Verification and Validation of a Multi-Scale Code, CUPID/MARS

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1. Introduction

This paper presents a coupling of MARS [1] with the CUPID code [2], and application to ROCOM TEST 1.1 [3]. The multi-scale analysis method can be either an "explicitly (weak)-coupled" or an "implicitly (strong)-coupled". In this paper, a CFD scale code, CUPID, has been coupled with a system scale code, MARS, implicitly by solving the pressure equations of the two codes simultaneously. This method has an advantage over the explicitly-coupled method in numerical stability and calculation time for an analysis of a transient two-phase flow where the boundary condition changes during the calculation.

2. Coupling Methods

The momentum modeling at the interface between cells Cf and Rf is performed in the MARS code. K and L indicate Cf and Rf in Figure 3. Old time variables of cell Cf are transferred from CUPID to MARS. No more considerations are then needed since cell Cf is regarded as a time-dependent volume in MARS. This results in

$$V_{k,f}^{n+1} = \alpha_{k,f} + \beta_{k,f}\left(\delta P_{Cf} - \delta P_{Rf}\right) \tag{1}$$

where $\alpha_{k,f}$ indicates $V_{k,f}^{*}$, a intermediate velocity.

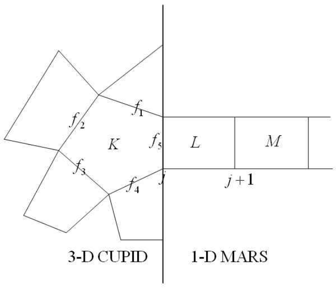

Fig. 3. CUPID/MARS Control Volumes for the Interface.

The effects of the connections should be taken into account for the conservation of momentum in the CUPID cells.

Because of the connections, the system pressure equation of MARS involves additional terms that involve the unknown velocities at the interface

$$\underline{\underline{A}}'_M \, \underline{\delta P} = \underline{b}'_M + \sum_{j=1}^{NC}\left(\underline{r}_{l,j} V_{l,j}^{n+1} + \underline{r}_{g,f} V_{g,j}^{n+1}\right) \tag{2}$$

where coefficients $r_{l,j}$ and $r_{g,j}$ are element vectors, of which all elements except the $Rf-th$ row are zeros. Substituting the unknown velocities in Eq. (2) with Eq. (1) and re-arranging then yields

$$\underline{\underline{A}}''_M \, \underline{\delta P} = \underline{b}''_M + \sum_{j=1}^{NC} \underline{d}\delta P_{Cj} \tag{3}$$

where $\underline{d}$ is a coefficient vector and subcript Cj indicates a neighboring CUPID cell Cf of a MARS cell Rf at the j interface.

Finally, multiplying Eq. (3) by the inverse of $\underline{\underline{A}}''_R$ gives a matrix equation that represents the pressure variations in MARS in terms of δP_{Cj}. That is, since cell R_i is also a MARS cell, δP_{Rf} can be written as

$$\delta P_{Rf} = \xi_f + \sum_{j=1}^{NC} \eta_{f,j}\delta P_{Cj} \tag{4}$$

The coefficients in Eq. (4) are obtained in MARS. The phasic velocity at the interface can also be represented in terms of δP_{Cj} from Eqs. (1) and (4):

$$V_{k,f}^{n+1} = \alpha_{k,f} + \beta_{k,f}\left[\delta P_{Cf} - \left(\xi_f + \sum_{j=1}^{NC}\eta_{f,j}\delta P_{Cj}\right)\right] \tag{5}$$

Equation (5) is used in the merging of the system pressure matrices. Since the implicit sinks are assumed to be connected to CUPID, the system pressure equation of CUPID also contains unknown velocities:

$$\underline{\underline{A}}'_C \, \underline{\delta P} = \underline{b}'_C + \sum_{jj=1}^{NC}\left(\underline{c}_{l,jj} A_{jj} V_{l,jj}^{n+1} + \underline{c}_{g,jj} A_{jj} V_{g,jj}^{n+1}\right) \tag{6}$$

where coefficients $\underline{c}_{l,jj}$ and $\underline{c}_{g,jj}$ are element vectors. A_{jj} is a cross-sectional are of $jj-th$ interface. By replacing the velocities in Eq. (6) with Eq. (5), the two system pressure equations are merged, maintaining their semi-implicitness, and only the pressure variations in the coupled cells of CUPID remain as unknowns.

$$\underline{\underline{A}}'_C \, \underline{\delta P} = \underline{b}'_C + \sum_{jj=1}^{NC}\sum_{k}^{g,l} \underline{c}_{k,jj}\left(\begin{array}{l} A_{jj}\alpha_{k,jj} + \\ A_{jj}\beta_{k,jj}\left[\delta P_{Cjj} - \left(\xi_{jj} + \sum_{j=1}^{NC}\eta_{jj,j}\delta P_{Cj}\right)\right] \end{array}\right) \tag{7}$$

The resulting matrix equation is solved by a sparse matrix that is modified from CUPID. Next, the velocities in Eq. (5) are obtained by back-substitutions. The pressure variations in MARS are obtained from Eq. (4). The remaining numerical sequences are performed in parallel by each code.

First, the discretized equations for momentum and scalar equations are set up for each code. Then, $\alpha_{k,jj}, \beta_{k,jj}, \xi_{jj}$,and $\eta_{jj,j}$ are obtained from a manipulation of the system pressure matrix of the MARS code and transferred to the CUPID code. The merge system pressure matrices are solved in the CUPID code. The pressure correction of the CUPID cell including shared junction j are transferred into MARS and the system pressure matrix equation is solved.

3. Verification and Validation

First, it should be confirmed whether the code integration scheme and its implementation are valid. General code assessment activities are then required. To check whether the mass at the interface cells of the MARS and CUPID regions is conserved or not, a forced convection flow in a single vertical channel was simulated (Fig. 1). The manometer flow oscillation problem is also a good example to verify the code integration results because the mass, energy, and momentum are transported between MARS and CUPID through a coupled mesh. These two kind of calculations showed that the CUPID/MARS integration scheme works well (Fig. 2). The ROCOM test was then chosen as a realistic multi-scaled example to reflect a reactor transient (Fig. 3).

4. Conclusions

A multi-dimensional thermal-hydraulic system code, CUPID/MARS, has been developed by consolidating the MARS and CUPID codes. This enables users to take advantage of the very general, versatile features of MARS and the realistic three-dimensional features of the CUPID code. CUPID/MARS will be very useful for analyzing the multi-scaled thermal hydraulic system like a nuclear reactor system, which includes 1-dimensional featured components such as pipes, valves, and pumps, and 3-dimensional featured components such as a reactor, steam generators, and a pressure riser.

A simulation of forced convection flows in a straight channel shows that total mass is conserved at the interface cells of the MARS and CUPID in both single and two phase flows. A calculation set of the manometer flow oscillation shows that the CUPID/MARS multi-scale coupling is successful in two-way direction in both two and single phase flows. The validation calculation for the Rossendorf Core Mixing (ROCOM) test, where the pressure vessel is calculated by the CUPID and the other components such as hot and cold legs are simulated by the MARS, shows that the multi-scale approach is cheap and convenient.

Acknowledgements

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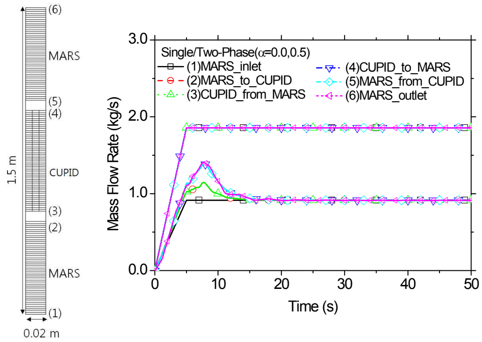

Fig. 1 Mass flow rate at several interface of inlet, four coupling interfaces, and outlet.

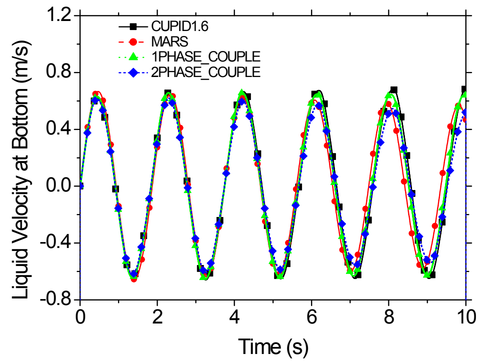

Fig. 2 Comparison of x-velocities in manometric oscillation.

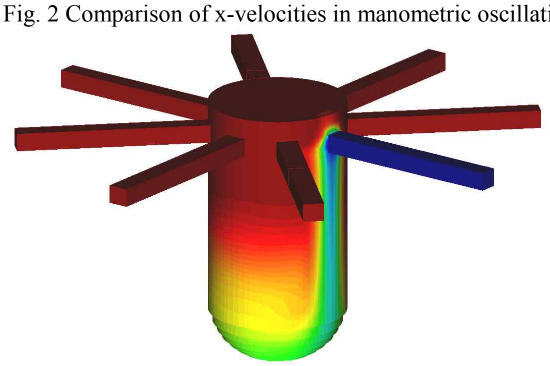

Fig. 3 Calculated coolant temperature distribution for time 0.42 after dense water injection in the ROCOM RPV.