Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Investigation of freeze valve release models applicable for molten salt reactor by OpenFOAM code

Juhyeong Lee[a], Chun Ye Hwan[a], Sung Joong Kim[a,b*]
[a]*Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763 Republic of Korea*
[b]*Institute of Nano Science & Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763* Republic of Korea
*Corresponding author: sungjkim@hanyang.ac.kr

***Keywords :** Molten salt reactor, Freeze plug, Melting, Computational fluid dynamics, Conjugate heat transfer.

1. Introduction

A liquid-fuel molten salt reactor (MSR) is one of the Gen-IV reactor systems that pursue high economics, safety, and low radioactive waste. Based on the unique characteristics of liquid fuel, an MSR uses a drain tank to isolate and cool the fuel during an accident. To operate the drain system, many MSRs adopt a freeze valve. In a transient situation, the high temperature of the liquid fuel melts the plug, opening the valve. Since the freeze valve operates without electricity, it is expected to enhance the passive safety of the MSR.

Recent MSR developments have also adopted freeze valves as a safety feature [1]. Since the freeze valve significantly influences accident scenarios during transient conditions, it is essential to evaluate its opening conditions and timing to understand the reactor's safety characteristics. However, due to the unique operating principle of the freeze valve, assessing its opening time requires a heat transfer analysis that considers complex heat transfer.

Previous studies have primarily focused on the melting of salt within the freeze plug by analyzing its temperature variation [2]. However, salt has relatively low thermal conductivity, whereas the surrounding pipe, designed for cooling during normal operation, has high thermal conductivity. In a transient scenario where valve cooling is interrupted, the pipe temperature is expected to rise first due to its higher thermal conductivity. Muhammad Ilham et al. identified the complete melting of salt near the pipe walls as the condition for valve opening [3]. Therefore, to accurately understand the melting behavior and dynamics of the salt within the valve, it is essential to analyze the overall heat transfer phenomena occurring inside the pipe.

In this study, we analyze the heat transfer mechanism of the freeze valve, considering conjugate heat transfer and phase-change heat transfer. The calculations were conducted using OpenFOAM 2406, and two different solvers were selected for comparison. The analysis compared the results obtained using chtMultiRegionFoam and icoReactingMultiphaseInterFoam by evaluating the presence or absence of heat transfer between the pipe and the salt, as well as the effects of different phase-change models.

2. Numerical method and conditions

2.1 Geometry and mesh generation

The geometry and mesh of the freeze valve were generated using SALOME 9.14.0, an open-source software that provides a generic pre- and post-processing platform for numerical simulation. Figure 1 shows a benchmark design of the freeze valve. The freeze valve was based on the MSRE freeze valve design, consisting of a pipe with a flattened section [4].

The mesh was generated in a tetrahedral shape, with 64,360 cells in the liquid region and 25,453 cells in the solid region.

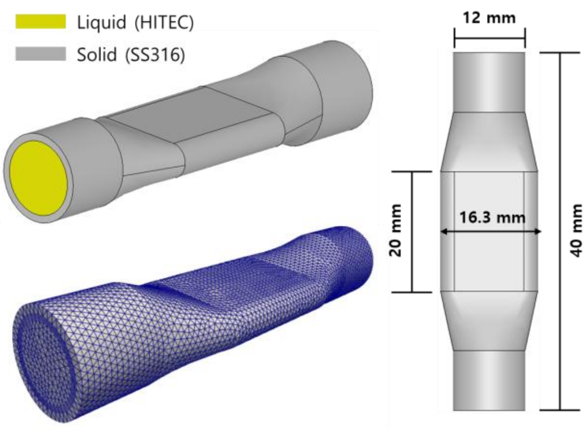

Fig. 1 A schematic of freeze valve and generated mesh for simulation

2.2 Analysis code

OpenFOAM is free C++ library and toolbox for the solution of various numerical problem. To solve the different types of numerical problems, OpenFOAM provides numerical solvers, which were developed to simulate a particular thermal-hydraulic phenomena and utilities for pre-/post- processing. Additionally, OpenFOAM is available in the GNU general public license, which allows users to access the OpenFOAM libraries and modify the source code. Because of freedom and flexibility of OpenFOAM, OpenFOAM has been used in many research and development for new finding.

2.3 Simulation condition

In this study, chtMultiRegionFoam and icoReactingMultiphaseInterFoam were selected to solve the phase-change heat transfer of the freeze valve. chtMultiRegionFoam was used to solve the heat transfer between the solid and liquid regions of the freeze valve pipe, while icoReactingMultiphaseInterFoam was chosen for its ability to simulate phase change between phases based on the VOF (Volume of Fluid) method. Although the VOF model is capable of simulating the interaction between two immiscible fluids, only the salt phase was considered in this analysis.

The boundary conditions of the simulation are as follows. To simulate the hot liquid from the core, an inlet at the top of the valve was set to a constant temperature of 508 K. The pipe walls were assigned a no-slip condition, and the pressure was assumed to be atmospheric. To represent the initially solidified plug, the initial temperature was set to 298 K.

To simulate phase-change heat transfer, chtMultiRegionFoam utilized the solidificationMeltingSource option within the fvOptions framework to account for enthalpy changes during phase transitions throughout the liquid domain. In contrast, icoReactingMultiphaseInterFoam employed the massTransferModel, which is based on the Lee model [5], to simulate phase transitions between liquid and solid salt phases. The overall simulation parameters are summarized in **Table 1.**

Table 1: Numerical analysis condition for freeze valve simulation

	Case 1	Case 2
Solver	chtMultiRegionFoam	icoReactingMultiphaseInterFoam
Phase change	solidificationMeltingSource	massTransferModel
Time step	0.01 s	
Radiation Model	N/A	
Inlet temperature	508 K	
Liquid temperature	Initial Temp T = 298 K	
Wall temperature	Upper wall = 508 K (Only Case 2) Side & bottom wall = zeroGradient	
Velocity condition	No slip	
Thermophysical properties [2] (HITEC)	Melting temperature 415 K ρ = 2107 kg/m^3, C_p = 1560J/kg-K, Thermal conductivity = 0.38 W/m-K Dynamic viscosity = 3.17 mPas	

3. Results and discussions

Figure 2 shows temperature contour over time of each case. In Case 1 (chtMultiRegionFoam), the solid region with high thermal conductivity heats up faster than the salt, leading to an increase in heat transfer from the pipe wall to the salt over time. Due to the larger heat transfer area, the overall temperature of the freeze valve rises more rapidly compared to Case 2 (icoReactingMultiphaseInterFoam), where the solid region is not modeled. As a result, Case 1 exhibits a more uniform temperature distribution. In contrast, Case 2 relies solely on heat transfer from the inlet at a fixed temperature. Due to the low thermal conductivity of salt, the temperature increases more gradually in this case. The average temperature at the center of the freeze valve is shown in **Figure 3**. After 50 minutes, the average temperature at the center was 446 K in Case 1 and 347 K in Case 2, showing a difference of approximately 100 K.

This difference in heat transfer significantly affected the melting process of the freeze valve. **Figure 4** illustrates the fraction of molten salt within the freeze valve over time. In Case 1, where heat transfer of pipe was modeled, the heated pipe rapidly transferred heat to the surrounding salt, initiating melting near the pipe walls. As a result, 99% of the salt had melted by 50 minutes. In contrast, in Case 2, due to the low thermal conductivity of the salt, only 28% of the salt had melted by 50 minutes, indicating a much slower melting process.

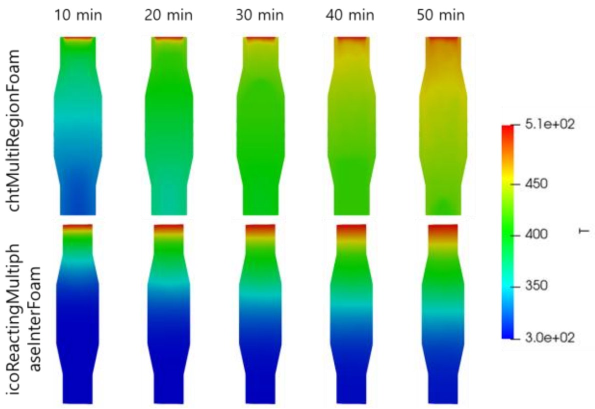

Fig. 2 Temperature of cross section along y-axis over time of each case

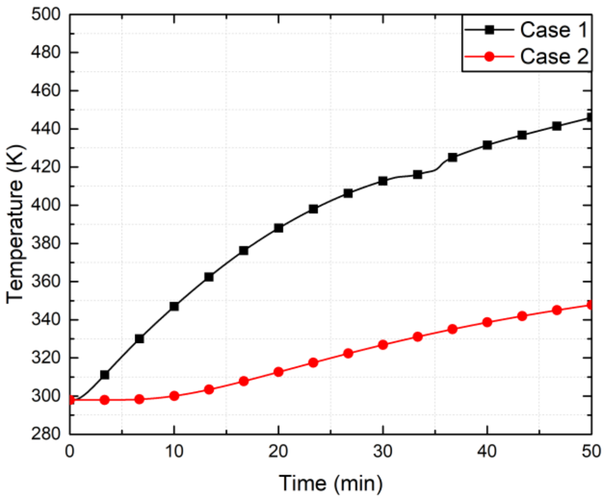

Fig. 3 Average temperature of freeze valve center over time of each case

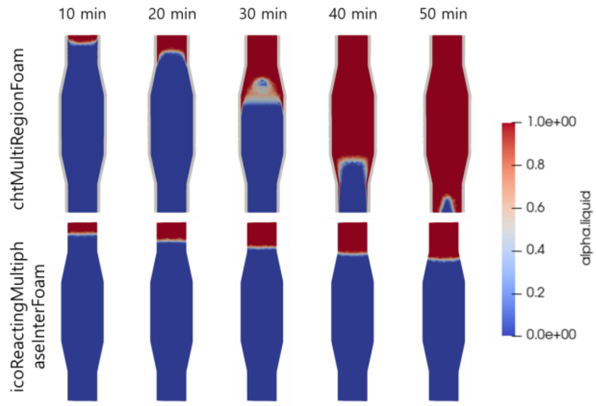

Fig. 4 Liquid fraction of cross section along y-axis over time of each case

4. Conclusions

In this study, freeze valve phase change was simulated through the OpenFOAM. By using two different solvers, the melting process of freeze valve and heat transfer were simulated considering conjugate heat transfer. In the heat transfer analysis of the freeze valve, the heat transfer area contributed by the pipe had a significant impact on the results. By incorporating more realistic external cooling conditions and the initial temperature of the pipe, it is expected that a more accurate simulation of the valve's melting process can be achieved.

ACKNOWLEDGMENTS

This research was supported by the National Research Foundation of Korea (NRF) and funded by the ministry of Science, ICT, and Future Planning, Republic of Korea (grant numbers RS-2021-NR056168), and the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (RS-2024-00439210).

REFERENCES

[1] Lee, C., Yeo, D., & Koo, G. H. A Preliminary Thermal Analysis and Modeling Study of MSRE Freeze Valve for K-MSR Valve Development.

[2] Riupassa, R. D., Basar, K., & Waris, A. (2022, June). Numerical Investigation of Freeze Valve Melting Behavior in Molten Salt Reactor using OpenFOAM. In Journal of Physics: Conference Series (Vol. 2243, No. 1, p. 012119). IOP Publishing.

[3] Ilham, M., & Okawa, T. (2023). A Simple Analytical Model to Predict the Freeze Plug Opening Time in Molten Salt Reactors. Journal of Nuclear Engineering and Radiation Science, 9(4).

[4] Korinek, T., Kahraman, M. C., Skarohlid, J., & Skoda, R. MOLTEN SALT FREEZE VALVE OPERATION: EXPERIMENTAL STUDY.

[5] Lee, W. H. (1980). A pressure iteration scheme for two-phase flow modeling. Multiphase transport fundamentals, reactor safety, applications, 1, 407-431.