Upwind Scheme and Local Head Model in CAP

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1. Introduction

CAP (Containment Analysis Package) code is a counterpart of SPACE code of RCS (Reactor Coolant System) analysis for the assessment of containment safety and performance. Containment environment is far different from RCS condition [1, 2, 3];

- Numerical cell of containment is lager than that of RCS by order of magnitude
- Flow pattern is nearly horizontal stratified flow (or pool/drop regime)
- Junction usually has a threshold to neighboring volume, and the flow is restricted by the threshold
- Fewer number of numerical cell is desirable for the analysis but relatively accurate calculation result is also necessary

Because of above reasons CAP code is required to have special features to model containment-specific phenomena. Some examples of such flow phenomena is 1) water on the floor does not flow to the neighboring room until the water level reach the bottom of the door, 2) water of different level in neighboring rooms oscillates because of the head difference not because of the static pressure difference, and so on.

Such phenomena can be easily simulated by water level oriented upwind scheme and local head model. This paper introduces and discusses the upwind scheme and local head model that has been developed in CAP code.

2. Water Level Oriented Upwind Scheme

2.1 Convective Properties in Junction of Lumped Parameter Model

Generally speaking upwind scheme means that the junction has the properties of upstream volume. Thus, the junction properties depend on the direction of flow in the junction. Containment environment is nearly always horizontal stratified flow condition or pool/drop flow pattern. So there is water on the floor and atmosphere on the water. In this situation the void fraction at junction by upwind scheme is fatally affected by the water level of upstream volume. For example, if the water level (El_{pool}) in upstream volume does not reach the bottom of junction (El_{jb}), the junction void fraction in the junction should be zero. Therefore, the transported field by convection through junction is only gas, whereas the water cannot be transported to the neighboring volume. Fig. 1 shows such a relation.

For the other situation of water level the other proper void fraction relation can be modeled. The other variable except the void fraction, such as density, specific energy, and so on take just the upstream properties.

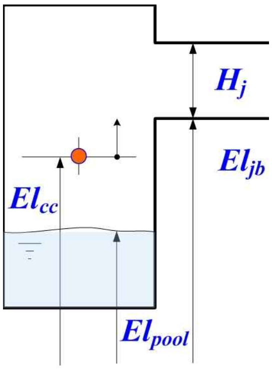

Fig. 1. Relation of void fraction and water level of upstream volume in the situation of the water level does not reach the bottom of junction.

2.2 Non-Convective Properties in Junction of Lumped Parameter Model

The junction properties besides in the convective term in momentum equation have the average values of neighboring volume properties. For the averaged void fraction in junction, however, we have to pay a careful attention because of the water level in each volume. If we define the upwind property of void fraction in each volume as $\tilde{\alpha}_{g,L}$ and $\tilde{\alpha}_{g,R}$, the junction void fraction of non-convective property should be

$$\hat{\alpha}_g = \frac{\tilde{\alpha}_{g,L} + \tilde{\alpha}_{g,R}}{2} \qquad (1)$$

3. Local Head Model

3.1 Local Head Model

Flow cannot be formed in the point of equation if the static pressures of neighboring volume are same each other, even though the local static head is different; of course in actual case the water flows because of the head difference. For the simulation of such flow we have to develop the local head model. One illustrative case is shown in Fig. 2.

The water level is below the junction bottom. In this case the local heads of gas and liquid can be expressed as followings;

$$for\ (El_{cc} < El_{jb})\ \ and\ (El_{pool} < El_{cc})$$

$$p_{l,head} = \rho_{dg} g \left(El_{cc} - El_{jb} \right) \qquad (2)$$

$$p_{g,head} = p_{d,head} = \rho_{dg} g \left(El_{cc} - El_{jb} \right)$$

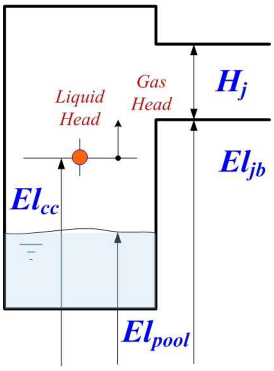

Fig. 2. Local head in case that the water level is volume center elevation, and the volume center elevation is below the junction bottom.

There are several cases according to the volume center elevation, water level, and junction elevation. For all the cases the local head of liquid and gas should be obtained [1].

3.2 Momentum Equation in Lumped Parameter Model

Three dimensional momentum equation, eq. 3, can be reduced to the lumped parameter form eq. 4 by integration, considering the water level oriented upwind scheme and local head model mentioned before.

$$\begin{aligned}
&\alpha_g \rho_g \frac{\partial \mathbf{v}_g}{\partial t} + \alpha_g \rho_g \mathbf{v}_g \cdot \nabla \otimes \mathbf{v}_g \\
&= -\alpha_g \nabla p + \alpha_g \rho_g \mathbf{g} + \nabla \cdot \left(\alpha_g \left(\mu_g + \mu_g^t \right) \nabla \otimes \mathbf{v}_g \right) \\
&+ \Gamma_{lg}^{EV} \left(\mathbf{v}_l - \mathbf{v}_g \right) + \Gamma_{dg}^{EV} \left(\mathbf{v}_d - \mathbf{v}_g \right) - \mathbf{v}_g \Gamma_g \\
&+ \left[F_{gl} \left(\mathbf{v}_l - \mathbf{v}_g \right) + F_{gd} \left(\mathbf{v}_d - \mathbf{v}_g \right) \right] - F_g^w \mathbf{v}_g \qquad (3) \\
&+ \begin{bmatrix} C_{gl}^{VM} \alpha_g \alpha_l \rho_{gl} \dfrac{\partial}{\partial t} \left(\mathbf{v}_l - \mathbf{v}_g \right) \\ + C_{gd}^{VM} \alpha_g \alpha_d \rho_{dg} \dfrac{\partial}{\partial t} \left(\mathbf{v}_d - \mathbf{v}_g \right) \end{bmatrix} + \mathbf{M}_g
\end{aligned}$$

$$\begin{aligned}
&V_e \hat{\alpha}_{g,e} \hat{\rho}_{g,e} \frac{\partial u_{g,e}}{\partial t} + \left(\tilde{G}_{g,E} - \tilde{G}_{g,P} \right) A_e u_{g,e} \\
&= A_e \hat{\alpha}_{g,e} \left[\left(p_P + p_{g,head,P} \right) - \left(p_E + p_{g,head,E} \right) \right] \\
&+ \hat{\alpha}_{g,e} \hat{\rho}_{g,e} g A_e \left(El_{jb,E} - El_{jb,P} \right) \qquad (4)
\end{aligned}$$

$$\begin{aligned}
&+ V_e \left[\Gamma_{lg,e}^{EV} \left(u_{l,e} - u_{g,e} \right) + \Gamma_{dg,e}^{EV} \left(u_{d,e} - u_{g,e} \right) - u_{g,e} \Gamma_{g,e} \right] \\
&+ V_e \left[F_{gl,e} \left(u_{l,e} - u_{g,e} \right) + F_{dg,e} \left(u_{d,e} - u_{g,e} \right) \right] - V_e F_{g,e}^w u_{g,e} \\
&+ V_e \begin{bmatrix} C_{gl,e}^{VM} \hat{\alpha}_{g,e} \hat{\alpha}_{l,e} \hat{\rho}_{gl,e} \dfrac{\partial}{\partial t} \left(u_{l,e} - u_{g,e} \right) \\ + C_{gd,e}^{VM} \hat{\alpha}_{g,e} \hat{\alpha}_{d,e} \hat{\rho}_{dg,e} \dfrac{\partial}{\partial t} \left(u_{d,e} - u_{g,e} \right) \end{bmatrix} + V_e M_{g,e}
\end{aligned}$$

4. Test Results

4.1 Horizontal Water Transport across Threshold

Water is injected at the bottom of the first volume and the water floods to the next volume when the water level reaches the bottom of the junction as shown in Figs. 3 and 4.

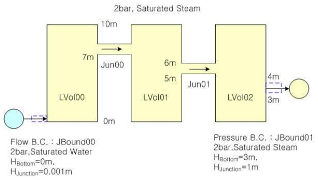

Fig. 3. Upwind scheme test.

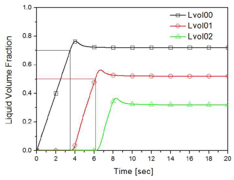

Fig. 4. Test results.

4.2 Two Volume Manometer

The different water induces the oscillating flows as shown in Figs. 5 and 6.

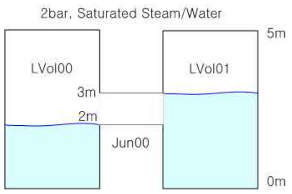

Fig. 5. Local head test.

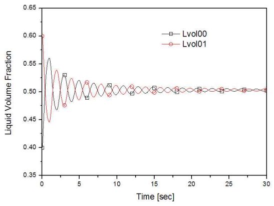

Fig. 6. Test results.

5. Conclusions

Water level oriented upwind scheme and local head model in CAP work well.

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