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Verification Methods of Pressure Matrix Integration and Reduction for Implicit Coupling of Two Codes Using One Code

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1. Introduction

For more stable coupled calculation of SPACE domain and CAP domain, an implicit coupling algorithm is now under development. SPACE is a system analysis code, and CAP is a containment thermal hydraulic analysis code. Two codes are already explicitly coupled to interactively calculate the break flow and backpressure.

In the current explicit coupling method between SPACE and CAP, the discharge flow rate is calculated using the current time-step upstream pressure and old time-step containment back pressure. The containment back pressure is calculated again from the discharged flow rate. The main problem of explicit method is a numerical stability when the flowrate is strongly depends on the pressure difference. Therefore, the development of an implicit coupling method is necessary to predict the flowrates more stably by solving the simultaneous pressure and flowrate.

The key point of implicit coupling is calculating the velocity of the coupling junction. The system pressure matrix of the hydrodynamic models in the two codes should be merged and solved simultaneously, and the integrated pressure matrix needs to be reduced to match the computational domain of each code. In this study, the validity of an algorithm for reducing the pressure matrix was tested by coupling two separate CAP codes independently.

2. Numerical Solution Scheme

In thermal-hydraulic analysis codes like SPACE and CAP, the velocity of a junction can be expressed as shown in equation (1).

$$V_j^n = \alpha_j + \beta_j(\delta P_k - \delta P_i) \qquad \text{Eq. (1)}$$

- V_j: velocity of junction j
- α_j, β_j: coefficients obtained explicitly
- $\delta P = P^n - P^o$

In this equation, the subscripts k and i represent the indices of the two nodes connected to junction j, and the superscripts o and n represent the values at the old and new time-steps, respectively. By substituting this equation into the governing equation and rearranging, a N × N pressure matrix can be constructed. The velocities at all junctions are determined, after the pressure changes at all nodes are determined by solving the N × N pressure matrix.

3. Integration Pressure Matrix and Reduction

Figure 1 illustrates the nodalization of SPACE/CAP, depicting the connection between node 2 and node 13, as well as between node 4 and node 5. Figure 2 shows the integrated pressure matrix of this nodalization. To solve the integrated pressure matrix, this matrix needs to be reduced to match the computational domain of each code.

To reduce the integrated pressure matrix to fit the calculation domain of CAP, it is necessary to have the pressure information of nodes 5 and 6 in SPACE, which can be substituted with the pressure information of nodes 3 and 4 in CAP.

To reduce the merged pressure matrix to match the calculation domain of CAP, it is necessary to get the pressure differences of nodes 5 and 13 of SPACE, which can be substituted with the pressure difference of nodes 2 and 4. The same applies to SPACE's pressure matrix construction. By utilizing this method, the integrated pressure matrix can be transformed into two reduced pressure matrices as shown in Figure 3. This approach was applied when coupling COBRA/RELAP5 [1].

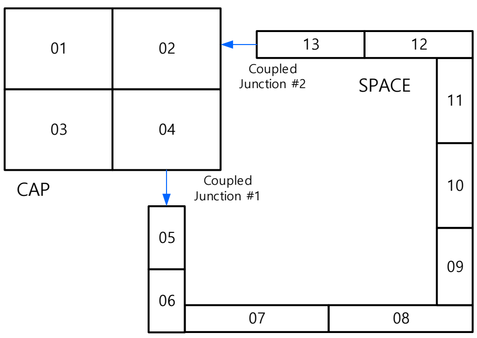


Fig. 1. SPACE/CAP sample nodalization

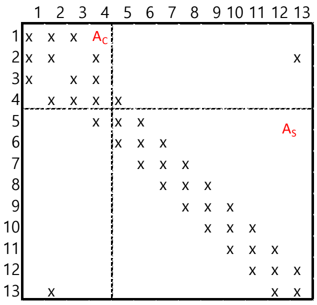
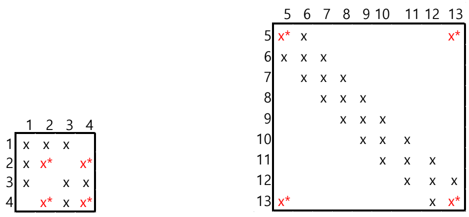


Fig. 2. Integrated pressure matrix of SPACE/CAP



(a) Pressure matrix of CAP (b) Pressure matrix of SPACE

Fig. 3. Reduced pressure matrix of each code

4. Test of Pressure Matrix Reduction Algorithm

The pressure field (or velocity field) determined by solving the reduced pressure matrix should be consistent with those obtained by solving the integrated pressure matrix. To verify this, we compared CAP standalone calculations results with those of CAP/CAP coupling for the same problem. In this test, the results from CAP standalone align with solving the integrated pressure matrix, whereas the results from CAP/CAP coupling align with solving the reduced pressure matrix.

4.1 Manometer problem

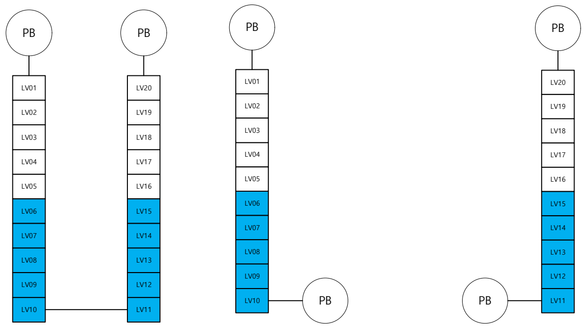
Figure 4 illustrates the nodalization of manometer problem. Figure 4a shows the nodalization of CAP standalone, while Figures 4b and 4c depict the nodalization of CAP/CAP coupling. In Figures 4b and 4c, the coupling nodes are designated as pressure boundaries. Since only liquid flows through the coupling junction, this test allows for testing the effectiveness of the pressure matrix reduction algorithm for single-phase flow.

Figure 5 displays the velocity at the coupling junction (connection between node 10 and 11). Additionally, figures 6 and 7 display the transient void fraction at nodes 05 and 15, respectively. Both CAP standalone and CAP/CAP coupling for the manometer problem showed nearly identical predictive results.

4.2 Water injection problem

Figure 8 shows the nodalization of water injection problem. Figure 8a represents the nodalization of CAP standalone, while Figures 8b and 8c depict the nodalization of coupled CAP/CAP coupling. As two fluids flow through the coupling junction, it enables testing the effectiveness of the pressure matrix reduction algorithm for two-phase flow.

Figure 9 illustrates the liquid mass flow rate transferred through the coupling junction, while Figure 10 shows the gas mass flow rate transferred through the coupling junction. Both CAP standalone and CAP/CAP coupling demonstrate very similar mass flow rates.



(a) CAP Only (b) Coupling #1 (c) Coupling #2

Fig. 4. Nodalization of manometer

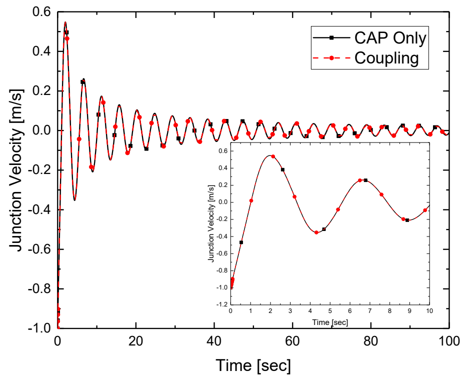


Fig. 5. Comparison results of standalone and coupling – junction velocity

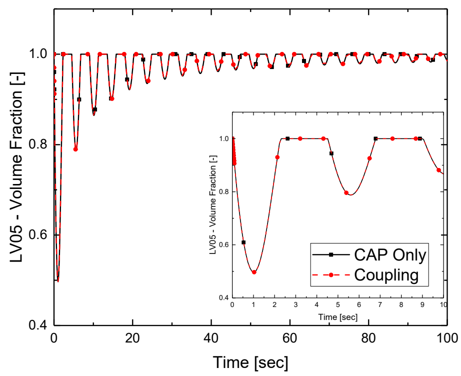


Fig. 6. Comparison results of standalone and coupling – LV05 void fraction

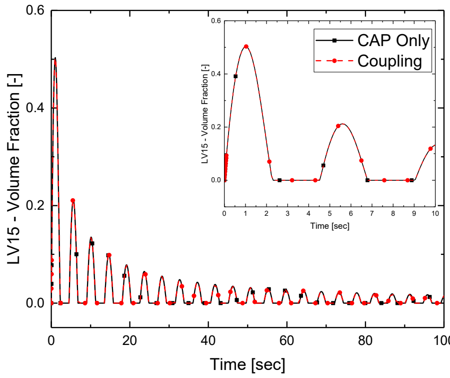
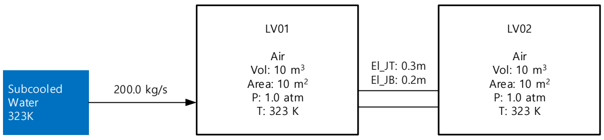
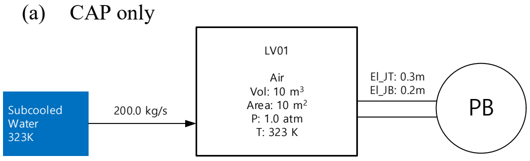


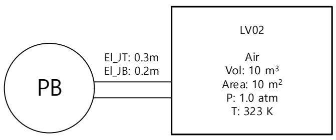
Fig. 7. Comparison results of standalone and coupling – LV15 void fraction



(a) CAP only



(b) Coupling #1



(c) Coupling #2

Fig. 8. Nodalization of water injection problem

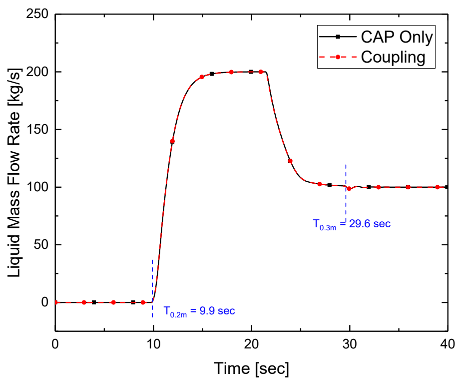


Fig. 9. Comparison results of standalone and coupling – liquid mass flow rate

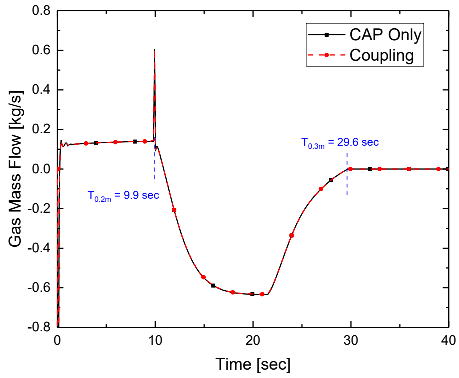


Fig. 10. Comparison results of standalone and coupling – gas mass flow rate

5. Conclusions

In this study, a method was developed to appropriately reduce the integrated pressure matrix to align with the computational domain of each code. To verify the effectiveness of this algorithm, the results of CAP standalone calculations were compared with those of CAP/CAP coupling calculation. In the future, this algorithm will apply to the development of SPACE/CAP implicit coupling.

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[1] J. J. Jeong, S. K. Sim, and S. Y. Lee, Development and Assessment of the COBRA/RELAP5 Code, Journal of Nuclear Science and Technology, Vol. 34(11), pp. 1087-1098, 1997.