Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

On the Form of Momentum Convection Term in the SPACE Multi-Dimensional Thermal-Hydraulic Module

Dongha Lee [a], Seungwook Lee [b], Byongjo Yun [a], Jae Jun Jeong [a*]
[a]*School of Mechanical Engineering, Pusan Nat'l Univ., Jangjeon2-dong, Geumjeong-gu, Busan, Korea*
[b]*Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: jjjeong@pusan.ac.kr*

1. Introduction

Extensive researches have been carried out to investigate the multi-dimensional two-phase flow phenomenon which can occur during a loss-of-coolant accident (LOCA) in the primary cooling system of a pressurized water reactor. For a realistic analysis of a LOCA, many system codes have been developed. These codes usually adopt a one-dimensional approach for the analysis of a two-phase flow and some of them have used a three-dimensional (3D) thermal-hydraulic module. However, the 3D two-phase flow modules still have great uncertainties in both physical models and numerical methods. Jeong et al. [1] showed that the form of two-fluid momentum equations significantly effects on the results of calculations, especially for a strongly heterogeneous two-phase flow.

The thermal-hydraulic safety analysis code, SPACE [2], also has a multi-dimensional thermal-hydraulic module. In this study, we modified the form of the momentum convection term of the SPACE code to improve its performance and assessed the modified code using the UPTF Test 7 [3] and DYNAS test [4].

2. Various Forms of Two-Fluid Momentum Equations

Commercial CFD (Computational Fluid Dynamics) codes, such as FLUENT [5], CFX [6], and STAR-CD [7], adopt a conservative form of momentum equations for k-phase as follows:

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k \vec{U}_k\right) + \nabla \cdot \left(\alpha_k \rho_k \vec{U}_k \vec{U}_k\right) = \vec{F}_k , \tag{1}$$

where $\vec{F}_k$ includes the pressure gradient, viscous and turbulent stress, body force, and interfacial momentum transfer.

However, most of thermal-hydraulic system codes, such as RELAP5/MOD3 [8], RELAP5-3D [9], MARS [10], and TRACE [11], use a non-conservative form of momentum equations for numerical convenience, which is obtained by expanding the first two terms in Eq. (1) and inserting the continuity equation of k-phase into the expended momentum equations. The continuity equation of k-phase is given by

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k\right) + \nabla \cdot \left(\alpha_k \rho_k \vec{U}_k\right) = \Gamma_k . \tag{2}$$

The resulting non-conservative form of momentum equation is

$$\alpha_k \rho_k \frac{\partial}{\partial t}\vec{U}_k + \alpha_k \rho_k \vec{U}_k \nabla \cdot \vec{U}_k + \vec{U}_k \Gamma_k = \vec{F}_k . \tag{3}$$

From a mathematical point of view, Eq. (1) and (3) are the same, but they lead to different results in numerical integrations. In the discretization equation of Eq. (1), the convection term is clearly defined at the surfaces of a control volume. On the other hand, when Eq. (3) is used, $\alpha_k \rho_k \vec{U}_k$ in the second term in the left-hand side (LHS) is defined at the center of a control volume. (i.e., the volume-averaged quantities are used.). The convection term represents the net balance of the momentum flux at the surfaces of a control volume. By using the volume-averaged quantities, the momentum convection cannot be appropriately represented when the two-phase flow is spatially heterogeneous. In other words, the non-conservative form of momentum equations can evoke inaccurate numerical solutions under some two-phase flow conditions.

Jeong et al. [1] recognized this defect and suggested a new discretization method called a semi-conservative form of momentum equations. The semi-conservative form of momentum equations can be obtained by expanding only the time derivative term in the LHS of Eq. (1), and then substituting Eq. (2):

$$\alpha_k \rho_k \frac{\partial}{\partial t}\vec{U}_k + \nabla \cdot \left(\alpha_k \rho_k \vec{U}_k \vec{U}_k\right) - \vec{U}_k \nabla \cdot \left(\alpha_k \rho_k \vec{U}_k\right) + \vec{U}_k \Gamma_k = \vec{F}_k . \tag{4}$$

As can see in Eq. (4), the semi-conservative form is not conservative in time, but conservative in space. The semi-conservative form of momentum equations has a characteristic that it is identical with the conservative form in a steady state. Park et al. [12] confirmed the advantages of the semi-conservative form of momentum equations compared to the non-conservative form using the CUPID code.

Meanwhile, the SPACE code use the following momentum equation [2]:

$$\alpha_k \rho_k \frac{\partial}{\partial t}\vec{U}_k + \alpha_k \rho_k \nabla \cdot \left(\vec{U}_k \vec{U}_k\right) - \alpha_k \rho_k \vec{U}_k \nabla \cdot \vec{U}_k + \vec{U}_k \Gamma_k = \vec{F}_k . \tag{5}$$

In the numerical methods, $\alpha_k \rho_k$ in the second and third terms in the left-hand side of Eq. (5) are defined as the volume-averaged quantities likewise the non-conservative form. Thus, SPACE can also evoke unphysical numerical solutions under strongly heterogeneous two-phase flow conditions.

In this study, the semi-conservative form of momentum equations was implemented into the SPACE multi-dimensional module.

3. Modification of the Momentum Convection Term

In the SPACE multi-dimensional module, the structured, staggered mesh system (Fig. 1) is used in rectangular and cylindrical coordinates. The cells with real lines and dotted lines in Fig. 1 are the continuity cells and momentum cells, respectively. The momentum equations are solved at the momentum cells.

In order to modify the form of momentum convection term of the SPACE multi-dimensional module, Eq. (4) was discretized along the x-direction in Fig. 1:

$$(\alpha\rho)^n_{i+1/2,j}\frac{\vec{U}^{n+1}_{i+1/2,j}-\vec{U}^{n}_{i+1/2,j}}{\Delta t} + \left[\frac{(\alpha\rho\vec{U}\vec{U})^n_{i+1,j}-(\alpha\rho\vec{U}\vec{U})^n_{i,j}}{\Delta x} - \vec{U}^n_{i+1/2,j}\frac{(\alpha\rho\vec{U})^n_{i+1,j}-(\alpha\rho\vec{U})^n_{i,j}}{\Delta x}\right] + \left[\frac{(\alpha\rho\vec{U}\vec{V})^n_{i+1/2,j+1/2}-(\alpha\rho\vec{U}\vec{V})^n_{i+1/2,j-1/2}}{\Delta y} - \vec{U}^n_{i+1/2,j}\frac{(\alpha\rho\vec{V})^n_{i+1/2,j+1/2}-(\alpha\rho\vec{V})^n_{i+1/2,j-1/2}}{\Delta y}\right] = \left(\vec{F}-\vec{U}\Gamma\right)^{n+1}_{i+1/2,j}. \qquad (6)$$

Meanwhile, the discretized equation of Eq. (5) is given by:

$$(\alpha\rho)^n_{i+1/2,j}\frac{\vec{U}^{n+1}_{i+1/2,j}-\vec{U}^{n}_{i+1/2,j}}{\Delta t} + (\alpha\rho)^n_{i+1/2,j}\left[\frac{(\vec{U}\vec{U})^n_{i+1,j}-(\vec{U}\vec{U})^n_{i,j}}{\Delta x} - \vec{U}^n_{i+1/2,j}\frac{\vec{U}^n_{i+1,j}-\vec{U}^n_{i,j}}{\Delta x}\right] + (\alpha\rho)^n_{i+1/2,j}\left[\frac{(\vec{U}\vec{V})^n_{i+1/2,j+1/2}-(\vec{U}\vec{V})^n_{i+1/2,j-1/2}}{\Delta y} - \vec{U}^n_{i+1/2,j}\frac{\vec{V}^n_{i+1/2,j+1/2}-\vec{V}^n_{i+1/2,j-1/2}}{\Delta y}\right] = \left(\vec{F}-\vec{U}\Gamma\right)^{n+1}_{i+1/2,j}. \qquad (7)$$

Comparing Eq. (6) and (7), $\alpha_k\rho_k\vec{U}_k$ in the convection term of Eq. (6) are clearly defined at the surfaces of a control volume.

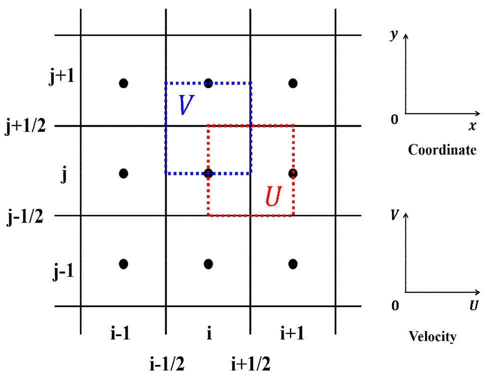

Fig. 1. The staggered-grid mesh

4. Assessment of the Modified SPACE Code

For the assessment of the modified SPACE code, the UPTF Downcomer Test 7 and the DYNAS tests were used.

4.1 UPTF Downcomer Test 7

The UPTF [3] is a real-scale test facility designed to investigate the thermal-hydraulic behavior of the primary coolant during the blowdown, refill, and reflood phase of a LOCA. Among various tests using this facility, Test 7 was performed to observe the behavior in the primary cooling system during the refill phase. To focus on the mechanical interaction of each phase, the test was conducted under the nearly saturated conditions. The test consists of four runs, and each run has several phases with various combinations of steam and ECC injection rate. Detailed test conditions are summarized in Table 1. The lower plenum water level was controlled by a drain valve at the bottom of the lower plenum.

To simulate the test, the downcomer was modeled using the multi-dimensional module with an 8 x 1 x 10 mesh as in Fig. 2.

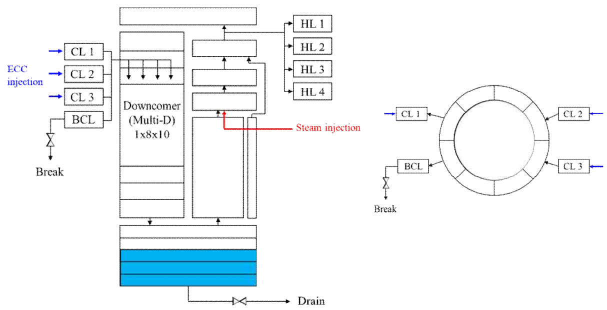

Fig. 2. Nodalization for the UPTF Test7

Table 1. Test conditions for the UPTF Test7

Run	Phase	Steam Injection (kg/s)	ECC Injection (kg/s)		
			CL-1	CL-2	CL-3
200	I	104	494	0	0
	II	54	736	30	0
	III	102	735	0	0
201	I	102	0	487	490
	III	102	493	487	489
202	I	128	0	486	491
203	I	69	735	0	0
	II	30	737	0	0
	III	71	737	0	733
	IV	51	493	485	487

Figs. 3 and 4 show the simulation results of Run 203 of UPTF Test 7. In case of the downcomer pressure, the calculation result of the modified SPACE code are not always better than the original code. The modified SPACE code consistently under-predicts the downcomer pressure. This can be improved by modifying the pressure drop model between the downcomer and the break. In this study, the water delivery to the lower plenum is a key parameter, which is closely related to the integrity of the nuclear fuel rods. As shown in Figs. 4 and 5, the modified SPACE code predicts the water delivery more closely to the experimental data than the original code for all cases.

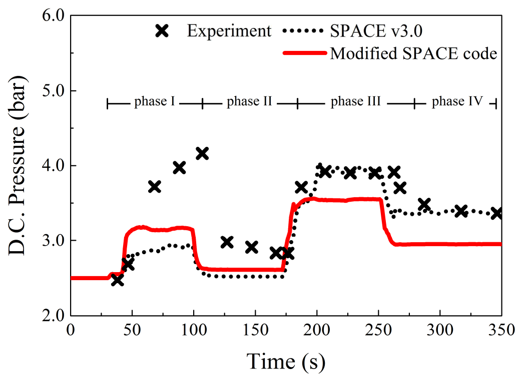

Fig. 3. Simulation result of the UPTF Test7 Run203 (Downcomer pressure)

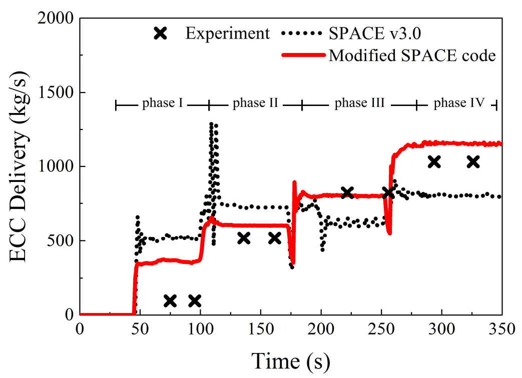

Fig. 4. Simulation result of the UPTF Test7 Run203 (ECC delivery)

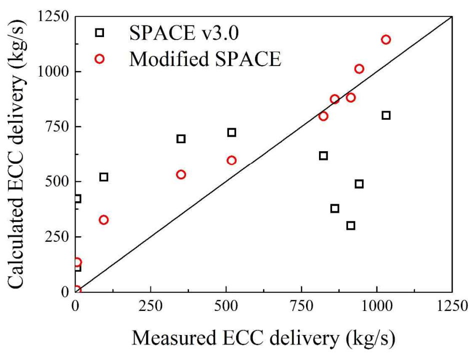

Fig. 5. Comparison of the measured and calculated water delivery

4.2 DYNAS Test

The objective of DYNAS (a test facility for DYNamics of Air/water System) test [4] is to investigate the two-phase flow behavior inside the downcomer during a transient condition. The test section of the DYNAS is a slab, which has 1.43 m in length and height with 0.11 m in width. Each test was conducted with changing the location of the inlet and outlet in order to observe various multi-dimensional two-phase flows. The local void fraction was measured at 225 points inside the test section using the impedance measurement method. The test consists of 20 cases distinguished by the location of the inlet and outlet, inlet flow rate. The test conditions are summarized in Table 2. The calculation grid was modeled as 17 x 17 mesh considering measurement location as shown in Fig. 6.

Table 2. Test conditions for the DYNAS

Case	AB/AC/BB/BC				AE/BE	
	01	02	03	04	01	04
Water (kg/s)	4.0	4.0	20.0	20.0	4.0	10.0
Air (g/s)	2.0	20.0	2.0	20.0	2.0	10.0

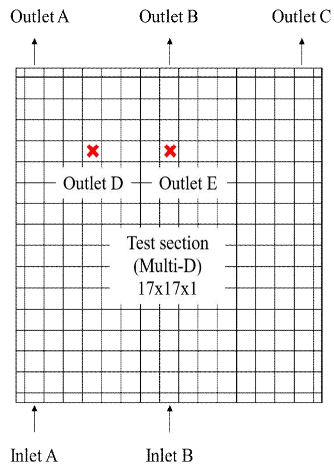

Fig. 6. Nodalization for the DYNAS

Fig. 7 shows the void fraction data of the DYNAS AB02 case. The modified SPACE predicts well the void fraction profile of the experimental data than the original code. The average void fraction errors are compared ~~is~~ in Table 3. The average error was obtained as follows:

$$\text{Average error} = \frac{\sum_{i=1}^{n} |C_i - M_i|}{n}, \qquad (6)$$

where C_i and M_i is the calculated value and measured value, respectively. n is the number of measurement points (in the DYNAS test, n is 225.). As can see in Table 3, the modified SPACE code shows improved results compared to the original code, especially with the high air injection.

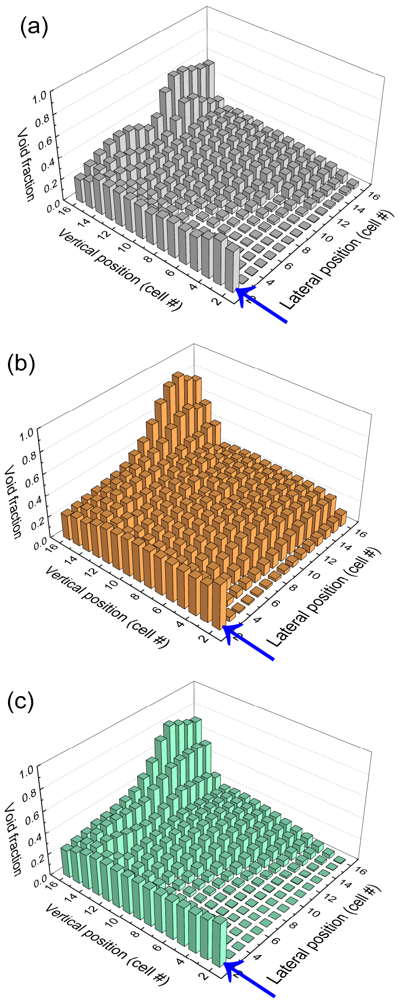

Fig. 7. Void fraction data of the DYNAS AB02:
a: Experiment, b: Original SPACE, c: Modified SPACE.

Table 3. Average void fraction error

Case		SPACE v3.0	Modified SPACE
AB	01	0.87	1.37
	02	13.40	4.77
	03	4.60	4.24
	04	16.40	10.80
AC	01	0.87	0.83
	02	15.00	3.83
	03	1.08	1.34
	04	12.40	8.28
BB	01	6.80	1.87
	02	44.20	29.60
	03	5.64	6.49
	04	13.90	10.50
BC	01	2.77	2.81
	02	21.20	18.10
	03	8.02	7.25
	04	10.60	16.50
AE	01	7.06	7.32
	04	9.53	9.24
BE	01	12.70	13.30
	04	11.00	14.70

5. Conclusions

In this study, the semi-conservative form of momentum equations was implemented into the SPACE multi-dimensional module. Thereafter, the modified code was assessed using two multi-dimensional two-phase flow experiments, UPTF Test 7 and the DYNAS tests. In the simulation results of the UPTF test7, the modified SPACE code predicted the water delivery more closely to the experimental data than the original code. For the DYNAS test, the results of the modified SPACE code showed the better agreement with the experimental data in general.

In conclusion, the computational accuracy of the SPACE multi-dimensional module was greatly improved by modifying the form of the momentum convection term, especially when the two-phase flow is strongly heterogeneous.

Acknowledgement

This work was supported by the Nuclear Research & Development Program of the NRF (National Research Foundation of Korea) grant funded by the MSIT (Ministry of Science, ICT), Republic of Korea (Grant code: No. NRF-2017M2A8A4015059)

REFERENCES

[1] J.J. Jeong et al., Improvement and assessment of the CATHARE2 three-dimensional module compared with the UPTF downcomer test 7, Nucl. Tech. 117, 267-280, 1997.

[2] SPACE 3.0 Manual Volume 1: Theory manual, KHNP, 2016.

[3] H. Glaeser, Analysis of downcomer and tie plate countercurrent flow in the upper tie plate test facility (UPTF), Proc. Fourth Int., 1989.

[4] D.J. Euh et al., Two-Dimensional Void Fraction Distribution by Measuring Impedance for the Steady State Air-Water Flow Conditions in Large Slab Geometry, KAERI, KAERI/TR-4056/2010, 2010.

[5] FLUENT 6.3, User's guide, FLUENT Inc., 2006.

[6] ANSYS CFX-Solver, Release 10.0: Theory, ANSYS Inc., 2005.

[7] STAR-CD version 4.0, STAR-CD Methodology, CD-adapco, 2006.

[8] RELAP5/MOD3 Code Manual Volume I: Code Structure, System Models, and Solution Methods, U.S. NRC, 1998.

[9] RELAP5-3D Code Manual Volume I: Code Structure, System Models and Solution Methods, INEEL, 2001.

[10] J.J. Jeong et al., Development of a multi-dimensional thermal-hydraulic system code: MARS 1.3.1, Nucl. Eng., Vol. 26, No. 18, pp. 1611-1642.

[11] TRACE V5.0, Theory manual, U.S. NRC, 2000.

[12] I.K. Park et al., Numerical effects of the semi-conservative form of momentum equations for multi-dimensional two-phase flows Nucl. Eng. Des., 239, 2365-2371, 2009.