x5
Pressure [bar]	164-166		
Power [MW]	1.5-3.4		
Mass flux [kg/m^{2}s]	1350-4250		
Central region average void fraction	0.0-0.5		
Axial power shape	Uniform	Cosine	Cosine
Number of test conditions	12	12	12

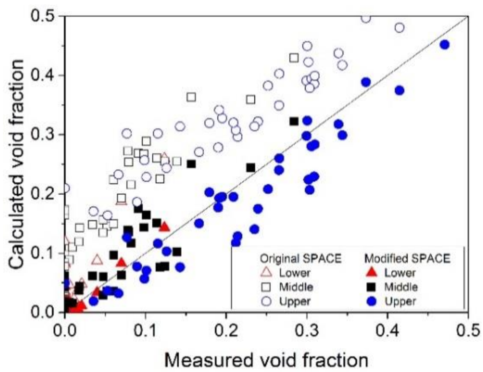


Fig. 4 Comparison of measured and calculated void fraction (PSBT rod bundle test – B5, B6, B7)

Table 3 The RMS error

Experiment	GE		
RMS error	Corner	Side	Inner
Original SPACE	0.0813	0.0122	0.0227
Modified SPACE	0.0374	0.0150	0.0197
Experiment	ISPRA		
RMS error	Corner	Side	Inner
Original SPACE	0.0207	0.0982	0.0328
Modified SPACE	0.0156	0.0137	0.0355
Experiment	PSBT		
RMS error	Lower	Middle	Upper
Original SPACE	0.0480	0.1275	0.1242
Modified SPACE	0.0117	0.0381	0.0459

3.2 Modification of void drift coefficient K_{VD}

To find an optimum void drift coefficient K_{VD}, the calculation results of the GE and ISPRA rod bundle experiments are compared. Figs. 5 and 6 show the sensitivity calculations of the GE and ISPRA rod bundle experiments, respectively. Fig. 5 shows that a void drift coefficient of 1.8 is suitable in predicting the GE rod bundle experiment data. On the other hand, Fig. 6 shows that 0.2 is a proper value for the ISPRA rod bundle experiment. To derive the optimum void drift coefficient, it is necessary to find out the flow parameters that affect the void drift phenomena.

Fig. 7 and 8 are the comparisons of exit mass flux in the corner, side and inner region, which show that mass flux of corner region is always lower than side region. So, K_{VD} was derived as a function of exit mass flux for the GE and ISPRA experimental data:

$$K_{VD} = 7.393e^{-0.001115G} \tag{4}$$

Fig. 9 and 10 show the calculation results using Eq. (4).

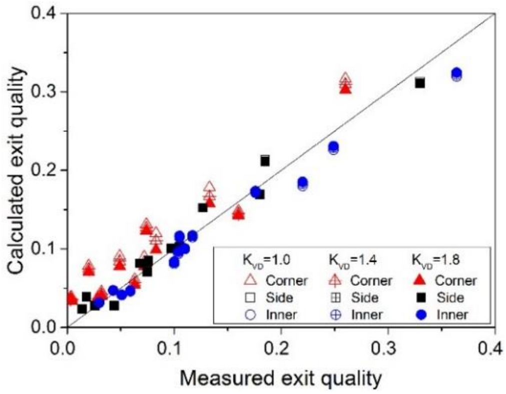


Fig. 5 Effect of void drift coefficient: the GE rod bundle test.

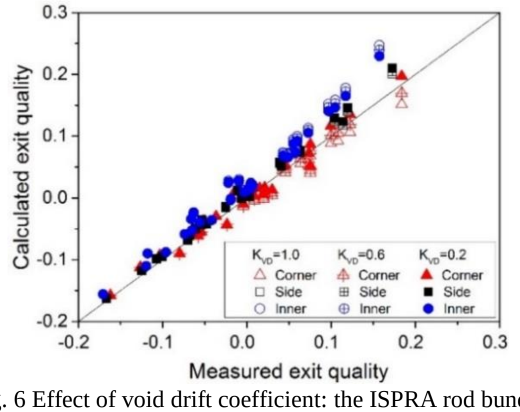


Fig. 6 Effect of void drift coefficient: the ISPRA rod bundle test.

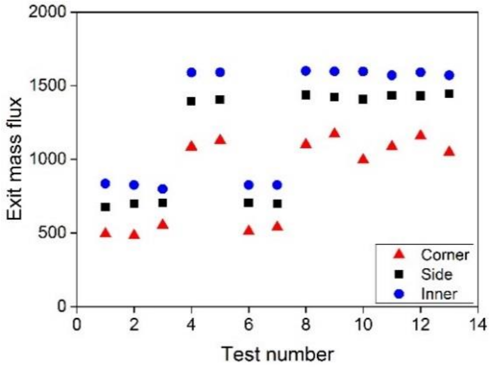


Fig. 7 Comparison of the exit mass fluxes: the GE rod bundle test.

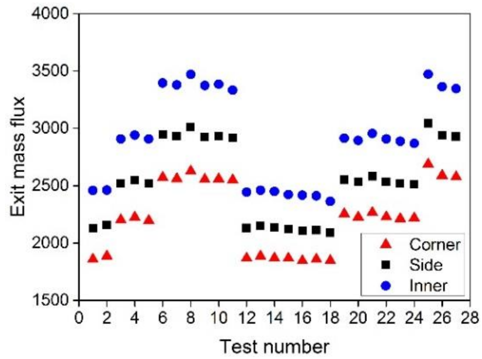


Fig. 8 Comparison of the exit mass fluxes: the ISPRA rod bundle test.

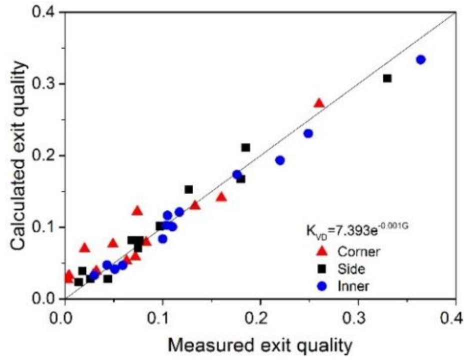


Fig. 9 The result using the new void drift coefficient: the GE rod bundle test.

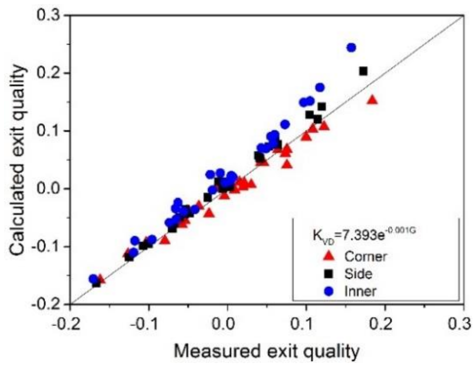


Fig. 10 The results using the new void drift coefficient: the ISPRA rod bundle test.

3.3 Effect of turbulent mixing parameter β

Generally, a mixing vane makes the turbulence stronger, so turbulent mixing parameter (β) should be more larger. Hwang [6] suggested a turbulent mixing parameter of 0.04 so as to take into account the effect of mixing vane. The PSBT rod bundle experiments, which used spacer grids with mixing vanes, were used to see the effect of β on the EVVD model. Fig. 11 shows the result of the calculations. When β is 0.04, better results were obtained.

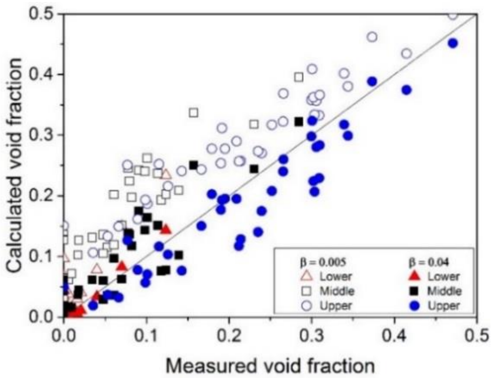


Fig. 11 Effect of β on void fraction: the PSBT rod bundle test of B5, B6, and B7.

4. Conclusions

The SPACE code is a thermal-hydraulic system code. In order to use SPACE for a subchannel analysis, a subchannel flow mixing model is needed first. In this study, the equal-volume exchange and void drift (EVVD) model is implemented into the SPACE v3.0 code as a subchannel flow mixing model. The modified SPACE code was assessed using the GE, ISPRA, and PSBT experimental data. The results of the modified SPACE show a better agreement with experimental data. An optimum void drift coefficient is derived as a function of mass flux using the GE and ISPRA rod bundle experimental data.

REFERENCES

[1] R. T. LAHEY, Jr., and F. J. MOODY, The Thermal-Hydraulics of a Boiling Water Reactor, 2^{nd} ed., pp. 122-138, American Nuclear Society (1977).

[2] Korea Hydro & Nuclear Power Co. Ltd., SPACE 3.0 manual Volume 1 theory manual, S06NX08-K-1-TR-36, Rev.0.

[3] S. G. BEUS, "A Two-Phase Turbulent Mixing Model for Flow in Rod Bundles,"WAPD-T-2438, Bettis Atomic Power Laboratory (1971).

[4] D. H. Hwang et al., "Assessment of the Interchannel Mixing Model with a Subchannel Analysis Code for BWR and PWR Conditions," Nucl. Eng. Des., 199, 257 (2000).

[5] J. J. Jeong et al., "Improvement of the subchannel flow mixing model of the MARS code," Nuclear technology, Vol. 156, pp. 360-368 (2006).

[6] D. H. Hwang et al., "Improvement of Analysis System for Core Thermal Hydraulic Field and CHF," KAERI/RR-980/90, Korea Atomic Energy Research Institute (1991). (in Korean).

[7] R. T. LAHEY, Jr., et al., "Two-Phase Flow and Heat Transfer in Multi-Rod Geometries: Subchannel and Pressure Drop Measurements in a Nine-Rod Bundle for Diabatic and Adiabatic Conditions," GEAP-13049, General Electric (1970).

[8] H. Herkenrath et al., Experimental Investigation of the Enthalpy and Mass Flow Distribution in 16-Rod Clusters with BWR-PWR Geometries and Conditions, EUR 7575 EN, ISPRA (1981).

[9] A. Rubin et al., "OECD/NRC benchmark based on NUPEC PWR subchannel and bundle tests (PSBT). Volume I: experimental database and final problem specifications," NEA/NSC/ DOC, 2010.