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Development of Critical Flow Model for the SPACE Code

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1. Introduction

To accurately predict the critical flow rate of single phase fluids or a steam-water mixture in a pipe is an issue of fundamental importance in the blowdown safety analysis of water cooled nuclear reactors. Therefore, a suitable critical model shall be selected to obtain reliable results at the break position. Several critical models for the SPACE have been developed to calculate the mass discharge from the system. The critical models are as follows:

- Ransom-Trapp model [1]
- Henry-Fauske / Moody model [2,3]
- HEM
- Henry-Fauske / HEM

These models are available as user option. At the present step, these models are being verified through simulation of separate effect experiments. Especially since Ransom-Trapp model is the default model in the SPACE, the main feature of the model and its application results will be presented in this paper.

2. Coupling of Critical and Momentum Equations

2.1 General description

Critical flow is a limiting condition which occurs when the mass flux will not increase with further decrease in the downstream pressure. Critical flow in a pipe is characterized by a steepening pressure gradient which becomes extremely large at the choking plane. If the calculated flow at any junction exceeds a limiting value set by the selected model, the three-field momentum equations are replaced with a critical flow equation and two difference momentum equations, and the junction is decoupled from the downstream volume.

2.2 Equations

The following equation is the approximate choking criterion of Ransom-Trapp model, which is modified to be compatible with three-field equations of the SPACE.

$$\frac{\alpha_g \rho_f U_g + \alpha_f \rho_g U_f}{\alpha_g \rho_f + \alpha_f \rho_g} = a_{HE}$$

Where,

$$\rho_f = \frac{\alpha_l \rho_l + \alpha_d \rho_d}{\alpha_l + \alpha_d},\ U_f = \frac{\alpha_l \rho_l U_l + \alpha_d \rho_d U_d}{\alpha_l \rho_l + \alpha_d \rho_d},\ \alpha_f = \alpha_l + \alpha_d$$

This choked flow criterion is used as both a criterion to determine if a flow is choked, and critical flow equation when the flow is choked. The criterion is checked using explicit velocities. If choking is predicted, the equation is then written in terms of new-time phasic velocities and solved in conjunction with a difference momentum equation derived from the vapor and liquid momentum equations and a difference equation from the vapor and droplet momentum equations. These subtractions eliminate pressure terms from the momentum equations and the equations are as follows:

$$\begin{aligned}
&\rho_g\left(\frac{\partial \mathbf{U}_g}{\partial t}+\left(\mathbf{U}_g\nabla\right)\mathbf{U}_g\right)-\rho_l\left(\frac{\partial \mathbf{U}_l}{\partial t}+\left(\mathbf{U}_l\nabla\right)\mathbf{U}_l\right)=-\frac{F_{gd}}{\alpha_g}(\mathbf{U}_g-\mathbf{U}_d)\\
&-\frac{F_{gl}}{\alpha_g}(\mathbf{U}_g-\mathbf{U}_l)+\frac{F_{lg}}{\alpha_l}(\mathbf{U}_l-\mathbf{U}_g)+\left(\rho_g-\rho_f\right)\mathbf{B}-\frac{F_{wg}}{\alpha_g}(\mathbf{U}_g)+\frac{F_{wl}}{\alpha_l}(\mathbf{U}_l)\\
&+\frac{1}{\alpha_g}\left(\Gamma_{l,E}(\mathbf{U}_l-\mathbf{U}_g)+\Gamma_{d,E}(\mathbf{U}_d-\mathbf{U}_g)\right)-\frac{1}{\alpha_l}\left(\Gamma_{l,C}(\mathbf{U}_g-\mathbf{U}_l)+S_D(\mathbf{U}_d-\mathbf{U}_l)\right)\\
&-C_{g,gd}\alpha_g\alpha_d\rho_{m,gd}\frac{\partial(\mathbf{U}_g-\mathbf{U}_d)}{\partial t}-C_{g,gl}\alpha_g\alpha_l\rho_{m,gl}\frac{\partial(\mathbf{U}_g-\mathbf{U}_l)}{\partial t}\\
&+C_{g,lg}\alpha_l\alpha_g\rho_{m,lg}\frac{\partial(\mathbf{U}_l-\mathbf{U}_g)}{\partial t}
\end{aligned}$$

$$\begin{aligned}
&\rho_g\left(\frac{\partial \mathbf{U}_g}{\partial t}+\left(\mathbf{U}_g\nabla\right)\mathbf{U}_g\right)-\rho_d\left(\frac{\partial \mathbf{U}_d}{\partial t}+\left(\mathbf{U}_d\nabla\right)\mathbf{U}_d\right)=-\frac{F_{gd}}{\alpha_g}(\mathbf{U}_g-\mathbf{U}_d)\\
&-\frac{F_{gl}}{\alpha_g}(\mathbf{U}_g-\mathbf{U}_l)+\frac{F_{dg}}{\alpha_d}(\mathbf{U}_d-\mathbf{U}_g)+\left(\rho_g-\rho_d\right)\mathbf{B}-\frac{F_{wg}}{\alpha_g}(\mathbf{U}_g)+\frac{F_{wd}}{\alpha_d}(\mathbf{U}_d)\\
&+\frac{1}{\alpha_g}\left(\Gamma_{l,E}(\mathbf{U}_l-\mathbf{U}_g)+\Gamma_{d,E}(\mathbf{U}_d-\mathbf{U}_g)\right)-\frac{1}{\alpha_d}\left(\Gamma_{d,C}(\mathbf{U}_g-\mathbf{U}_d)+S_E(\mathbf{U}_l-\mathbf{U}_d)\right)\\
&-C_{g,gd}\alpha_g\alpha_d\rho_{m,gd}\frac{\partial(\mathbf{U}_g-\mathbf{U}_d)}{\partial t}-C_{g,gl}\alpha_g\alpha_l\rho_{m,gl}\frac{\partial(\mathbf{U}_g-\mathbf{U}_l)}{\partial t}\\
&+C_{g,dg}\alpha_d\alpha_g\rho_{m,dg}\frac{\partial(\mathbf{U}_d-\mathbf{U}_g)}{\partial t}
\end{aligned}$$

As in semi-implicit algorithm, the three equations can be expressed in the following matrix form.

$$\begin{bmatrix} m11 & m12 & m13 \\ m21 & m22 & m23 \\ m31 & m32 & m33 \end{bmatrix}\begin{bmatrix} U_g^{E(n)} \\ U_l^{E(n)} \\ U_d^{E(n)} \end{bmatrix}=\begin{bmatrix} dUcdP \\ 0 \\ 0 \end{bmatrix}(\delta P_{owner}^{n})+\begin{bmatrix} S_{RT} \\ S_{gl} \\ S_{gd} \end{bmatrix}$$

The velocity components can also be obtained through a linear relationship between velocity and pressure.

3. Application Results

3.1 Marviken Test

In order to verify the ability of the critical flow model, the code is applied to Marviken Test 24 problem [4], which is particularly well-suited for validating the subcooled choking model. The facility consists of a 5.2m diameter, 24.55m long, vertically oriented cylindrical vessel. The test geometry is modeled using pipe components, which consist of main pipe with 39 volumes and discharge pipe with 6 volumes. The volumes in the discharge pipe and the bottom volumes in the main component are filled with subcooled water at about 5MPa. The top volumes in pipe component contain saturated steam region and saturated water region. The outlet boundary condition is given at bottom face.

A comparison of the measured and calculated pressure at the top of the vessel is shown in figure 1. The pressure response of the Marviken vessel is governed by flashing of the hot layer of water at the top of the vessel. The calculated value is high at the beginning of the transient, and then slightly underpredicts for the majority of the subcooled region, slightly overpredicts for the saturated flow region. The overprediction of initial pressure has been attributed to the nucleation delay model used in the SPACE. On the whole, the prediction of transient behaviors shows a good agreement with the measured data.

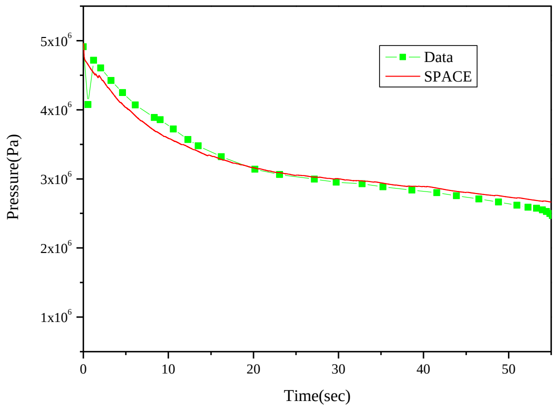

Figure 1 Pressure Variation at the Top of the Vessel

3.2 GE Level Swell Test

The GE Level Swell experiments [5] were designed to measure transients in a large tank which was depressurized via a blowdown line and orifice. The initial conditions for the test were a system pressure of 6.92MPa and a water level of 3.167m. In order to simulate the experiments, the test domain consists of 26 volumes and the initial liquid temperature is assumed to correspond to the saturation temperature. The outlet boundary is located at the top of the vessel and oriented vertically. The outlet junction is modeled using the abrupt area change model.

As shown in the figure 2, the analysis result at the beginning of the transient shows a tendency to depressurize rapidly. The omission of the wall heat capacity is considered to be the cause of this behavior. The pressure response of the vessel is also governed by flashing of water. The flashing produces a slow response to pressure changes, and most of the results are qualitatively in agreement with the physics of this problem.

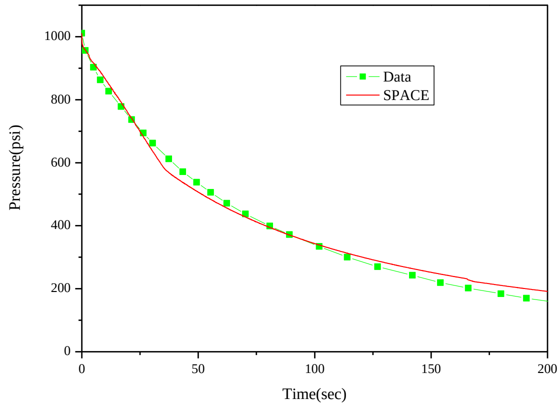

Figure 2 Pressure Variation at the Top of the Vessel

4. Conclusions

The critical flow calculation module was incorporated into the SPACE code. As an effort for verification, the critical flow model was assessed for various experiments. Overall, the SPACE performed well for the critical flow problems. It is concluded from the test results that the SPACE code with the critical flow model predicts the complex phenomena of choked flow properly.

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