Multi-Dimensional Flow Model in the SPACE Code

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1. Introduction

Various efforts to implement multidimensional flow models in system codes have been underway for several decades[1-3]. Table 1 compares the multidimensional models (R = RELAP5-3D V4.0, T = TRACE V5.0 Patch 5, M = MARS-KS 2.0, S = SPACE 3.2)

In SPACE 3.2, the multidimensional convection term was implemented using the finite volume method, but the term was not validated thoroughly. Moreover, the viscous term was also included.

This study presents the recent effort to implement multidimensional convection, viscous, and turbulence effects into the SPACE code, using the finite-difference method.

Table 1. Status of system codes

Multidimensional model		R	T	M	S
Contection term	Mass	O	O	O	O
	Energy	O	O	O	O
	Momentum	O	O	O	O
Viscous terms	Momentum	O	X	O	X
Turbulence effect	Energy	X	X	O	X
	Momentum	X	X	O	X

2. Multi-dimensional flow model

While the sum and difference momentum equations are used in the one-dimensional flow model, the phase-intensive form of each phase momentum equation is used in the multi-dimensional flow model.

Two-coordinate systems were implemented: rectangular and cylindrical coordinates. Only cylindrical multi-dimensional momentum equations are described here. Equations (1) to (3) show the convection terms in the radial, circumferential, and axial components, respectively, of each phase momentum equation.

$$u_r \frac{\partial u_r}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta} - \frac{u_\theta^2}{r} + u_z \frac{\partial u_r}{\partial z}, \qquad (1)$$

$$u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{u_r u_\theta}{r} + u_z \frac{\partial u_\theta}{\partial z}, \qquad (2)$$

$$u_r \frac{\partial u_z}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta} + u_z \frac{\partial u_z}{\partial z}. \qquad (3)$$

Equations (4) to (6) show the viscous terms in the radial, circumferential, and axial components, respectively, of each phase momentum equation.

$$\nu_{eff}\left(\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2} + \frac{\partial^2 u_r}{\partial z^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{u_r}{r^2} - \frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}\right) + \frac{\nu_{eff}}{3}\left(\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial^2 u_\theta}{\partial r \partial \theta} + \frac{\partial^2 u_z}{\partial r \partial z} - \frac{u_r}{r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{1}{r^2}\frac{\partial u_\theta}{\partial \theta}\right), \qquad (4)$$

$$\nu_{eff}\left(\frac{\partial^2 u_\theta}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2} + \frac{\partial^2 u_\theta}{\partial z^2} + \frac{1}{r}\frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r^2} + \frac{2}{r^2}\frac{\partial u_r}{\partial \theta}\right) + \frac{\nu_{eff}}{3}\left(\frac{1}{r}\frac{\partial^2 u_r}{\partial \theta \partial r} + \frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2} + \frac{1}{r}\frac{\partial^2 u_z}{\partial \theta \partial z} + \frac{1}{r^2}\frac{\partial u_r}{\partial \theta}\right), \qquad (5)$$

$$\nu_{eff}\left(\frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2} + \frac{\partial^2 u_z}{\partial z^2} + \frac{1}{r}\frac{\partial u_z}{\partial r}\right) + \frac{\nu_{eff}}{3}\left(\frac{\partial^2 u_r}{\partial z \partial r} + \frac{1}{r}\frac{\partial^2 u_\theta}{\partial z \partial \theta} + \frac{\partial^2 u_z}{\partial z^2} + \frac{1}{r}\frac{\partial u_r}{\partial z}\right), \qquad (6)$$

where ν_{eff} is the effective kinematic viscosity, including the turbulence effect.

The multi-dimensional convection and viscous terms were implemented using the finite-difference method. The first-upwind scheme was applied to the convection terms. Basically, the central difference schemes were used to compute the viscous terms.

3. Results

Various problems were simulated to validate the multi-dimensional flow model. Selected results are presented in this paper. Figure 1 shows the vapor flows (1 bar, 393 K) predicted by SPACE and CFD. In this flow, the convection and viscous effects are comparable. The horizontal velocity profile along the vertical centerline predicted by SPACE is similar to that by CFD, indicating the validity of the convection and viscous terms in the rectangular coordinates.

Figure 2 shows the radial inviscid flow of the liquid. The radial velocity decreases inversely with radius. The predicted velocities in the non-uniform grids match the theoretical velocities, indicating the validity of the cylindrical convection term.

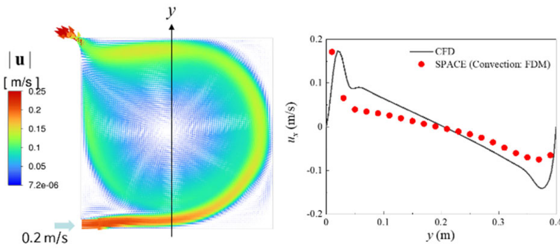

Fig. 1 Single-phase vapor flow in a 2D cavity

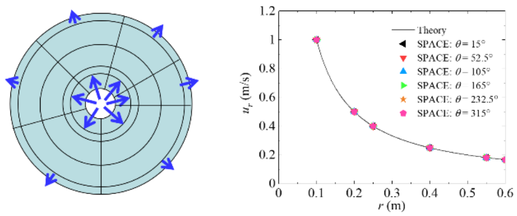

Fig. 2 Pure-radial liquid flow

Figure 3 shows the fully-developed liquid flow in an annulus. The predicted velocities in the non-uniform grids match the theoretical velocities, confirming the validity of the cylindrical viscous term.

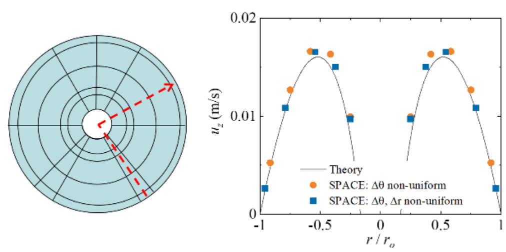

Fig. 3 Fully-developed liquid flow in an annulus

KAERI measured the distributions of void fraction in a two-dimensional slab [4]. Figure 4 shows the experimental and SPACE results for condition BB01-I. Air is injected through the inlet port placed at the middle and bottom of the slab. The outlet port is placed at the middle and top of the pool. Figure 5 shows the experimental and SPACE results for condition BB04-I, where the outlet port is placed at the side of the pool. The void fraction trend predicted by SPACE is similar to the experimental trend.

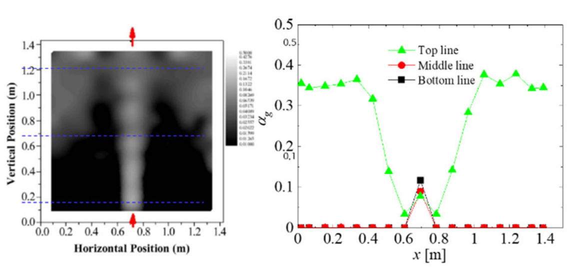

Fig. 4 Simulation of DYNAS experiment: BB01-I

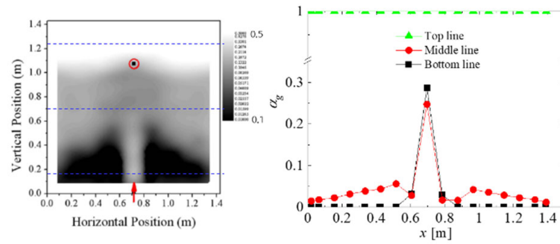

Fig. 5 Simulation of DYNAS experiment: BB04-I

4. Conclusions

A multi-dimensional flow model was developed in the SPACE code. Through various simulations, we confirmed that the model functions well. This model will be used jfor LOCA analysis.

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