Development and Assessment of SPACE Critical Flow Model

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1. Introduction

The SPACE code is designed to predict the nuclear system transients. The critical flow is an important consideration in the area of nuclear reactor safety. In reactor blowdown transients, choked flow would exist at a location of the break. Physically, choking occurs when a fluid velocity is equal to or exceeds acoustic signals. The SPACE code employs a critical flow model of Trapp and Ransom[1], extending to three fields. Verification was performed on Edwards-O'Brien blowdown test[2].

2. SPACE Critical Flow Model

The choking model used in SPACE was designed to account for both subcooled and two-phase conditions.

Subcooled choking model in SPACE is based on the Burnell[3]. In the early stage of a reactor blowdown, the fluid approaching the break is a subcooled liquid. The fluid will undergo a phase change at the break because the downstream pressure is much lower than the system pressure. The phase change accompanies a sudden change of sound speed. Such for a throat condition as a break, a choking criterion for single phase can be derived using the Bernoulli equation.

$$U_c = \left[U_0^{\,2} + 2\frac{(P_0 - P_{throat})}{\rho} \right]^{0.5} \tag{1}$$

where U is a velocity; ρ is a density; and subscript 0 refers to upstream condition. The P_{throat} represents the pressure modeled by Alamgir and Lienhard[4] and Jones[5] at the throat.

The two-phase choking model employed in SPACE is based on the model of Trapp and Ransom for non-homogeneous and equilibrium flow. The choking criterion for two-phase flow is derived by the characteristic analysis of four governing equations of total mass conservation, two phasic momentum conservations, and total energy conservation. When non-differential source terms such as wall drag and heat transfer are omitted for the characteristic analysis, the equations are

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g + \alpha_f\rho_f\right) + \frac{\partial}{\partial x}\left(\alpha_g\rho_g U_g + \alpha_f\rho_f U_f\right) = 0 \tag{2}$$

$$\alpha_g\rho_g\left(\frac{\partial U_g}{\partial t} + U_g\frac{\partial U_g}{\partial x}\right) + \alpha_g\frac{\partial P}{\partial x} + C\alpha_g\alpha_f\rho_m\left(\frac{\partial U_g}{\partial t} + U_f\frac{\partial U_g}{\partial x} - \frac{\partial U_f}{\partial t} - U_g\frac{\partial U_f}{\partial x}\right) \tag{3}$$

$$\alpha_f\rho_f\left(\frac{\partial U_f}{\partial t} + U_f\frac{\partial U_f}{\partial x}\right) + \alpha_f\frac{\partial P}{\partial x} + C\alpha_f\alpha_g\rho_m\left(\frac{\partial U_f}{\partial t} + U_g\frac{\partial U_f}{\partial x} - \frac{\partial U_g}{\partial t} - U_f\frac{\partial U_g}{\partial x}\right) \tag{4}$$

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g s_g + \alpha_f\rho_f s_f\right) + \frac{\partial}{\partial x}\left(\alpha_g\rho_g s_g U_g + \alpha_f\rho_f s_f U_f\right) = 0 \tag{5}$$

where C is a virtual mass coefficient; s is entropy; and subscripts g, f, and m refer to the steam, liquid, and mixture, respectively. The last terms of Eqs. (3) and Eqs. (4) represent interphasic force terms caused by relative acceleration. U_f is derived by conserving mass fluxes of continuous liquid and droplet.

Equation (2) through (5) can be written in terms of the four unknowns α_g, ρ_m, U_g, and U_f. The matrix representation of these equations is of the form

$$A(\overline{U})\left[\partial\overline{U}/\partial t\right] + B(\overline{U})\left[\partial\overline{U}/\partial x\right] + C(\overline{U}) = 0 \tag{6}$$

where the $\overline{U}$ consists of the four unknown variables. The characteristic roots, (λ_i, $i \le 4$), of the equation (6) are defined as the roots of the 4th-order polynomial,

$$determinant\left(\overline{A}\lambda - \overline{B}\right) = 0 \tag{7}$$

Choking occurs when a signal propagating with the largest velocity relative to the fluid is stationary; that is, the maximum value of the real part of the characteristic root($\lambda_{i,real,max}$) is zero. The approximate choking criterion is

$$\frac{\alpha_g\rho_f U_g + \alpha_f\rho_g U_f}{\alpha_g\rho_f + \alpha_f\rho_g} = a_{HE} \tag{8}$$

where the a_{HE} is a homogeneous equilibrium sound speed. The SPACE code is dealing with the three-field representation of two-phase flow, hence the two-field of the equation (8) has to be extended to the three-field equation. Under the assumption that the densities of droplets and continuous liquid are the same at the choked plane, two-field choking criterion can be expressed as follows

$$\frac{\alpha_g\rho_f U_g + \rho_g\alpha_l U_l + \rho_g\alpha_d U_d}{\alpha_g\rho_f + \alpha_l\rho_g + \alpha_d\rho_g} = a_{HE} \tag{9}$$

where subscripts l, d refer to the continuous liquid and droplet, respectively. When the void fraction approaches unity, the LHS of equation (9) becomes the vapor velocity. Therefore this criterion can apply to the vapor phase only. Choking is determined to occur if the calculated criterion is equal to or larger than the sound speed of homogeneous equilibrium model.

3. Assessment of SPACE Critical Flow Model

This section presents the verification of the SPACE critical flow model using the Edwards-O'Brien blowdown problem[2]. This experiment was designed to simulate the sudden depressurization on the simple pipe. A nodalization scheme used in the SPACE assessment is shown in Figure 1. Figure 2 and Figure 3 present the pressure and void fraction comparing with measurement and predictions at 1.64m, node 8, from the break, respectively. This assessment is also carried out using the RELAP5 to benchmark the SPACE results.

During the subcooled liquid exits through the break, the pressure calculated by RELAP5 is slightly underestimated comparing with SPACE prediction. Overall, the results of SPACE and RELAP5 underpredict the void fraction. However, the pressure predictions are very close to the measurements throughout the transient.

4. Conclusions

Subcooled choking model and two-phase choking model in SPACE adopted the modified Burnell model and Trapp and Ransom model extended to three-field, respectively. Three-field choking criterion presents the equation (9). The model was assessed against the data from the Edwards-O'Brien blowdown test. The SPACE predictions provide very reasonable agreements with the measurements.

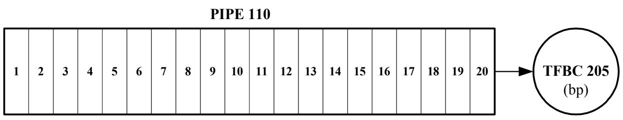

Fig. 1. SPACE nodalization for Edwards-O'Brien blowdown

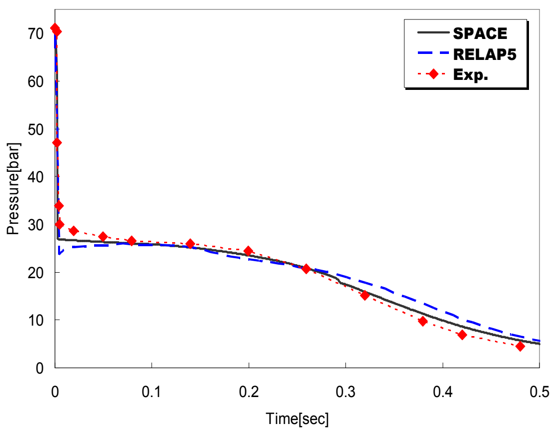

Fig. 2. Comparison of the pressure at node 8

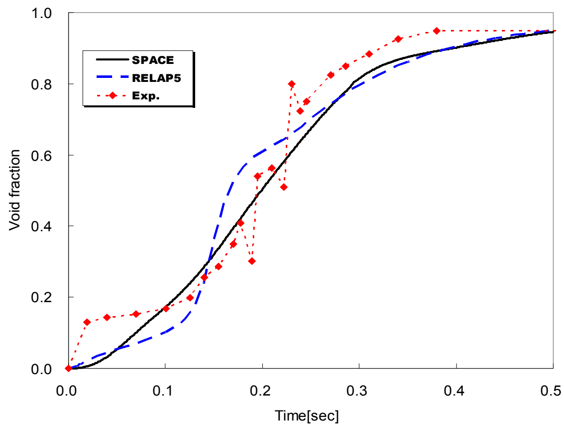

Fig. 3. Comparison of the void fraction at node 8

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