

Preliminary Numerical Analysis of Freeze Valve Opening Time with Consideration of Salt Plug Solidification in a Molten Salt Reactor

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1. Introduction

A freeze valve is a key component that directly contributes to the safety of liquid-fueled molten salt reactors (MSRs). It blocks the flow path using a solid salt plug formed by locally solidifying the molten salt inside the pipe. During normal operation, the solid salt plug is maintained by external cooling, whereas the flow path can be opened when drainage is required by terminating the cooling and allowing the solid salt to melt through heat transferred from the surrounding system. This configuration enables reliable flow isolation under high-temperature and corrosive conditions while providing passive opening characteristics under accident conditions [1].

The opening of the freeze valve determines the initiation of salt drainage, and an increase in the melting time can delay the drainage process, thereby directly affecting the peak temperatures of the reactor structures and fuel salt [2]. The melting time of a freeze valve is determined not only by the melting point of the salt but also by various factors, including the size of the solid salt plug, its initial temperature and degree of subcooling, and the heat transfer conditions. Aji et al. [3] experimentally investigated the major parameters affecting the melting behavior of freeze valves and identified the diameter and length of the solid material, the temperature of the hot liquid, and the thermal diffusivity of the material as key factors affecting the melting time. Jiang et al. [4] demonstrated that wall temperature and valve geometry significantly affect the solidification behavior and formation of the frozen salt plug.

Most previous freeze valve studies have treated melting and solidification separately, prescribing a preformed solid salt plug with fixed geometry and temperature. However, the solid-liquid interface and temperature distribution established during solidification can strongly affect subsequent melting and valve opening. Therefore, coupled solidification to melting analysis is required to realistically evaluate freeze valve opening time under MSR accident conditions.

2. Numerical Model

Valve opening occurs when a continuous liquid flow path forms, before the solid salt plug melts completely. A simple energy-balance estimate cannot fully capture this process, necessitating numerical analysis. Therefore, FLOW-3D CAST [5] was employed as the CFD code

for the coupled simulation of solidification and subsequent melting behavior. Two cases were considered to evaluate the freeze valve opening behavior. In the first case, the entire solid salt plug in the central region of the freeze valve was initially prescribed at a uniform subcooling of 10 °C. In the second case, the melting calculation was initiated from the solid salt distribution obtained through the solidification simulation. The initial salt conditions and computational geometry used for the conventional melting analysis are shown in Fig. 1. The upper region, indicated in red, was filled with liquid FLiBe at 650 °C, whereas the central solid plug region, indicated in blue, was initialized at 444 °C, which is 10 °C below the melting point of FLiBe. A helium region at 400 °C was specified at the bottom of the freeze valve. Hastelloy N was used as the wall material, with a thermal conductivity of 20.3 W/m·K. FLOW-3D represents solid boundaries on a Cartesian grid using the Fractional Area/Volume Obstacle Representation (FAVOR) method [5]. Based on this feature, a uniform cell size of 0.0009 m was used, resulting in 494,592 cells including the wall block.

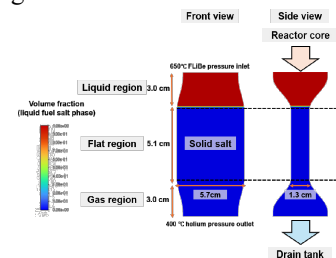


Fig. 1. Initial conditions for freeze valve opening calculation

3. Results and Discussion

The results of the conventional melting analysis, in which the freeze valve was initially filled with solid FLiBe uniformly subcooled by 10 °C, are presented in Fig. 2. The calculated melting time to valve opening was 978 s. As shown in the figure, the liquid salt fraction exhibits a rapid increase near the end of the melting process. This abrupt increase occurs when the solid salt remaining near the wall is completely melted, thereby opening a flow path and allowing the upper liquid salt to drain downward through the freeze valve. Accordingly, the onset of this rapid increase in the liquid salt fraction was defined as the freeze valve opening time in the present study. Further validation of the predicted temperature distribution and solid-liquid

interface evolution should be needed to improve confidence in the calculated valve opening time.

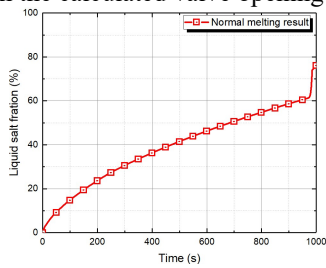


Fig. 2. Melting analysis with a prescribed initial solid plug

A solidification simulation was performed, and the resulting solid-salt geometry and temperature distribution were used as the initial conditions for the subsequent melting analysis. The results of the solidification simulation are shown in Fig. 3. During the solidification calculation, wall boundary conditions of 650 °C were applied to the upper and lower sections adjacent to the solidification region to represent the operation of the heaters. The wall temperature in the freeze-plug region was maintained at 350 °C, based on the wall-temperature control procedure employed during MSRE operation [1]. After completion of the solidification process, the lower boundary was opened to discharge the high-temperature liquid salt, and the emptied lower region was filled with helium. The subsequent melting calculation was then initiated from this solidified state. The solidification simulation produced a noticeably different plug configuration from that assumed in the conventional melting analysis. The frozen salt extended farther along the wall, whereas less solidification occurred near the central region, resulting in a concave solid-liquid interface. In addition, a nonuniform temperature distribution developed within the solid salt. Although the entire region was in the solid state, a greater degree of subcooling was observed near the outer wall, while the temperature near the central region remained relatively high.

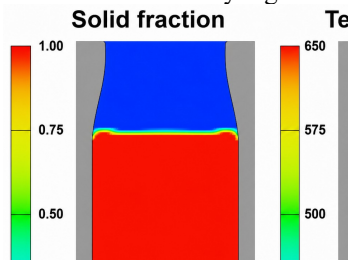


Fig. 3. Solidified salt geometry and temperature distribution

The melting behavior obtained using the solidification result as the initial condition is presented in Fig. 4. Melting initially progressed from the outer region owing to heat conduction through the Hastelloy N wall. Compared with the conventional melting case, the initial melting rate was lower due to the locally lower temperature near the wall and the thicker solidified salt layer formed during the preceding solidification process. However, as melting progressed, the relatively high temperature and smaller solidified thickness near the

central region accelerated the overall melting process. Consequently, the freeze valve opened at 723 s, significantly earlier than in the conventional melting analysis. These results suggest that the thickness of the solidified salt layer along the flow path may affect the valve opening time. The effects of valve diameter and cooled-section length on the resulting plug geometry and temperature distribution should be evaluated in future work to establish quantitative design guidelines.

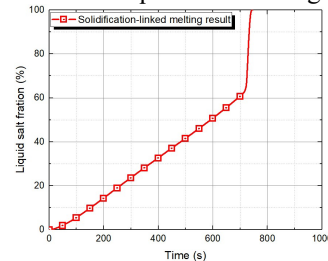


Fig. 4. Melting analysis results using the solidification results

4. Conclusions

Accounting for the preceding solidification process reduced the predicted valve opening time from 978 to 723 s, demonstrating its significant influence on freeze-valve melting behavior and the importance of considering solidification for realistic opening-time predictions. However, the present analysis is limited by the lack of validation of the temperature distribution in the lower gas region and the solidification process. Further code-to-code verification will be conducted to improve the reliability of the analysis.

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