Comparative assessment of two-phase crossflow behavior of system codes in bundle

Yunseok Lee [a], Taewan Kim [a*]
[a] *Department of Safety Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea*
[*] *Corresponding author: taewan.kim@inu.ac.kr*

Keywords : MARS-KS, TRACE, Crossflow, Interfacial drag

1. Introduction

The MultiD component is an original three-dimensional (3D) component of thermal-hydraulic regulatory confirmatory code, MARS-KS [1]. However, the 3D component was seldomly used in safety analysis. Therefore, MultiD was a nonmainstream component having lack of component maintenance. Meanwhile, as the recent regulatory attention has focused on the importance of multi-dimensional behavior within the reactor core, the multi-dimensional components have been widely used in safety analyses. However, MultiD requires more verification and validation for extensive use for the regulatory purposes because of aforementioned limitation.

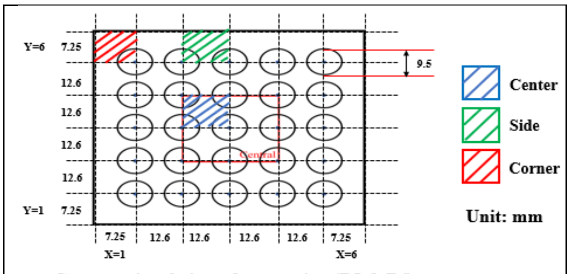
In the previous study, the assessment was conducted based on the code-to-code comparison with TRACE, a safety analysis code of US NRC [2], against the PSBT bundle experiment [3]. The results of the assessment revealed that the crossflow had great influence on void prediction in bundle. It was revealed that the 3D component of TRACE significantly overpredicted the void fraction, as it calculated restricted crossflows compared to MultiD. Meanwhile, MultiD relatively underestimated the void fraction with more active crossflows than TRACE [4]. In this study, further assessment has been conducted using latest versions of both codes, TRACE V5.0 Patch 8 and MARS-KS 2.0, respectively. Comparing closure models of both codes for crossflow calculations, the model sensitivities on the bundle void prediction have been examined.

2. Assessment results

As listed in Table I, the test section contained 25 heater rods, and the void measurement was made at the central four subchannels. For the code-to-code comparison, the assessment models were developed keeping same modeling approaches for both codes. In total, 36 subchannels were individually modeled using the 3D components of both codes with 72 uniform axial nodes. The system pressure and inlet coolant conditions were modeled by connecting pressure sink and upstream dummy hydraulic volumes at the end and inlet of the test section, respectively.

Fig. 2 depicts the results of void fraction calculations using 3D models of both codes. As aforementioned, the results clearly revealed that the Vessel component of TRACE significantly overcalculated the central void fraction, showing higher vapor concentration compared to the wall side. Meanwhile, MultiD showed flatter void distribution compared to TRACE, showing underestimation tendency at the higher void region. As shown in Fig. 3, the flat void distribution of MultiD was derived from active crossflow calculations distributing the central void toward the peripherals.

Table I: Specification of PSBT bundle test section [3]



Cross-sectional view of test section (B5 & B6)

Parameter (Unit)	Corner	Side	Center
Flow area (mm^2)	34.842	55.909	87.878
Hydraulic diameter (mm)	6.346	8.126	11.778
Heated length (mm)	3658		

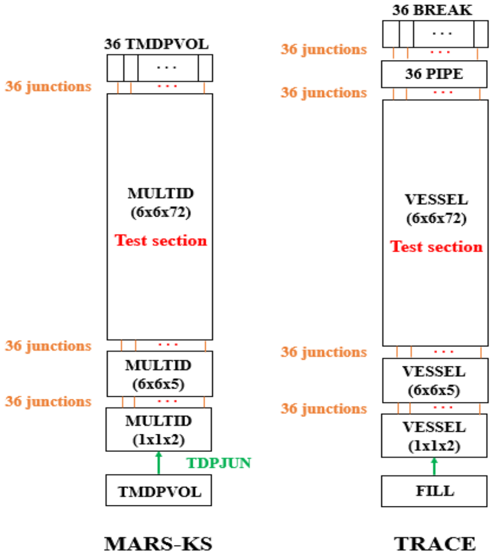
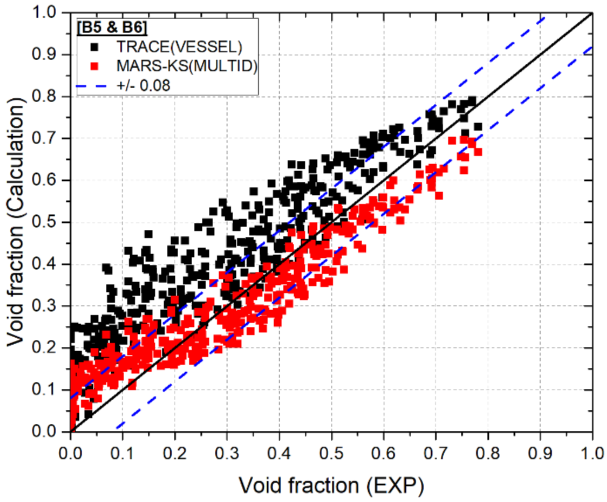
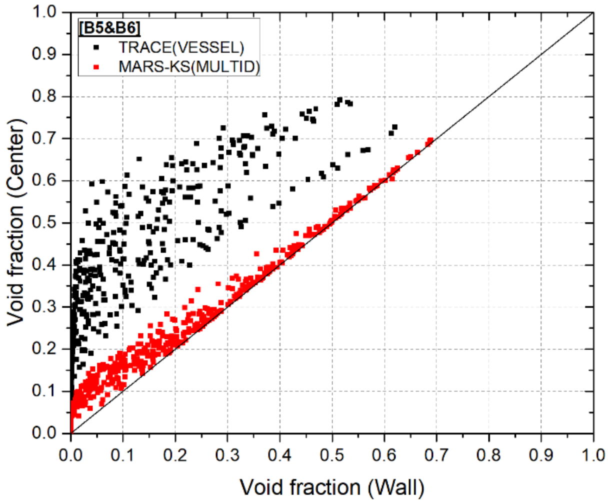


Fig. 1. Assessment models for PSBT bundle test



(a) Central void fraction



(b) Wall-to-center void distribution

Fig. 2. Assessment results – void fraction

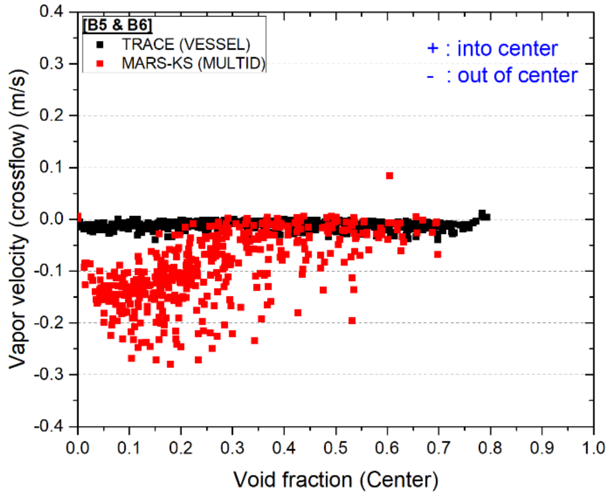


Fig. 3. Assessment results – vapor crossflow velocity

2.1 Crossflow models

$$\gamma\alpha_k\rho_k\frac{\partial v_k}{\partial t}+\gamma\alpha_k\rho_k(v_k\cdot\nabla v_k) \\ =-\gamma\alpha_k\rho_k\nabla P_k+\gamma\Gamma_k(v_k-v_{\sigma k})+\gamma f_{\sigma k}+\gamma f_{wk} \qquad (1)$$

$$\gamma\alpha_k\rho_k\frac{\partial v_k}{\partial t}+\gamma\alpha_k\rho_k(v_k\cdot\nabla v_k) \\ =-\gamma\alpha_k\rho_k\nabla P_k+\gamma\Gamma_k(v_k-v_{\sigma k})+\gamma f_{\sigma k}+\gamma f_{wk} \\ +\nabla\cdot(\gamma\tau_k)+\gamma f_{vmass} \qquad (2)$$

Eqs. (1) and (2) represent the general forms of crossflow momentum equations for Vessel and MultiD components, respectively. The first term on the right-hand-side (RHS) of both equations reveals net force imposed by pressure gradient. The second term indicates momentum transfer due to phase change. The third and fourth terms represent the frictional forces imposed by phasic interface and wall, respectively. In case of MultiD, two-additional terms exist as it considers viscous stress and virtual mass effects, respectively. Therefore, in order to compare the crossflow calculations in steady-state conditions, those three-common terms except the pressure gradient should be examined since these closure models determine the pressure and corresponding velocity profiles. Furthermore, since MultiD additionally includes viscous stress and virtual mass terms, the influence of these terms should be also examined.

However, as depicted in Fig. 4, it was revealed that those two-additional terms of MultiD had no significant influence on the crossflow calculations as well as the void prediction in bundle. Thus, the attention has been given to three common closure terms, which are momentum transfer due to phase change, interfacial and wall frictions, respectively.

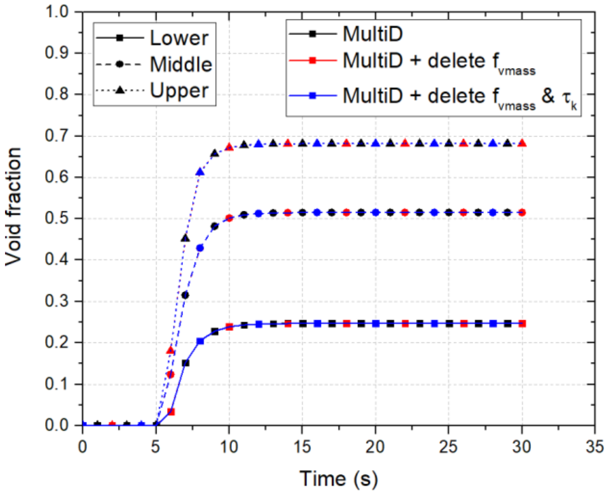


Fig. 4. Result sensitivity on viscous stress and virtual mass terms

2.2 Sensitivity on Interfacial and wall frictions

Especially, for both interfacial and wall frictions, both codes apply different scheme as listed in Table II and III. In case of TRACE, it implements the drift flux model for both vertical and horizontal flows and neglects vapor wall friction under the void fraction below 80% [2]. Meanwhile, MARS-KS applies the drift flux model only for the vertical flow and implements the drag coefficient model on the horizontal flow [3]. The results depicted in Fig. 5 clearly revealed that the application of drift flux model on the horizontal flow made significant drag on the crossflow calculations of TRACE.

Fig. 6 clearly shows the impact of the interfacial friction on the crossflow calculations. By directly applying the interfacial drag model of TRACE into MARS-KS, the MultiD tended to overcalculate the vapor at the center as the enlarged interfacial drag restricted the crossflows. The root mean square error (RMSE) results clearly indicate that MultiD exhibited similar predictability to TRACE under low void region below 30%, while such significant changes were not made in high void region exceeding 30%. As depicted in the figure, MultiD maintained similar crossflow behaviors in the high void region. This indicates that the overcalculation of TRACE at the high void region was not solely due to the interfacial drag.

As aforementioned, both codes had different wall friction treatment. TRACE neglected the wall friction on the vapor under the void fraction below 80% for both vertical and horizontal flows. This indicated that TRACE imposed less hydraulic resistance on the vapor phase. However, such difference was not the root cause of the overestimation in the high void region. As depicted in Fig. 7, even though the same wall and interfacial friction models of TRACE were applied, it did not make great change in the results of MultiD at the high void region. Therefore, further examination including phase change models is required to explain the difference in the high void region.

Table II: Comparison of interfacial drag model

Flow type	Flow regime	Models	
		TRACE	MARS-KS
Vertical	Bubbly	Churn-Turbulent (Ishii [5])	EPRI [9] (G≥100 kg/m2-s) Zuber-Findley [10] (G<100 kg/m2-s)
	Slug	Kataoka-Ishii [6]	
	Annular -mist	Drop (Ishii-Chawla [7]) + Film drag (Wallis [8])	Drag coefficient (Ishii-Chawla [7])
Horizontal	Bubbly	Churn-Turbulent (Ishii [5])	Drag coefficient (Ishii-Chawla [7])
	Slug	Kataoka-Ishii [6]	
	Annular -mist	Drop (Ishii-Chawla [7]) + Film drag (Wallis [8])	

Table III: Comparison of wall drag model

Parameter	Models	
	TRACE	MARS-KS
Friction factor	Churchill [9]	Darcy-Weisbach
Two-phase multiplier	Ferrell-Bylund empirical boiling correction [10]	HTFS [11]

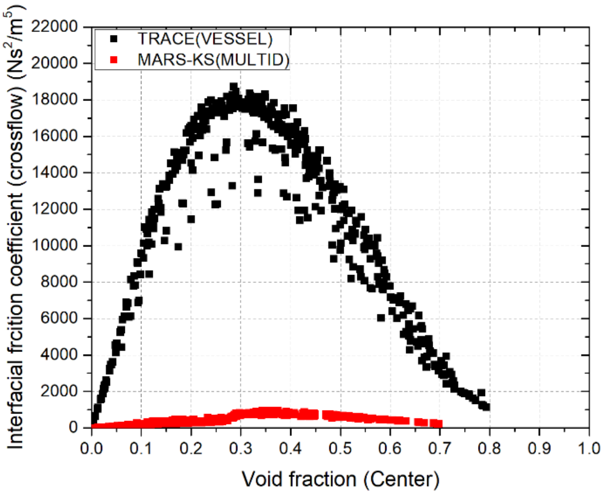
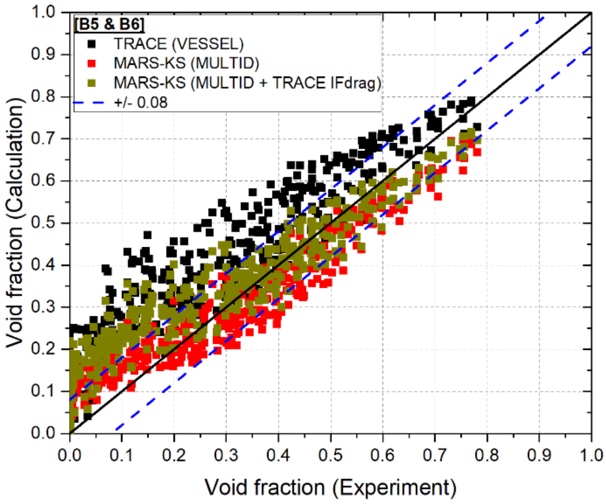


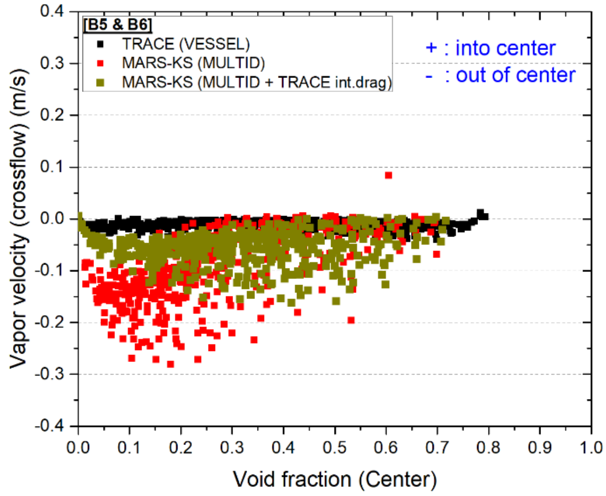
Fig. 5. Result comparison - Interfacial drag coefficient

Table IV: Root mean square error comparison

Void fraction	RMSE [CAL – EXP]		
	TRACE	MARS-KS	MARS-KS (TRACE int.drag)
< 30%	0.1528	0.0759	0.1196
> 30%	0.1010	0.0707	0.0489
All	0.1336	0.0737	0.0965



(a) Central void fraction



(b) Vapor crossflow velocity

Fig. 6. Result sensitivity on interfacial drag

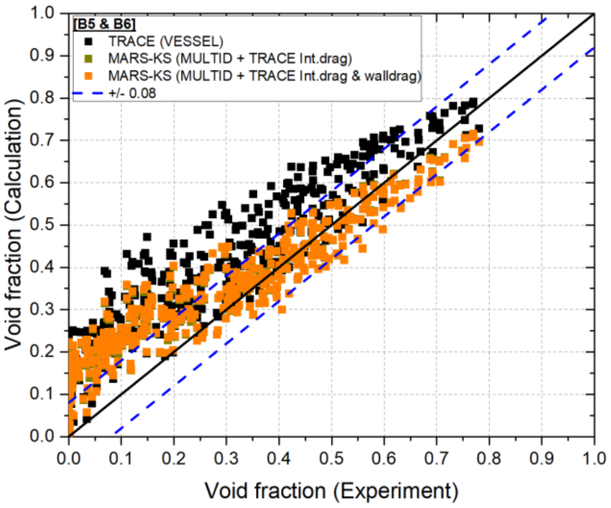


Fig. 7. Result sensitivity on wall drag

3. Conclusion

In this study, a comparative assessment of the 3D components in TRACE and MARS-KS was performed against PSBT bundle experiments. Through the assessment, it was confirmed that the code predictions for the void fraction in bundle had great sensitivities on the crossflow calculations. Comparing the crossflow models of both codes, it was found that the interfacial friction had a great impact on the crossflow calculations. Especially, in case of TRACE, as it applied too large interfacial drag with the drift flux model, the code calculated more restricted crossflows, and this made to overcalculate the void fraction compared to MARS-KS. However, it was found that those results were not solely due to the overestimation of the interfacial friction. By applying the same interfacial drag model of TRACE, it was confirmed that the MultiD changed to overcalculate the void fraction only at the low void conditions below 30%. At the high void region exceeding 30%, MultiD maintained similar crossflow behaviors. Considering the different wall friction treatment between both codes, further evaluation was made by comparing the results with additionally applying the same wall and interfacial friction models of TRACE into MARS-KS. However, the expected changes were not captured in the results. Thus, it can be concluded that further examination is required to figure out the difference in the high void region. Therefore, as a next work of this study, further assessment will be performed including phase change model.

REFERENCES

[1] Korea Institute of Nuclear Safety, MARS-KS code manual, Volume Ⅰ: Theory manual, KINS/RR-1822 Vol.1, 2018.

[2] United States Nuclear Regulatory Commission, TRACE V5.0 theory manual, Field equations, solution methods, and physcial models, 2020.

[3] A. Rubin, A. Schoedel, M. Avramova, OECD/NRC Benchmark Based on NUPEC PWR Subchannel and Bundle Tests (PSBT), Volume I: Experimental Database and Final Problem Specifications, OECD Nuclear Energy Agency, NEA/NSC/ DOC(2010), 2010.

[4] Y. Lee and T. Kim, Influence of two-phase crossflow for void prediction in bundles using thermal-hydraulic system codes, Energies, 13, 3686, 2020.

[5] M. Ishii, One-dimensional drift-flux model and constitutive equations for relative motion between phases in various flow regimes, Argonne National Laboratory report ANL-7747, 1977.

[6] I. Kataoka and M. Ishii, Drift flux model for large diameter pipe and new correlation for pool void fraction, Int. J. Heat Mass Transfer, 30, 1927-1939, 1987.

[7] M. Ishii and T. C. Chawla, Local drag laws in dispersed two-phase flow, Argonne National Laboratory report, ANL-79-105 (NUREG/CR-1230), 1979.

[8] G. B. Wallis, Annular two-phase flow, Part 1: A simple theory, J. of Basic Eng., 59-72, 1970.

[9] S. W. Churchill, Friction factor equations spans all fluid-flow regimes, Chemical Eng., 91-92, 1977.

[10] J. K. Ferrell and J. W. McGee, A study of convection boiling inside channels, Final report, Volume III, North Carolina State University, 1966.
[11] K. T. Chaxton, J. G. Collier, and J. A. Ward, H.T.F.S Correlation for two-phase pressure drop and void fraction in tubes, AERE-R7162, 1972.