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Enhancement of weld failure and tube ejection model in PENTAP program

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1. **Introduction**

The determination of the penetration tube failure modes and timing at the lower head is important tasks under a given severe accident condition. The penetration tube failure modes and the mechanisms were identified [1]. The reactor vessel pressure, the debris mass, the debris temperature, and the component of material can have an effect on the penetration tube failure modes. Furthermore, these parameters are inter-related.

There are some representative severe accident codes such as MELCOR, MAAP, and PENTAP program. MELCOR decides on a penetration tube failure by its failure temperature such as 1273K simply [2]. MAAP considers all penetration failure modes and has the most advanced model for a penetration tube failure model [3]. However, the validation work against the experimental data is very limited.

PENTAP program which evaluates the possible penetration tube failure modes such as creep failure, weld failure, tube ejection, and a long term tube failure under given accident condition was developed by KAERI [4].

The experiment for the tube ejection is being performed by KAERI [5]. The temperature distribution and the ablation rate of both weld and lower vessel wall can be obtained through the experiment. This paper includes the updated calculation steps for the weld failure and the tube ejection modes of the PENTAP program to apply the experimental results.

2. Model for failure mode

2.1 Model review for weld failure and tube ejection

The important input data and assumptions for weld failure and the tube ejection modes in the PENTAP program are the debris temperature, the cavity pressure, the clearance gap size ($\delta_{clearance}$), the temperature distribution of the weld and the reactor vessel wall, and the outer wall temperature (or external wall condition).

The weld failure is determined by comparing the shear stress (τ_w) and the yield stress (σ_{YP}). The yield stress can be determined by inputting the debris temperature and the weld temperature distribution. The shear stress is obtained from the reactor pressure, the weld depth, and the penetration tube diameter as follows

$$\tau_w = \frac{(\mathrm{P_i} + \mathrm{P}_m)\pi \mathrm{r_o^2}}{2\pi \mathrm{r_o L_w}} = \frac{(\mathrm{P_i} + \mathrm{P}_m)\mathrm{r_o}}{2\mathrm{L_w}} \qquad (1)$$

where, $\mathrm{L_w}$, $\mathrm{r_0}$, $\mathrm{P_m}$ and $\mathrm{P_i}$ are the length of weld, outer diameter of penetration tube, the pressure due to the debris mass and the cavity pressure.

If it is satisfied the below condition, it is determined that the weld part is not failed. In this case, the tube ejection doesn't happen.

$$\sigma_{\mathrm{yp}} > \sqrt{3}\tau_w \qquad (2)$$

However, if weld failure occurs, the tube ejection is check. The determination of tube ejection is as follows. The detail description of this procedure is in Ref. [6].

(1) Calculate the free thermal expansion of tube and hole at each control volume as shown in Fig 2.1.

(2) Calculate the pressure expansion of tube at each control volume.

(3) Obtain the tube-hole radial gap(δ_{i}) at pressure and temperature,
$\delta_{\mathrm{i}} = (r_{\mathrm{h}} + \Delta r_{\mathrm{h}}) - (r_{\mathrm{o}} + \Delta r_{\mathrm{o}}) - \delta_{clearance}$.
where, r_{h}, Δr_{h}, and Δr_{o} are the hole diameter, the hole expansion length, and the tube expansion length.

(4) Find tube-hole interface pressure at each control volume,

$$\delta_{\mathrm{i}} < 0: \ P_{\mathrm{th}} = \text{lesser of} \begin{cases} \dfrac{\delta_{\mathrm{i}} \cdot E\left(r_{\mathrm{o}}^2 - r_{\mathrm{i}}^2\right)}{r_{\mathrm{o}}\left[r_{\mathrm{o}}^2(1 - 2\nu_{\mathrm{t}}) + r_{\mathrm{i}}^2(1 + \nu_{\mathrm{t}})\right]} \\ \dfrac{2}{\sqrt{3}}\sigma_{\mathrm{u}} \ln\left(\dfrac{r_{\mathrm{o}}}{r_{\mathrm{i}}}\right) \\ \text{Required pressure to cause compression} \\ \text{failure of the tube materal} \end{cases}$$

$$\delta_{\mathrm{i}} \geq 0: \ P_{\mathrm{th}} = 0$$

(5) Calculate the total thermal binding shear force,
$$V_{\mathrm{T}} = \sum_{n=1}^{n} f \cdot P_{\mathrm{th}} 2\pi r_{\mathrm{o}} \Delta l_{\mathrm{t}}$$
where, Δl_{t} and f are the length of the control volume and the friction factor, usually 0.27 for high-temperature and oxidized conditions.

(6) Comparing the ejecting pressure force which is $F_{\mathrm{p}} = (p_{\mathrm{i}} + p_m)\pi r_{\mathrm{o}}^2$ with the binding shear force

(7) When $F_P > V_T$, the tube ejection occurs.

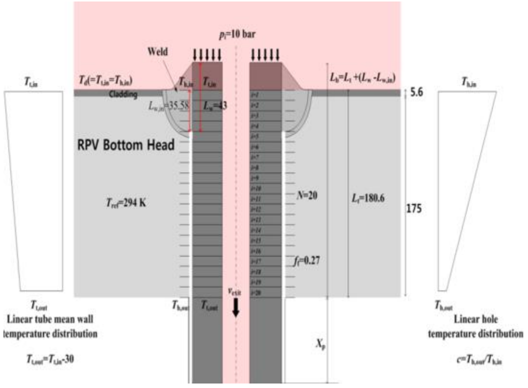

Fig. 2.1 Conceptual schematic of failure models

2.2 Updated calculation steps

At the weld failure mode, the weld melting process and the change in the weld temperature distribution are added. So, as the time goes on, the decrease in the weld depth (L_W) leads to the increase in the shear stress.

At the tube ejection mode, the lower vessel wall ablation rate and the change in the temperature profile of the vessel wall and the tube with time are applied. So, as the time goes on, the contacting length decreases. As a result, the binding shear force decreases.

The figure 2.2 shows the calculation flow of the updated PENTAP program.

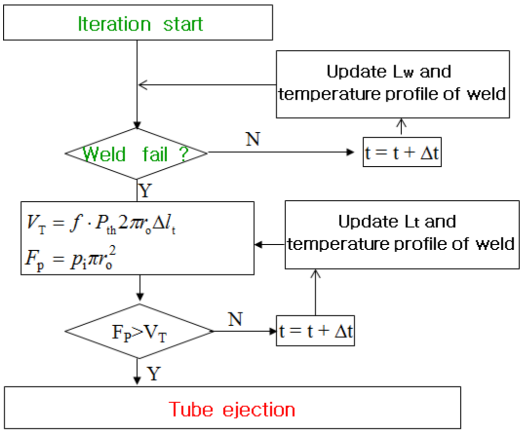

Fig. 2.2 Calculation steps

3. Results

To calculate the tube ejection models, we assumed that the wall temperature profile of the tube and hole are linear, the temperature difference between internal tube wall and outer tube wall is 30K, the ratio of $T_{h,out}$ to $T_{h,in}$ is constant as shown in Fig 2.1. If the melting process doesn't consider, the tube ejection doesn't occur until debris temperature reaches 2347K when *c* which is the ratio of $T_{h,out}$ to $T_{h,in}$ is 0.73 as shown in Fig 3.1. However, the lower vessel wall melts above 1700K. So, if updated calculation steps are applied, it is found that the binding shear force is smaller than the ejecting pressure after some time. The reason is that the binding force decreases due to the decrease in the contact surface as the thickness of the lower vessel wall decreases. In this case, the ablation rate 0.244mm/s, after 700s, the binding shear force reaches 4.560 kN as shown in Fig. 3.2.

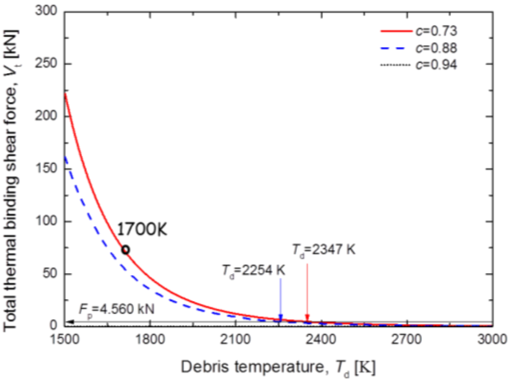

Fig. 3.1 Change of binding shear force with debris temperature

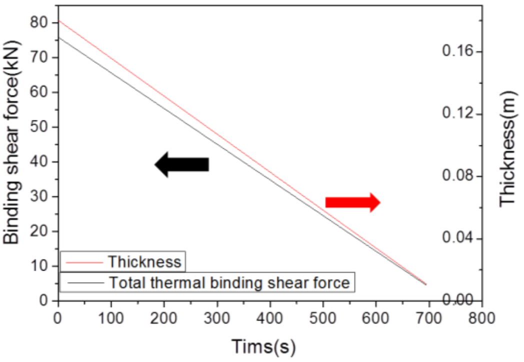

Fig. 3.2 Change of binding shear force with time at 1700K

In this study, the temperature distribution and the ablation rate were considered. However, in order to evaluate the possible penetration tube failure modes in MAAP and PENTAP, many assumptions are still needed to put the input condition. Among them, one of the key parameter is the gap clearance to determine the tube ejection. If the gap clearance data put into the PENTAP program with the temperature distribution and the ablation rate, the prediction ability of weld failure and tube ejection will improve. So, we plan to put the information of the gap clearance which is obtained ANSYS into PENTAP calculation steps.

4. Conclusions

PENTAP program can evaluate the possible penetration tube failure modes. It still requires a large amount of efforts to increase the prediction of failure modes. Some calculation steps are necessary for applying the experimental and the numerical data in the PENTAP program. In this study, new calculation steps are added to PENTAP program to enhance the weld failure and tube ejection models using KAERI's experimental data which are the ablation rate and temperature distribution of weld and lower vessel wall. In the future, the new steps for the gap clearance data from numerical analysis will be added to improve the prediction capacity of the tube ejection mode in PENTAP.

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