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Porous Media Approach of a CFD Code to Analyze a PWR Component with Tube or Rod Bundles

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1. Introduction

This paper presents a strategy to innovate CFD code into a PWR component analysis code. A porous media approach is adapted to two-fluid model and conductor model, and a pack of constitutive relations to close the numerical model into component analysis code. The separate verification calculations on open media, conductor model and porous media approach are introduced.

2. Governing Equation for Porous Media

The discretized governing equations can be obtained by integrating above differential governing equation of CUPID code [1, 2]. The control volume to integrate the equation is presented in Fig. 1, in which i , j , $\vec{S}_f$, $\vec{n}_f$,and D_{ij} are target cell, neighbor cell, surface vector, surface normal vector, and distance between two cells.

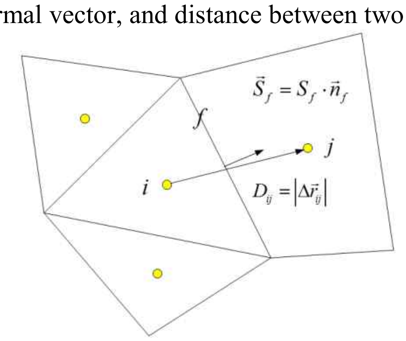

Fig. 1. CUPID control volume for FVM method

The volume integrated formulation of mass conservation equation is as follows:

$$\int \frac{\partial}{\partial t}(\alpha_k \rho_k) dV + \int \alpha_k \rho_k \vec{u}_k \cdot \, d\vec{S} = \int \Gamma_k dV \, . \tag{1}$$

The volume integrated formulation of momentum conservation equation is as follows:

$$\begin{aligned} &\int \alpha_k \rho_k \frac{\partial \vec{u}_k}{\partial t} dV + \int (\alpha_k \rho_k \vec{u}_k \vec{u}_k) \cdot d\vec{S} - \vec{u}_k \int (\alpha_k \rho_k \vec{u}_k) \cdot d\vec{S} \\ &= -\int \alpha_k \nabla P dV - \int (\alpha_k \mu_k \nabla \vec{u}_k) \cdot d\vec{S} + \int \alpha_k \rho_k \vec{g} dV \\ &+ \int S_k dV + \int \vec{M}_{wk} dV \end{aligned} \quad , \tag{2}$$

where S_k are sum of phase change, interfacial momentum exchange, virtual mass, and non-drag forces and $\vec{M}_{wk}$ is wall friction in a porous media.

$$S_k = \overrightarrow{M}_k^{mass} + \overrightarrow{M}_k^{drag} + \overrightarrow{M}_k^{VM} + \overrightarrow{M}_k^{non-drag} \; , \tag{3}$$

$$\vec{M}_{wk} = -F_{wk} \vec{u}_k \, , \tag{4}$$

$$F_{wk} = \left(\frac{f_k}{2D_h} + \alpha_k \frac{K}{L} \right) \rho_k \, |\vec{u}_k| \, , \tag{5}$$

where f_k , K , D_h , L wall friction factor, form loss factor, hydraulic diameter, and cell length. The volume integrated formulation of energy conservation equation is as follows:

$$\begin{aligned} &\int \frac{\partial(\alpha_k \rho_k e_k)}{\partial t} dV + \int (\alpha_k \rho_k e_k \vec{u}_k) \cdot d\vec{S} = \\ &-\int P \frac{\partial \alpha_k}{\partial t} dV - P \int \alpha_k \vec{u}_k \cdot d\vec{S} + \int \alpha_k k_k \nabla T_k \cdot d\vec{S} \\ &+ \int E_k dV + \int q''_{flu-sol,k} dA + q''_{flu-por,k} A_{flu-por,k} \end{aligned} \tag{6}$$

where E_k includes phase change, interfacial heat transfer, volume heat source, and $q''_{flu-por,k}$ is the heat transfer in a porous media.

$$q''_{flu-por,k} = h_{flu-por,k} (T_{por} - T_{flu,k}) \, , \tag{7}$$

where, $h_{flu-por,k}$ and $A_{flu-por,k}$ are heat transfer coefficient and heat transfer area, respectively. Both of the fluid and conductor are included in one cell, and the conduction equation of a conductor is as follows:

$$\begin{aligned} &\int \rho_{por} C_{P,por} \frac{\partial T_{por}}{\partial t} dV = \int \nabla \cdot k_{por} \nabla T_{por} dV \\ &+ \int q'''_{por} dV + \int q''_{por-sol} dA - q''_{flu-por} A_{flu-por} \end{aligned} \, . \tag{8}$$

3. Separate Verification of the Code

Two-fluid model in an open media

We have another conceptual problem to verify the phase separation due to the gravity. The mixture of air and water is contained in a square tank of 1 m x 1 m, which is discretized into a grid of 2500 meshes. The initial void fraction, pressure, and temperature are 0.5, 1.0 MPa, 320.15 K. The calculation was accomplished for 10 seconds. The calculation grid and calculated void fraction contours for 2 s and 5 s are presented in Fig. 2.

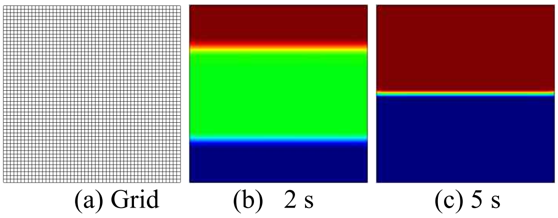

Fig. 2. Phase separation

Conductor Module

Independent verification calculation for thermal conductor model was conducted before the thermal conductor model is coupled with the fluid model. An independent verification calculation is for a conduction problem in a $1m \times 1m$ rectangle solid conductor. The calculated temperature distribution is compared to the analytical temperature field. The structured mesh and unstructured mesh are also used for validating the code under the unstructured mesh.

The adiabatic wall boundary condition is endowed to the wall number 1, 2, and 3 of Fig. 3 and the constant temperature boundary condition($T_1 = 400K$) are endowed to the wall number 1. The uniform volume heat of $q''' = 10kW/m^3$ is inflicted to the solution domain. The calculated temperature contours of Fig. 3 are reasonable to reflect cold constant temperature boundary and the volume heat flux.

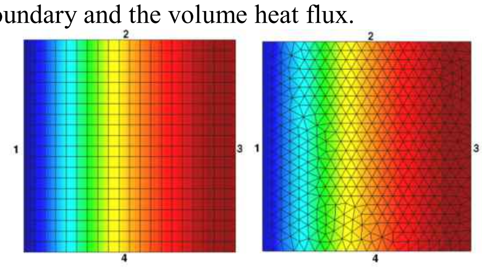

Fig. 3. Calculated temperatures for structured and unstructured meshes

Porous Media Module

The evaluation calculation for the porous media module was conducted. The two-phase flow involves the flow regime, interfacial heat and mass transfer, and interfacial drag, so that the evaluation calculation was done for single phase flow.

The wall friction coefficient and the heat transfer coefficient between fluid and solid in a porous are needed to calculate the pressure drop and the heat transfer. This calculation was conducted with the simplified models given by:

$$F_{wk} = 10.0 \cdot \rho_k \cdot |\vec{u}_k| \quad (9)$$

$$H_{l,por} = h_{l,por} \cdot A_{flu-por} \cdot part_l = 10000 \quad (10)$$

$$H_{g,por} = h_{g,por} \cdot A_{flu-por} \cdot (1 - part_l) = 100 \quad (11)$$

Single phase heat balance problem is set as Fig. 4, in which initial condition and boundary condition are presented. Inlet region is only for fluid, and the middle and exit region are porous region which has porosity of 0.5 and 0.9, respectively. The water of 300 K comes in through inlet with the velocity of 1.0 m/s. The exit is set to pressure boundary of 1.0 MPa.

Fig. 4(b) shows the velocity vectors, which indicates that the injected fluid with a velocity of 1 m/s accelerates through the porous media. The liquid velocity at the middle region with a porosity of 0.5 increases to double of inlet velocity, and the velocity at the exit region with a porosity of 0.9 is about 1.11 times of inlet velocity. These verification calculations show that the code can predict the velocity change.

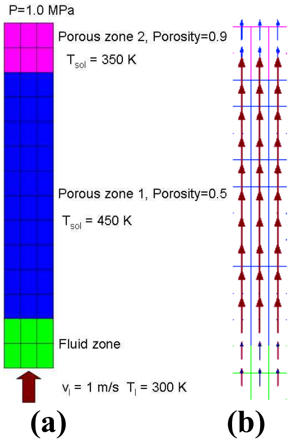

Fig. 4. Conceptual problem to test porous model and calculated velocity vectors.

4. Conclusion

Based on the CUPID code, the component analysis code has been developed. For porous media model, constitutive correlations of a two-phase flow regime map, interfacial area, interfacial heat and mass transfer, interfacial drag, wall friction, wall heat transfer and heat partitioning in flows through tube or rod bundles are added. Separate calculations were also conducted to verify the developed code.

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REFERENCES

[1] J. J. Jeong, H. Y. Yoon, I. K. Park, and H. K. Cho, "The CUPID Code Development and Assessment Strategy," Nuclear Engineering and Technology, 42, 6, pp.636-655 (2010).

[2] H. Y. Yoon, H.Y. Cho, H. R. Lee, I. K. Park, and J. J. Jeong, "Multi-Scale Thermal-Hydraulic Analysis of PWRs Using the CUPID Code," Nuclear Engineering and Technology, 44, 8, pp.831-846 (2012).