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Improvement of dynamic motion model in MARS-KS for downcomer modeling of a maritime reactor with cross-junction connection

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1. Introduction

There has been growing interest in floating nuclear power plant [1] or maritime reactor to use nuclear power in propulsion or supplying electricity to coastal area. Due to the waves and tides in the ocean environment, the reactor can be exposed to dynamic condition such as inclination, heaving or rolling. Therefore, it is necessary to analyze the effect of dynamic motion on the maritime reactor in the viewpoint of reactor design and safety. In this purpose, the nuclear safety analysis codes, which have a simulation capability of dynamic motion, have been developed such as RETRAN-02/GRAV [2], RETRAN-03/MOV [3], RETRAN-03/INT [4] and RELAP5-3D [5].

Meanwhile, MARS-KS [6] is a thermal-hydraulic analysis code for the regulation of land-based nuclear power plants in Korea, developed by the Korea Atomic Energy Research Institute (KAERI) based on the RELAP5/MOD3 and COBRA-TF. Likewise, the dynamic motion model is included in MARS. In the previous research, the model verification works were carried out by conceptual problems and model improvements were performed including implementation of user-supplied table and modification of flow regime determination under inclination [7].

However, these activities are limited to one-dimensional simulation though the oceanic motion actually occurs in a three-dimensional form. Therefore, it is necessary to confirm the multi-dimensional modeling and simulation capability of the dynamic motion model in MARS-KS. In this point of view, the preliminary research should be carried out in order to extend the simulation capability of MARS-KS dynamic motion model to multi-dimensional simulation.

In this study, the cross-junction connecting problem was identified for downcomer modeling using the dynamic motion model. Then it was resolved by code modification for the dynamic motion model and verification was performed using the conceptual problems including downcomer modeling under dynamic condition.

2. Improvement of dynamic motion model in MARS-KS for downcomer modelling

In this section, the improvement of dynamic motion model in MARS code for downcomer modeling is described. At first, it was figured out that the dynamic motion model had a limitation for downcomer modeling using cross-junction connection. Secondly, in order to resolve this problem, the necessary procedure to connect the cross-junction was implemented in the calculation module of MARS code. In addition, it was verified with two conceptual problems including downcomer modeling under dynamic motion.

2.1 Dynamic motion model in MARS-KS and its limitation in cross-junction connection

The dynamic motion model in MARS code can calculate the additional acceleration and coordinate transformation of the computational node under the condition of dynamic motion. The additional acceleration is mathematically modeled in momentum equation based on following Navier-Stokes equation for non-inertial frame [5].

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\nabla\cdot\boldsymbol{\tau}+\rho(\mathbf{g}-\mathbf{a}_{add}) \tag{1}$$

where

$$\mathbf{a}_{add}=-\frac{d^2\mathbf{R}}{dt^2}-2\boldsymbol{\Omega}\times\mathbf{u}-\frac{D\boldsymbol{\Omega}}{Dt}\times\mathbf{r}-\boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r}) \tag{2}$$

In RHS of Eq. (2), each term is corresponding to frame acceleration, Coriolis acceleration, tangential acceleration, and centrifugal acceleration, in turn. Eq. (1) is implemented as one-dimensional form of momentum equation in MARS code as follows [7].

$$\begin{aligned}&\alpha_g\rho_g\frac{\partial v_g}{\partial t}+\alpha_f\rho_f\frac{\partial v_f}{\partial t}+\frac{1}{2}\alpha_g\rho_g\frac{\partial {v_g}^2}{\partial x}+\frac{1}{2}\alpha_f\rho_f\frac{\partial {v_f}^2}{\partial x}\\&=-\left(\frac{\partial P}{\partial x}\right)+\rho_m B_x-\alpha_g\rho_g FWGv_g-\alpha_f\rho_f FWFv_f-\Gamma_g(v_g-v_f)\end{aligned} \tag{3}$$

where FWG is the gas wall drag coefficient, FWF is the liquid wall drag coefficient, and Γ_g is the volumetric vaporization rate. The body force term ‘B_x’ is modified in accordance with the variation of acceleration, expressed as ‘g’ and ‘a_{add}’ in the Eq. (1) and (2). Secondly, the coordinate transformation is modeled by using rotation matrix for X, Y, and Z axes in the Cartesian coordinates as shown in Eq. (3). The details of the dynamic motion model and its verification works were explained in Beom et al. [7].

$$[M_{rot}]=[\mathrm{M_Z}]\mathrm{M_Y}][\mathrm{M_X}] \tag{4}$$
$$=\begin{bmatrix}\cos\theta_z & -\sin\theta_z & 0\\ \sin\theta_z & \cos\theta_z & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\theta_y & 0 & \sin\theta_y\\ 0 & 1 & 0\\ -\sin\theta_y & 0 & \cos\theta_y\end{bmatrix}$$
$$\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_x & -\sin\theta_x\\ 0 & -\sin\theta_x & \cos\theta_x\end{bmatrix}$$

Meanwhile, the fluid flow is assumed to be one-dimensional in dynamic motion model, since MARS code solves one-dimensional momentum equation as depicted in Eq. (3), except the case of MultiD simulation. However, the component where the multi-dimensional phenomena is important, such as downcomer of the reactor under the accident condition, crossflows can be simulated by connecting hydrodynamic volumes with cross-junctions. For this purpose, MARS classified six surfaces according to the flow direction of the volume as depicted in Fig. 1. The incoming face is ‘face 1’, the outgoing face is ‘face 2’, and the rest ‘face 3’ to ‘face 6’ represent for the other two axes perpendicular to the direction of main flow. For example, faces 3 to 6 can connect volumes in the case of cross-junction connection.

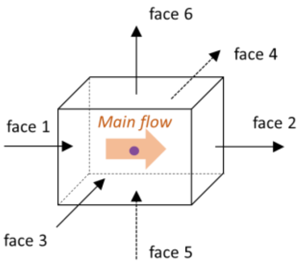

Fig. 1. Six faces of the hydrodynamic volume in MARS-KS

However, in the present version of the dynamic motion model, it cannot recognize the face 3 to 6 but can use the main flow direction (face 1 and 2) exclusively. If one connects two adjacent volume laterally using face 1 and 2 in the dynamic motion model, as depicted in Fig. 2, the gravitational force is induced between two volumes though they actually have no height difference each other.

Therefore, any hydrodynamic modeling with cross-junction connection such as downcomer cannot be well simulated in the present dynamic motion model. It is a critical limitation for the dynamic motion modeling in MARS for simulating three-dimensional oceanic motion. In order to extend a simulation capability of MARS dynamic motion model to multi-dimensional flow, code modifications were carried out for cross-junction connection in the dynamic motion model as describe in the following section.

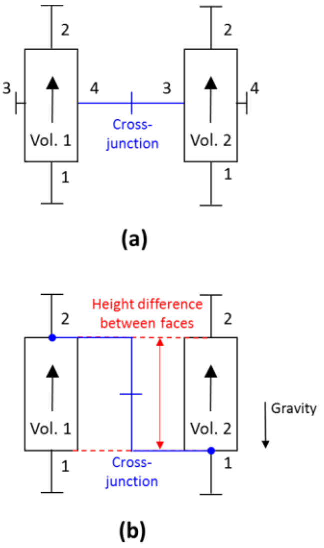

Fig. 2. Cross-junction connection problem in the dynamic motion model, (a) general case, (b) in the dynamic motion model (before modification)

2.2 Modification of cross-junction connection in the dynamic motion model

To resolve the issue, the dynamic motion model is improved through two steps. Firstly, we added a procedure in the ‘ExtraProcedure’ calculation module in MARS for recognizing face 3 to 6 in the dynamic motion model. Then, as shown in Fig. 3, it was necessary to calculate the gravity according to the height difference between two volumes connected by cross-junction under dynamic conditions like inclination or rotation. This procedure was added in the ‘HydroSolveM’ calculation module in MARS.

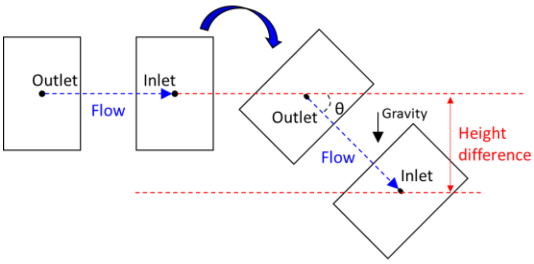

Fig. 3. Height difference between hydrodynamic volumes connected with cross-junction under inclined condition

2.3 Verification with two conceptual problems

Verification of the modification work was performed with two conceptual problems. The first problem, as shown in Fig. 4, is to simulate the two-dimensional tank with inclination and rotation modeled by six one-dimensional vertical pipes and cross-junctions connecting them. The pipes are partially filled with water to check the movement of water under inclined (30˚) and rotating (30˚ and 100 s periods) conditions.

The water level in the pipe should be changed as flow is generated at the cross-junction due to the inclination change. The verification result of the first problem is shown in Fig. 5 The water level is maintained under inclination and rotating motion. For the quantitative verification, the water level in the pipe numbered 100 calculated in MARS is compared with analytic solution. The simulation results are agreed with those of analytic solution within maximum error of 0.02% and 0.78 % for inclination and rotating motion, respectively.

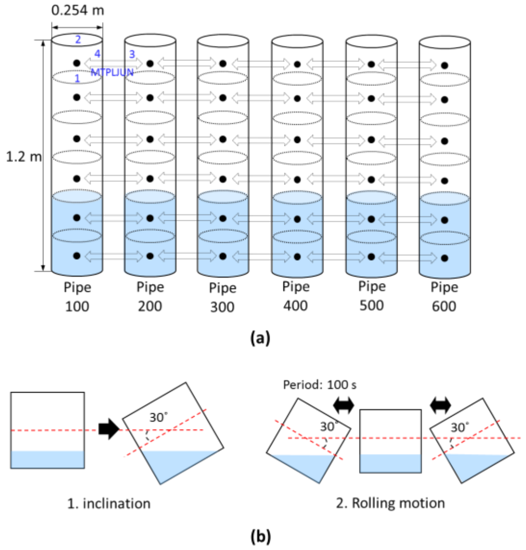

Fig. 4. Definition of conceptual problem 1, (a) MARS nodalization (b) dynamic motion condition

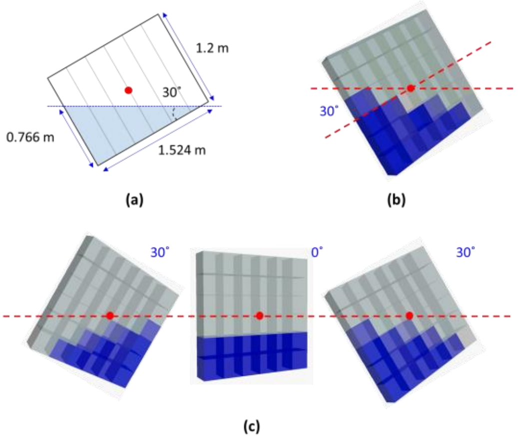

Fig. 5. Simulation result of conceptual problem 1, (a) analytic solution (b) inclination (c) rolling motion

The second problem is to simulate the downcomer inclination (45˚) and rolling motion (45˚ and 100 s periods) by using four pipes with cross-junction connecting them as shown in Fig. 6. Before the code modification, although the pipes stand vertical without any motion, the water levels in pipes are not identical as it is under inclined condition as depicted in Fig. 6-(c). It is because the cross-junction misconnects the two volumes of each pipe with wrong faces, as illustrated in Fig. 2-(b). It causes unintended height difference between volumes connected with cross-junction so the water flows due to gravitational force.

After the code improvement, MARS simulation results were compared with analytic solution for water levels of four pipes. Fig. 7 shows simulation result of downcomer under X and Y-axes inclination with water levels. MARS well predicts the water level difference of each pipe within maximum error of 1.6% and 1.7 % for X and Y-axes, respectively. In addition, in the case of rolling simulation as shown in Fig. 8, the simulation results show good agreement within maximum error of 0.4 % and 1.1 % for X and Y-axes, respectively.

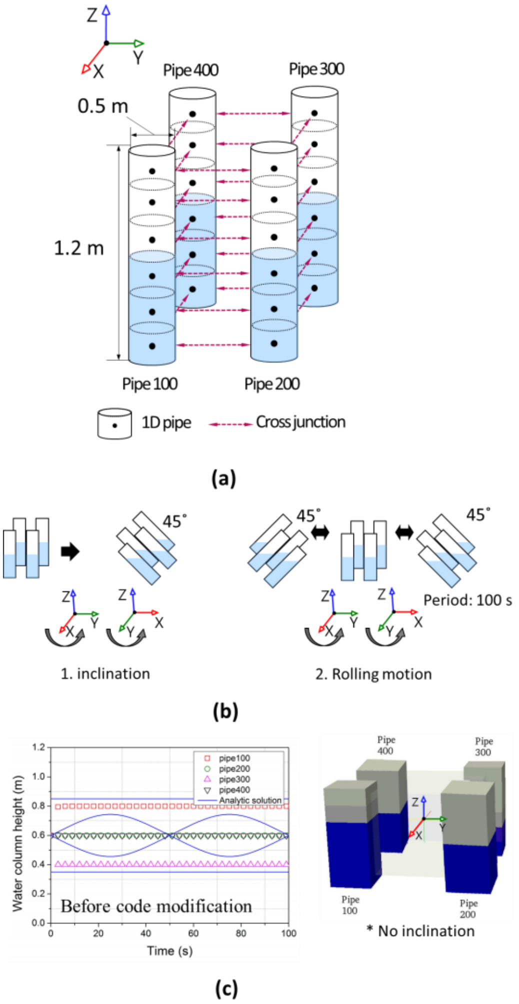

Fig. 6. Definition of conceptual problem 2, (a) MARS nodalization (b) dynamic motion condition (c) simulation result before code modification (no inclination)

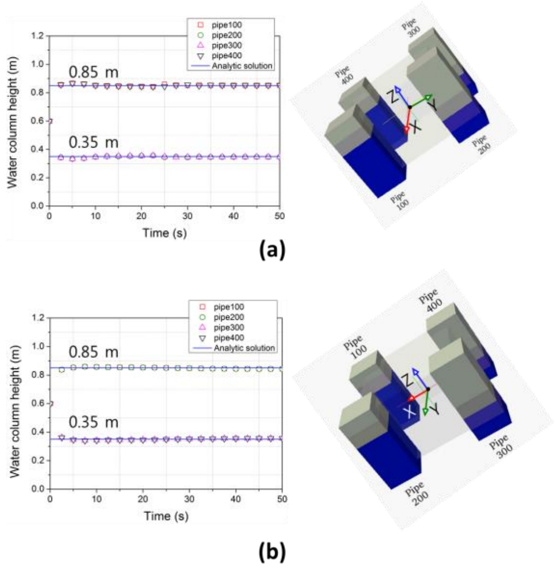

Fig. 7. Simulation result under inclination of conceptual problem 2, the water level in each pipe, (a) X-axis (b) Y-axis

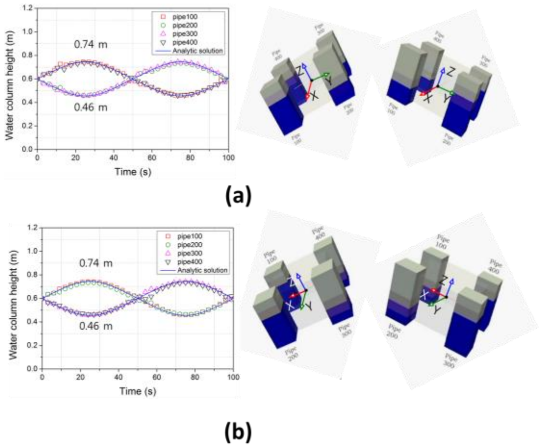

Fig. 8. Simulation result under rolling motion of conceptual problem 2, the water level in each pipe, (a) X-axis (b) Y-axis

3. Conclusions

The MARS-KS dynamic motion model was improved for downcomer modeling with cross-junction connection. Before code modification, due to its limitation in modeling of junction connection in dynamic motion model, the code cannot accurately model the cross-junction. In order to resolve this problem, the face recognizing process is implemented in ‘ExtraProcedure’ module and the calculation procedure that consider height difference between hydrodynamic volumes connected with cross-junction under inclination is added in ‘HydroSolveM’ module in MARS-KS. These modifications were verified by two conceptual problems including downcomer modeling with cross-junction connection. In result, the dynamic motion model in MARS-KS can model the downcomer using four pipes under dynamic motion.

In the future work, the generalized multi-dimensional modeling criteria of dynamic motion model in MARS-KS should be established. For example, in the modified version of dynamic motion model, the cross-junction connections between the volumes are limited to the directions perpendicular to faces 1 to 6 such as shown in downcomer modeling in the conceptual problem 2 of this study. Therefore, it is also necessary to improve the dynamic motion model to allow cross-junction modeling for arbitrary directions.

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