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Developmental status of the staggered mesh hydraulic solver in SPACE

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1. Introduction

SPACE is a nuclear power plant safety analysis code, which is under development through a joint research between Korean nuclear industry and research institute. It adopts two-phase three field governing equations. Several mesh systems and numerical schemes, such as structured, unstructured, staggered, collocated meshes, semi-implicit, and nearly implicit numerical schemes, have been tried so far[1]. In this paper, focus is placed on the evaluation of its nodalization capability as a system analysis code. Especially, the flexible feature of the staggered mesh system of SPACE will be described, focusing on how to model the complex geometries and various types of their connections typically encountered in nuclear power plant systems. The semi-implicit numerical solution scheme using the staggered mesh system and some of the application results will be also presented.

2. Mesh system

2. 1 Staggered mesh system

The staggered mesh system of SPACE is based on the orthogonal hexahedral shape of cell and the surrounding faces. All of the geometric quantities are described in terms of cell volume, centroid, face area, and face center, so that Cartesian and cylindrical mesh systems can be simultaneously operated in this mesh system. Each scalar cell has normally six faces in three-dimensional Cartesian or cylindrical mesh blocks. But two-dimensional Cartesian meshes or one-dimensional pipe can be also represented only by reducing numbers of the surrounding faces. Direction of the cell and the associated faces can be distinguished by the unique number sequentially given to each face. Each momentum cell is shifted by the half size of scalar cell so that it consists of the front half part of the owner scalar cell and the back half part of the neighbor scalar cell. Each face can be divided into several sub-faces. With these sub-faces, one-dimensional or three-dimensional branches are easily modeled in the SPACE code staggered mesh system. Generally curved pipes can be also represented by providing a specific inclined angle to each scalar cell.

2.2 Mesh generation and system construction

Unless the branch or cross-flow typed sub-faces are used, the hexahedral staggered meshes have similar features to a structural mesh system. Therefore, the simple mesh blocks can be easily generated on an algebraic basis, on the contrary to the general polyhedral unstructured meshes which generally need a mesh generator. The SPACE code provides a simple way to construct various types of mesh blocks, such as three-dimensional Cartesian, cylindrical, one-dimensional pipe, and so on. It also provides a methodology to construct complex systems by connecting the already generated mesh blocks with the block linkage data given by users. The information of block mesh generations and block mesh connection is described in detail in the reference [2].

3. Numerical solution scheme

3.1 Discretized equations

Using the definition of flux terms at faces, phasic mass and energy conservation equations can be expressed as follows.

- Continuity equation

$$\frac{\varepsilon V}{\Delta t}\left(\alpha_l^{n+1}\rho_l^{(n+1)}-\alpha_l\rho_l\right) = -\sum_{i=1,id=facEid(i)}^{facEcount}\varepsilon_{(id)}^{E}\,{}^{d}\alpha_{l(id)}^{E}\,{}^{d}\rho_{l(id)}^{E}\left(\iota(i)Flux_{l(id)}\right)+\gamma_l+\theta_l \tag{1}$$

- Energy equation

$$\frac{\varepsilon V}{\Delta t}\left[\left(\alpha_l^{n+1}\rho_l^{(n+1)}e_l^{(n+1)}-\alpha_l\rho_l e_l\right)+P\left(\alpha_l^{(n+1)}-\alpha_l\right)\right] = -\sum_{i=1,id=facEid(i)}^{facEcount}\iota(i)\varepsilon_{(id)}^{E}\,{}^{d}\alpha_{l(id)}^{E}\left({}^{d}\rho_{l(id)}^{E}\,{}^{d}e_{l(id)}^{E}+P_{(id)}^{E}\right)Flux_{l(id)}+E_l+\Phi_l \tag{2}$$

In the hexahedral shape of a scalar cell, each orthogonal face can be categorized into three different types, depending on the direction of the face vector. The components of the cell velocity vector, $U_{(k)}$, are calculated by averaging the same type face velocities. If the transverse direction velocity is denoted by $XU_{(k)}$ at each face, the momentum equation can be expressed as follows.

- Momentum equation

$$\begin{aligned}
&\frac{\varepsilon V}{\Delta t}\left(U_l^{E(n+1)}-U_l^{E}\right)+\varepsilon_{(k)}^{E,Neigh}\,{}^{d}U_{l(k)}^{Neighbor}\left(A_{(k)}U_{l(k)}^{Neighbor}\right)-\varepsilon_{(k)}^{E,Own}\,{}^{d}U_{l(k)}^{Owner}\left(A_{(k)}U_{l(k)}^{Owner}\right)\\
&+\sum_{E,typ\neq k}^{Owner.cell}\varepsilon_{(id)}^{E}\,{}^{d}XU_{l(id)(k)}^{Fhcell}(\iota(i)\frac{1}{2}Flux_{l(id)})+\sum_{E,typ\neq k}^{Neighbor.cell}\varepsilon_{(id)}^{E}\,{}^{d}XU_{l(id)(k)}^{Bhcell}(\iota(i)\frac{1}{2}Flux_{l(id)})\\
&+F_{l(k)}V-\quad U_l^{E}\varepsilon_{(k)}^{E,Neighbor}\left(A_{(k)}^{Neighbor}U_{l(k)}^{Neighbor}\right)+U_l^{E}\varepsilon_{(k)}^{E,Owner}\left(A_{(k)}^{Owner}U_{l(k)}^{Owner}\right)\\
&-U_l^{E}\sum_{E,typ\neq k}^{Owner.cell}\varepsilon_{(id)}^{E}(\iota(i)\frac{1}{2}Flux_{l(id)})-U_l^{E}\sum_{E,typ\neq k}^{Neighbor.cell}\varepsilon_{(id)}^{E}(\iota(i)\frac{1}{2}Flux_{l(id)}) \qquad (3)\\
&=\frac{1}{\rho_l}\varepsilon_{(id)}^{E}A_{(id)}^{E}(P_{owner}^{n+1}-P_{neighbor}^{n+1})+\varepsilon V\frac{1}{\alpha_l\rho_l}\left(-F_{wl}U_l^{E(n+1)}\right)+\varepsilon V\mathbf{B}\cdot\mathbf{n}^{E}+M_l+\Theta_l
\end{aligned}$$

3.2 Time advancement scheme

In the semi-Implicit scheme, the convection terms of momentum equations are discretized in explicit manner, while the pressure gradient terms are implicitly treated. The system pressure matrix can be derived by substituting the linear relationship between velocity and pressure gradient into the implicit velocity terms of mass and energy conservation equations, and inverting the cell matrix. After the system pressure matrix is solved, the solutions for other primitive variables are obtained by the back substitution.

4. Test results

4.1 Nodalization of a typical reactor coolant system

Fig. 1 shows an example of nodalization for a typical reactor coolant system. It consists of 16 blocks each of which represents the lower plenum, reactor core, upper plenums, reactor head, downcomer, hot leg, two cold legs, pressurizer, surge line, and steam generator U-tube, and so on, respectively. Cartesian type block meshes are constructed for the reactor vessels including the downcomer, The hot leg and cold legs, pressurizer, surge line, and SG U-tubes are constructed by using the type of pipe block meshes. With the component block connection technique is used to merge all of the already constructed component mesh blocks into a node system representing the reactor coolant system.

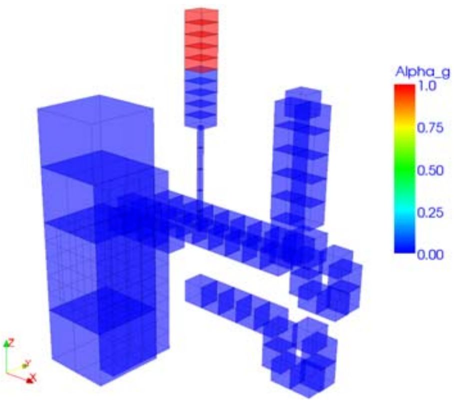

Figure 1 Nodalization for a typical reactor coolant system and initial void distribution

4.2 Blowdwn test

A simplified test for blowdown phenomena during a cold leg break LOCA are performed with the above nodalization of a typical reactor coolant system. The entire system is initially filled with saturated water at 150 bar, except the upper half of the pressurizer which is filled with saturated vapor at the same pressure. Fig. 2 shows the distribution of void fraction during blowdown. The depletion process of system inventory is found to be quite reasonable.

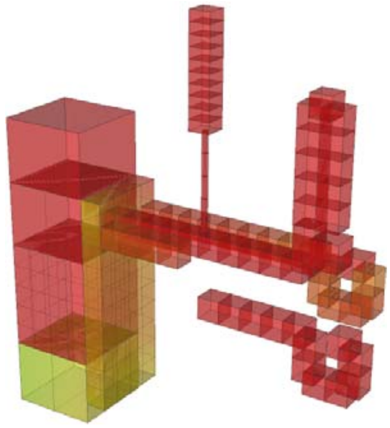

Figure 2 Distribution of void fraction at 10 seconds.

5. Conclusion

In this paper, nodalization capability of the staggered mesh system of SPACE is demonstrated. The SPACE staggered mesh system can accommodate three-dimensional Cartesian mesh blocks, one-dimensional curved pipes, branches, and cross-flow junctions. The multi-components mesh connection technique is found to be useful to nodalize much complex system. Finally, the simplified blowdown test shows that the semi-implicit numerical scheme works properly with the flexible mesh system of SPACE.

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REFERENCES

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