Revisit of Penetration Failure Models and Calculations for APR1400 ICI Penetrations

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1. Introduction

For the Korean PWRs (pressurized water reactors), there are many ICI (in-core instrumentation) penetrations installed at the reactor bottom head, i.e., 45 nozzles in OPR1000 and 61 nozzles in APR1400. Therefore, it is necessary to estimate the penetration failure because the penetrations are considered as the most vulnerable with respect to the reactor vessel failure during a severe accident [1]. In this paper, the existing penetration failure models were reviewed briefly and simple analytical calculations were performed for the ICI penetrations of APR1400.

2. Penetration Failure Models and Calculations

2.1 Melt Velocity for Gravity and Pressure Driven Flow

Figure 1 illustrates the cross-section of the reactor bottom head and ICI tube located at the center of the APR1400 bottom head. It was conservatively assumed that the ZrO_2 molten debris keeps in contact with the bottom head, and the temperatures of the entire weld T_{weld}, tube $T_{\mathrm{t,in}}$ and vessel hole $T_{\mathrm{h,in}}$ at the vessel inner surface are all the same as the debris temperature T_{d}. The thimble tube and coolant inside the ICI tube were not considered. A linear distribution along the length of the tube through the vessel wall was assumed with the temperature in the tube at the outside radius of the head being 30 K lower, and the ratio of the inner wall temperature to the outer wall temperature of the vessel, $c=T_{\mathrm{ho}}/T_{\mathrm{hi}}$, being constant over the duration of the accident history. The value of c depends on the debris bed, i.e., 0.73 for a molten pool, 0.88 for ceramic slurry, and 0.94 for metallic bed [2].

The melt velocity at the outside of the vessel v_{d} can be obtained from Bernoulli's equation for a steady, adiabatic flow, and is given as

$$v_{\mathrm{d}} = \sqrt{\frac{2\Delta p/\rho_{\mathrm{d}} + 2gL_{\mathrm{b}}}{4f_{\mathrm{f}}L_{\mathrm{b}}/d_{\mathrm{i}} + K + 1}}\ , \qquad (1)$$

where Δp is the pressure difference between the inside and outside of the vessel (p_{i}-p_{o}); ρ_{d}, the debris density; L_{b}, the melt travel distance; g, the gravitational constant; d_{i}, the inner diameter of the tube; and K, the entrance loss coefficient. The Balsius correlation was used for a calculation of the fanning fraction factor f_{f} for the turbulent melt flow, which is expressed as

$$f_{\mathrm{f}} = 0.079\,\mathrm{Re}_{\mathrm{d}}^{-1/4}\ , \qquad (2)$$

where Re_{d} is the Reynolds number ($\rho_{\mathrm{d}}v_{\mathrm{d}}d_{\mathrm{i}}/\mu_{\mathrm{d}}$) and μ_{d} is

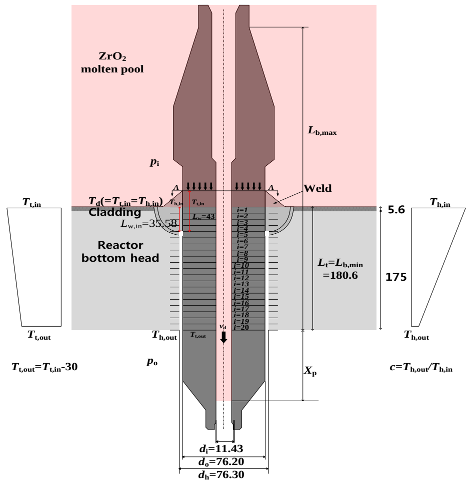

Fig. 1 A schematic of the APR1400 bottom head and ICI penetration at the reactor center

the debris density. By neglecting the entrance loss coefficient K in Eq. (1), the melt velocities for the range of pressure difference possible in PWR reactor vessels are shown in Fig. 2. In the depressurized condition ($\Delta p \approx 1$ MPa) during a severe accident, the melt velocity ranges from 15.4 m/s to17.3 m/s.

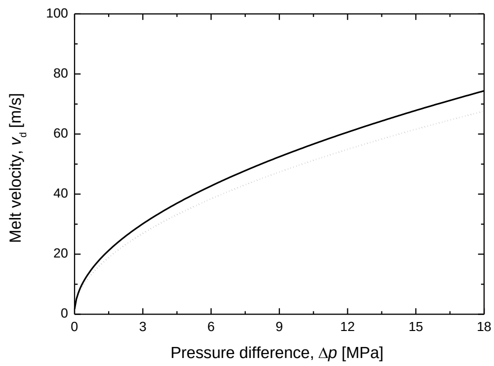

Fig. 2 Melt velocities driven by gravity and pressure

2.2 Melt Penetration Distance

There are two models generally used to estimate the melt penetration distance X_{p}: the modified bulk freezing model (MBFM) [2] and conduction layer model (CLM) [3]. The melt penetration distance by MBFM for the circular tubes without a coolant is expressed as

$$X_{\mathrm{p}} = 0.4\cdot \mathrm{Pe}^{0.6}\frac{\left(T_{\mathrm{d}} - T_{\mathrm{mp,d}}\right) + L_{\mathrm{d}}/c_{\mathrm{p,d}}}{T_{\mathrm{d}} - T_{\mathrm{t}}}\ , \qquad (3)$$

where Pe is the Peclet number ($d_{\mathrm{i}}v_{\mathrm{d}}\rho_{\mathrm{d}}c_{\mathrm{p,d}}/k_{\mathrm{d}}$); $T_{\mathrm{mp,d}}$, the melting temperature; L_{d}, heat of the fusion; $c_{\mathrm{p,d}}$, specific heat; and k_d, the conductivity of the debris. In CLM, X_p is expressed as

$$X_p = \frac{d_i}{2f} \ln\left[\frac{T_d - T_{mp,d}}{T^* - T_{mp,d}}\right] + 0.155\,\mathrm{Re}_d^{8/11} d_i \left[\frac{\mathrm{Pr}}{B}\right]^{7/11}, \quad (4)$$

where the first and second terms on the right-hand side are the melt penetration distance corresponding to the superheated and saturated melts, respectively. T^*-$T_{mp,d}$ implies the minimum degree of superheat for the melt to travel before solidification chokes off the flow (T^*-$T_{mp,d} \approx 10$ K). Pr is the Prandtl number ($\mu_d c_{p,d}/k_d$) and B is given as follows:

$$B = \left[1 + \frac{2c_{p,d}\left(T_{mp,d} - T_t\right)}{L_d}\right]^{1/2} \quad (5)$$

The predictions of melt penetration distance by MBFM and CLM are shown in Fig. 3 in terms of the debris temperature and melt velocity, where Δp was fixed to be 1 MPa. As shown in the figure, the CLM predicts a greater melt penetration distance than MBFM over the whole range of debris temperatures.

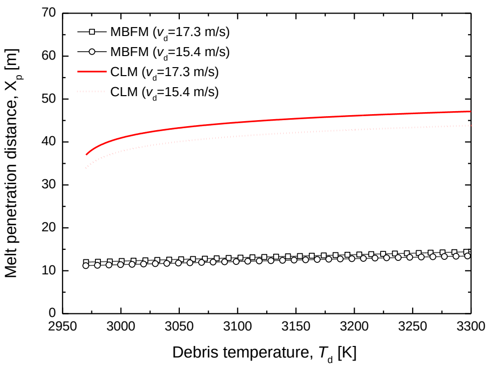

Fig. 3 Comparison of melt penetration distance

2.3 Tube ejection and rupture

Tube ejection begins with degrading the penetration tube weld strength to zero as the weld is exposed to temperatures that range up to melting, and then overcoming any binding in the hole in the vessel wall that results from a different thermal expansion of the tube and vessel wall. The weld failure criterion is given as

$$\sigma_u \le \sigma_e, \quad (6)$$

where σ_u is the ultimate strength of the weld and the effective stress σ_e is expressed as

$$\sigma_e = \sqrt{3}\tau_w = \sqrt{3}\left(\frac{p_i r_o}{2L_w}\right), \quad (7)$$

where τ_w is the shear stress in the weld; L_w, weld length; r_o, tube outer radius.

Assuming that the weld fails and the tube-hole radial gap δ_i is negative (i.e., tube-hole interference condition), the tube-hole interface pressure P_{th} is given as

$$P_{th} = \text{lesser of} \left\{ \begin{array}{l} \dfrac{\delta_i \cdot E\left(r_o^2 - r_i^2\right)}{r_o\left[r_o^2\left(1-2v_t\right) + r_i^2\left(1+v_t\right)\right]} \\ \dfrac{2}{\sqrt{3}}\sigma_u \ln\left(\dfrac{r_o}{r_i}\right) \end{array} \right\}, \quad (8)$$

where E is Young's modulus; v_t, poisson's ratio; and r_i, the inner radius of the tube. The total frictional shear force V_T available to resist tube ejection is then the summation for n segments of the tube, as follows:

$$V_T = \sum\left(f \cdot P_{th}\, 2\pi r_o \Delta L_t\right)_n, \quad (9)$$

where f is a frictional coefficient between the tube and the vessel hole, and ΔL_t is a segment size. The ejecting pressure force F_p is simply given as

$$F_p = p_i \pi r_o^2 \quad (10)$$

If F_p is greater than V_T, the tube is ejected. Figure 4 shows the variation of V_T with the debris temperature at Δp = 1 MPa. As shown in the figure, there exist limits of debris temperatures for preventing the tube ejection. Moreover, the maximum debris temperature for preventing a tube rupture was obtained as 2154 K.

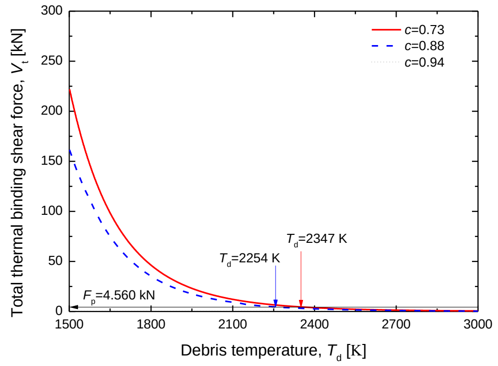

Fig. 4 Variations of thermal binding shear force

3. Conclusions

The analytical models of the penetration failure were reviewed, and estimations were performed for the APR1400 ICI penetration. For better predictions, the more realistic thermo-physical properties of the debris, ICI tube, and reactor bottom head should be obtained.

ACKNOWLEDGEMENT

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