Transactions of the Korean Nuclear Society Virtual Autumn Meeting
October 21-22, 2021

Improvement of bundle void prediction of MARS-KS by introducing inter-channel mixing model

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1. Introduction

The persisting improvement of the thermal-hydraulic system codes has changed its capability, and nowadays they are utilized to produce best-estimated results for more realistic prediction of reactor transients [1]. Even more, some of them has been developed feasible to conduct multi-dimensional analysis by using their own multi-dimensional component. MARS-KS is a best-estimate system code with multi-dimensional capacity using its own multi-dimensional component, namely MULTID [2]. In addition to the multi-dimensional concern, the MULTID includes a turbulent mixing model for inter-channel mixing, and this introduces a difference from crossflow formulation for existing one-dimensional component. However, it has been found from the previous study that the turbulent mixing model of MULTID has no influence on the bundle void prediction [3]. This is because the corresponding mixing model only concerns molecular diffusion, not direct inter-channel mixing. This study has been conducted to improve the bundle void prediction by MULTID. The improvement has been made by introducing turbulent mixing model of state-of-the-art subchannel codes, which implements direct exchange between channels.

2. Methods and Results

As afore mentioned, the code improvement has been made by applying the turbulent mixing model, which is widely adopted for the subchannel analysis. The model is categorized into two methodologies depending on the flow condition [4]. When it comes to single-phase flow, the model postulates inter-channel mixing based on equal mass exchange, and this is called as equal-mass exchange (EM) model. On the other hand, for two-phase flow, the model postulates net mass exchange between channels based on the concept of equal volume exchange. Furthermore, the model considers void drift phenomenon for non-uniform void distribution within a bundle. This is called as equal-volume exchange and void drift (EVVD) model. By implementing these models into the field equation of MARS-KS, the improvement has been made, and the assessment has been performed against the PWR Subchannel and Bundle Test (PSBT) benchmark data [5] used for the previous work [3]. Before showing the assessment results, detailed description of the turbulent mixing model will be given through the following paragraphs.

2.1 Equal-Mass exchange (EM)

The concept of the EM model is that inter-channel mixing occurs by exchanging equivalent mass between channels. Therefore, there is no net mass movement, but the momentum and energy become changed as a consequence of the mixing. The net momentum and energy exchange are defined as Eq. (1) and Eq. (2), respectively.

$$M'_{A\leftrightarrow B} = w'\Delta\vec{u} \tag{1}$$

$$Q'_{A\leftrightarrow B} = w'\Delta h \tag{2}$$

where, w' is equivalently exchanged mass flow. $\Delta\vec{u}$ and Δh stand for the difference in fluid velocity and enthalpy, respectively. The exchanged mass flow is conventionally defined as Eq. (3) by introducing mixing coefficient β.

$$w' = \beta \bar{G} A_{gap} \tag{3}$$

The mixing coefficient is defined as the ratio of mixing mass flux due to turbulence to the averaged axial mass flux $\bar{G}$.

2.2 Equal-Volume exchange and Void Drift (EVVD)

The EVVD model postulates the net mass exchange based on the concept of equivalent exchange of the volume. Therefore, once the exchanging volumes have different density, net movement of the mass could be implemented. From this, the net mass, momentum, and energy exchanges are derived as:

$$w'_{A\leftrightarrow B} = \left(\frac{\varepsilon}{l_m}\right)_{TP} A_{gap}\big[(\hat{\rho})_B - (\hat{\rho}\,)_A - k_{VD}\{(\hat{\rho}\,)_B - (\hat{\rho}\,)_A\}_{EQ}\big] \tag{4}$$

$$M'_{A\leftrightarrow B} = f_T\left(\frac{\varepsilon}{l_m}\right)_{TP} A_{gap}\big[G_B - G_A - k_{VD}\{G_B - G_A\}_{EQ}\big] \tag{5}$$

$$Q'_{A\leftrightarrow B} = \left(\frac{\varepsilon}{l_m}\right)_{TP} A_{gap}\left[\left(\widehat{\rho h}\right)_B - \left(\widehat{\rho h}\,\right)_A - k_{VD}\left\{\left(\widehat{\rho h}\,\right)_B - \left(\widehat{\rho h}\right)_A\right\}_{EQ}\right] \tag{5}$$

where, $\left(\frac{\varepsilon}{l_m}\right)_{TP}$ denotes two-phase turbulent mixing velocity, and this term is conventionally defined by Beus correlation [6]. The coefficient f_T is called turbulent momentum factor, which is defined as the ratio of momentum mixing to energy mixing. The value of f_T is generally given as unity. The terms $\hat{\rho} = \alpha_g \rho_g + \alpha_f \rho_f$ and $\widehat{\rho h} = \alpha_g \rho_g h_g + \alpha_f \rho_f h_f$ define the mixture density and enthalpy, respectively. By the way, the terms denoted by 'EQ' represent the mixing due to the void drift, which interferes the net exchanges not to reach uniform void distribution. These void drift terms are adjusted by multiplying the coefficient k_{VD}, namely void drift coefficient.

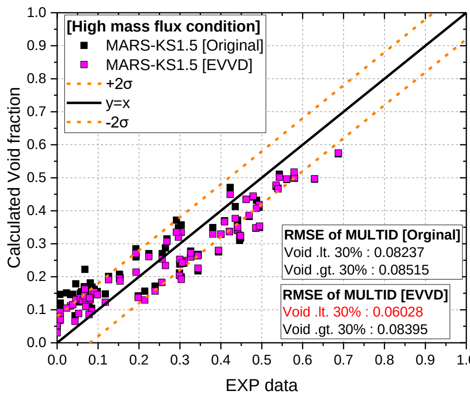
2.3 PSBT benchmark assessment

The code improvement has been assessed by using the model in the previous assessment [3]. This study presents the assessment based on the selected cases listed in Table I, in order to figure out the effect of mass flux. The case selection has been made by sorting the cases which cover various void measures in the given mass flux range. The improved code calculation has been conducted by giving the mixing and void drift coefficients as 0.02 and 1.0, respectively. For the assessment, the results of improved MULTID have been compared with the previous MULTID results which models only molecular diffusion.

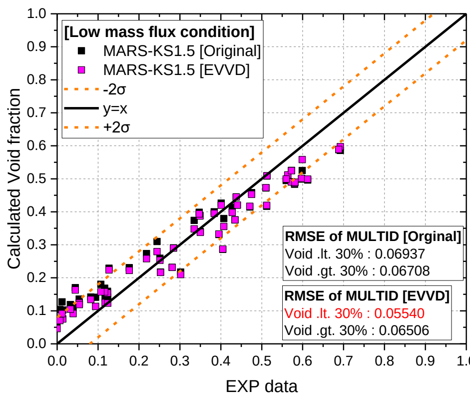
As depicted in Fig. 1, the results generally show improved void prediction. Especially, in the case of high mass flux condition, a great improvement has been made for the low void region where the previous results show overprediction tendency. Also, the results in low mass flux condition show improved void prediction in low void region, but not remarkable as in the high mass flux condition. This is because the introduced turbulent mixing model defines the mixing proportional to the channel mass flux condition. That is, the predicted mixing in the low mass flux condition must be smaller than one in the high mass flux condition. By the way, in both cases, the results in high void region show no significant improvement. This is because the inter-channel void gradient becomes smaller in the high void region. As a result, the predicted mixing becomes smaller as well. However, when comparing the root mean square error (RMSE) against the experimental values, the results clearly indicate that overall prediction tendency becomes improved by introducing the inter-channel mixing model. Therefore, it is clearly confirmed that the inter-channel mixing model has a great influence to void prediction within a bundle.

Table I: Selected cases for the assessment

Test series	Case number	Test conditions
B5	5.1122, 5.1232, 5.1341, 5.2131, 5.2241, 5.2332, 5.3112, 5.3222, 5.3331, 5.4212, 5.4321, 5.5202, 5.5311, 5.6311, 5.6321	[High mass flux] Pressure: 4.8~16.4 MPa Inlet temperature: 436~595 K Mass flux: 7~15 $10^6 kg/m^2hr$
	5.1452, 5.2452, 5.3442, 5.4432, 5.4562, 5.5431, 5.5551, 5.6441, 5.6551	[Low mass flux] Pressure: 4.8~16.6 MPa Inlet temperature: 422~595 K Mass flux: 2~5 $10^6 kg/m^2hr$
B6	6.1122, 6.1231, 6.1342, 6.2132, 6.2242, 6.2342, 6.3122, 6.3232, 6.3332, 6.4222, 6.4332, 6.5211, 6.5332, 6.6321, 6.6331	[High mass flux] Pressure: 4.8~16.5 MPa Inlet temperature: 426~585 K Mass flux: 8~15 $10^6 kg/m^2hr$
	6.1452, 6.2461, 6.3451, 6.4452, 6.4562, 6.5442, 6.5562, 6.6451, 6.6561	[Low mass flux] Pressure: 4.9~16.6 MPa Inlet temperature: 417~585 K Mass flux: 2~5 $10^6 kg/m^2hr$



(a) high mass flux condition



(b) low mass flux condition

Fig. 1 Void prediction of MULTID

3. Conclusion

As the previous work showed the necessity of the improvement of void prediction in a bundle, the improvement of MULTID in a best-estimate system code, MARS-KS, has been performed in this study. The improvement has been made by introducing inter-channel mixing model to describe direct exchanges between channels. The inter-channel exchange model consists of the EM and EVVD models for single- and two-phase conditions, respectively. From the assessment against PSBT benchmark data, it has been revealed that the improved MULTID results in better prediction of the void fraction compared to the results from original MULTID. Even more, it was indicated that the void fraction prediction using the improve MULTID was highly improved in the low void region where an excessive over-prediction was observed with the original MULTID. From this, it has been clearly confirmed that the capability of the MULTID component of MARS-KS in predicting the void distribution within a bundle has been improved owing to the inter-channel mixing model.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety(KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea. (No. 2003002)

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