Numerical Simulation of the Penetration Tube Ejection using PENTAP plus

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1. Introduction

Korean PWRs (Pressurized Water Reactors) have several ICI (In-Core Instrumentation) penetration tubes that penetrate the reactor vessel through the reactor bottom head. APR1400 has 61 ICI penetrations to monitor the in-core status [1]. They are attached to the inside of the reactor bottom head by a partial penetration weld. The penetrations are considered as the most vulnerable parts with respect to the reactor vessel failure when a severe accident like the Fukushima accident occurs, since the melted core material (corium) relocated to the lower plenum of the reactor pressure vessel. Therefore, the determination of the failure modes and the timing at the lower head, is an important task under a given sever accident condition.

The penetration tube failure modes and mechanisms were identified by J. L. Rempe et.al [2]. Penetration tube failure can be divided into the two categories: tube ejection out of the vessel lower head and rupture of the penetration tube outside the vessel. Tube rupture assumes that the debris bed has melted the instrument tube inside the reactor and melt migrates down into the tube to a location outside the vessel wall where a pressure rupture can occur, thus breaching the pressure boundary. Tube ejection begins with degrading the penetration tube weld strength to zero when the weld is exposed to higher temperatures that range up to melting and then overcoming any binding force in a reactor vessel wall-penetration tube interface which results from differential thermal expansion of the tube and the reactor vessel. So, the inside of reactor vessel pressure, the debris mass, the debris temperature, and the component materials can have an effect on the penetration tube failure modes. Furthermore, these parameters are inter-related. In these reasons, the failure model in the severe accident code requires a large amount of effort to increase the prediction of failure mode.

Here, we focused on the tube ejection phenomena. The numerical simulation was undertaken to find the conditions which do not occur the tube ejection using PENTAP plus [3] program, which was developed by KAERI. PENTAP plus can evaluate the possible penetration tube failure modes such as a weld failure, a tube ejection failure under the given accident conditions

2. Numerical Simulation

2.1 PENetration tube Analysis Program (PENTAP) plus

The PENTAP plus [3] was modified based on the PENTAP, which was developed by Park et al. [4]. The modifications are as follows; the ultimate tensile strength is determined by inputting the debris temperature since the weld was assumed as one lumped model for the previous model. Although this assumption is very conservative, it is not a reasonable assumption because the weld temperature depends on each location. In the modified model, the yield stress of the weld is obtained the sum of the yield stress of each layer. Also, ablation effect of both the vessel wall and the weld was considered for the conservative model. The detail of the procedure of the tube ejection determination is reported in Ref. [3].

Figure 1 shows a modified calculation flow for the determination of the weld failure and the tube ejection. In this program, if the temperature of the weld, the tube, and the vessel exceeds the melting temperature after updating temperature profile, the ablation phenomena for the weld and the vessel wall were considered

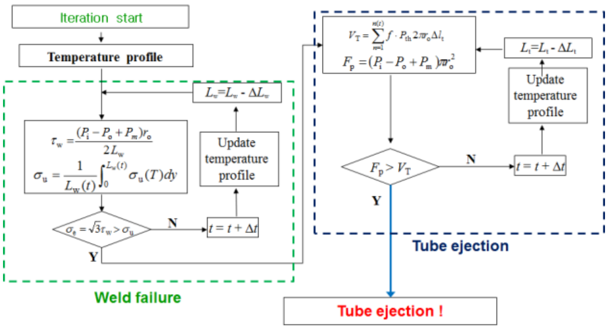

Fig. 1. PENTAP plus calculation flow steps for tube ejection

2.2 Numerical model

In order to investigate the conditions which do not occur the tube ejection, the binding shear force in a reactor vessel wall-penetration tube interface which results from differential thermal expansion of the tube and the reactor vessel is compared with the tube ejection force which results from differential pressure of the inside and outside reactor vessel. The computation domain is shown on the figure 2, where L_t, L_w, d_0, d_i, P_o, P_i, and f are the total length of the reactor vessel and the length of the weld, the outer diameter and inner diameter of the penetration tube, the pressure outside the reactor vessel and inside the reactor vessel, and the friction factor. The APR 1400 ICI penetrations design values were used. The material of the reactor vessel wall is

SA508, Gr.3 Cl.1) and the material of the penetration tube is Inconel 690. The material properties of Inconel 690 is from Ref. 5. Furthermore, the following assumptions were used.

1. The tube-hole radial gap (δ_i) is 50 μm, the tube-hole radial gap at given the pressure and temperature ,
   $$\delta_i = (r_h + \Delta r_h) - (r_o + \Delta r_o) - \delta_{clearance} \qquad (1)$$
   where r_h , Δr_h , Δr_o and are the hole diameter, the total hole expansion length, and the total tube expansion length.
2. The pressure difference between the inside reactor vessel and the outside reactor vessel is 10 bar.
3. If the melt migrates down into the tube to a location outside the vessel wall, the penetration tube temperature is the same as the melt temperature which is not higher than the melting temperature. If not, the penetration tube temperature profile is the same as the reactor vessel temperature profile.
4. The vessel temperature has a linear profile and the internal vessel wall temperature is 2000 K.
5. Since the material properties are not always available for elevated temperatures, the linearly extrapolates from known values.
6. For the external wall condition, the outer wall temperature was set to be 120°C due to the nucleate boiling condition, the effects of convection, and phase change are assumed negligible at the outer wall for simplicity.

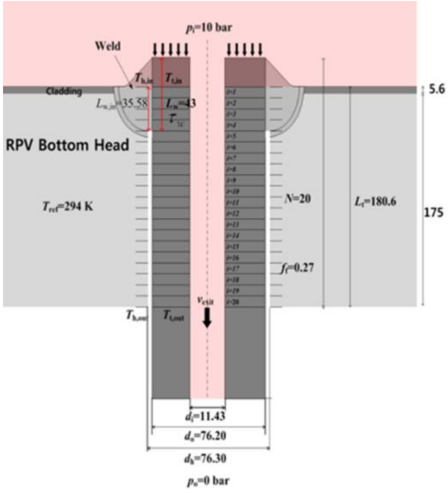

Fig. 2 Conceptual schematic of the failure model

2.3 Numerical results

When the melt migrates down into the tube to a location outside the vessel wall, it was compared to binding shear force with tube ejection force with various melt temperature at the external cooling condition as shown on Fig. 3. In this case, it is not observed the tube ejection. Also, we performed numerical simulations as the external wall temperature changes from 120°C to 1200°C with melt temperature. The figure 4 shows the numerical results when the melt temperature is 1200°C. It is observed that the tube ejection occurs near the melt temperature. In this case, the tube ejection fore is higher than the binding shear force near 1150°C.

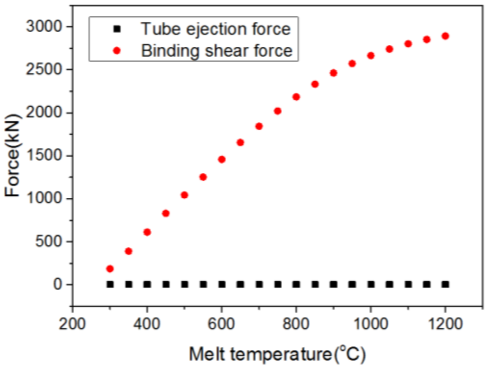

Fig. 3 Binding shear force with melt temperature at the external cooling condition.

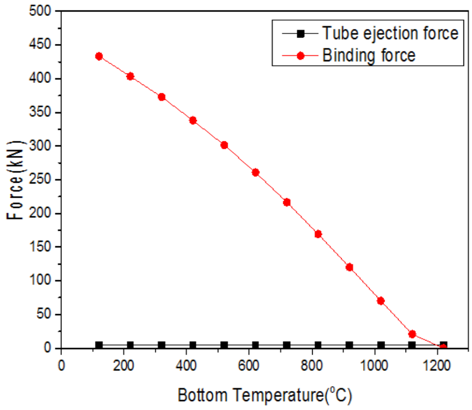

Fig. 4 Binding shear force with external wall temperature when the melt temperature is 1200 °C

If the melt does not pass through the tube, it is observed the tube ejection always occurs. The reason is that there is no binding shear force. Because we assumed that the penetration tube temperature profile is the same as the reactor vessel temperature profile, the tube cannot adhere to the reactor vessel due to the differential thermal expansion of the tube and the reactor vessel which results from the different temperature. The required temperature difference between the tube and the reactor vessel wall to attach to each other was obtained as the tube temperature increases. Figure 5 shows the required temperature difference with the tube temperature. The required temperature difference decreases until near 1250K and then increases. It is also observed that the minimum required temperature difference is larger than about 30K. The reason is that the thermal expansion coefficient of the tube (Inconel 690) faster than the reactor vessel wall increase as the temperature increases. Until now, the expansion direction of the tube and hole assumed as Eq.(1), however, the expansion direction differs at the penetration tube location of the lower head. Although the Eq. (1) is the most conservative assumption to determine the failure mode, if Eq.2 is applied instead of Eq.1 in the procedure of the tube ejection determination, the tube ejection does not observed any cases.

$$\delta_{\mathrm{i}} = \left(r_{\mathrm{h}} - \Delta r_{\mathrm{h}}\right) - \left(r_{\mathrm{o}} + \Delta r_{\mathrm{o}}\right) - \delta_{clearance} \qquad (2)$$

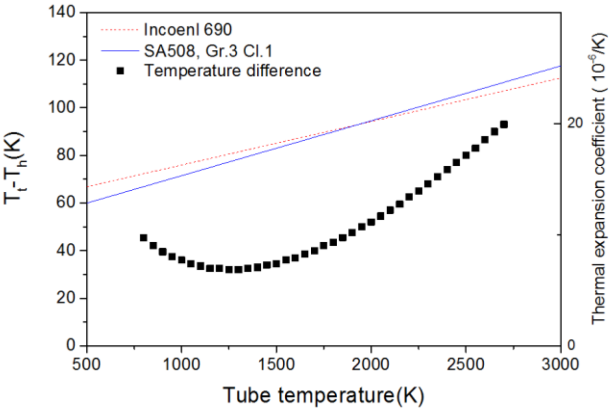

Fig. 5 Required temperature difference with tube temperature [3]

One of the key parameters is the temperature difference between the tube and the reactor vessel to determine the tube ejection. The temperatures are strongly dependent on the melt compositions and reactor vessel pressure according to the severe accident scenarios. So, it is hard to decide the temperature profile of the tube and the reactor vessel. However, we can say that if the melt migrates down into the tube to a location outside the vessel wall, it is advantageous to avoid the tube ejection because it makes large temperature difference between the tube and the reactor vessel, although it is highly possible to lead to tube rupture.

3. Conclusions

The numerical simulation was undertaken to find the conditions which occur the tube ejection using PENTAP plus. It is observed that if the melt migrates down into the tube to a location outside the vessel wall, the tube ejection does not occur although it is highly possible to lead to tube rupture. Also, the penetration tube ejection is very sensitive to the temperature distribution. However, it is hard to decide the temperature profile of the tube and the reactor vessel, because the temperatures are strongly dependent on the melt compositions and reactor vessel pressure according to the severe accident scenarios. So, the more precise temperature distributions are needed, in order to get higher determination of the tube ejection,

Acknowledgments

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