Verification of a 1-D Freezing Model in Modelica Using a Natural Circulation Loop Model

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1. Introduction

Molten salt reactors (MSRs) are advanced nuclear systems that use high-temperature molten salts, enabling high thermal efficiency and supporting a range of passive safety concepts. In accident scenarios of an MSR, such as a reactor pump trip, forced circulation can be lost; if decay heat is not adequately removed, system temperatures may rise excessively, degrading structural integrity and overall safety performance. Therefore, it is essential to quantitatively evaluate whether heat removal pathways can maintain sufficient heat transport capability under accident and transient conditions. In particular, molten salts used in MSRs have relatively high melting temperatures, so local temperatures can drop below the melting point during transients, resulting in solidification. Solidification may adversely affect decay heat removal by reducing mass flow rate, and it may also cause component damage due to volume change during solidification.

Performing high-fidelity computational fluid dynamics (CFD) analyses that include solidification at the system level is often impractical due to the substantial computational cost. However, the Modelica language provides advantages for relatively fast transient simulation using one-dimensional (1-D) system-code-level representations.

TRANSFORM, a nuclear systems library for Modelica developed at Oak Ridge National Laboratory further supports MSR system analysis by providing relevant components. In prior work, Lim et al. [1] developed a 1-D fuel-salt freezing model within the Modelica–TRANSFORM framework by formulating governing equations for solidification. The study demonstrated the model's basic behavior through qualitative tests. However, experimental validation was not performed due to the limited availability of suitable data.

In this study, we verify the applicability of the previously developed salt freezing model using two representative scenarios. First, for a natural circulation loop in which freezing does not occur, we compared a Modelica-based loop including the freezing model with experimental data to confirm that the model can reproduce natural circulation behavior under non-freezing conditions. Second, for a slab pipe geometry in which freezing occurs, we compared the simulation results with an analytical solution to evaluate the physical fidelity and predictive accuracy of the model. These verifications demonstrate the feasibility of a Modelica-based system analysis framework that accounts for solidification in future MSR decay heat removal transient and accident analyses.

2. Method

2.1. 1-D Freezing Model in Modelica

The freezing model developed by Lim et al. is a 1-D model that assumes uniform solidification in a circular pipe geometry. A schematic of the freezing pipe model is shown in Fig. 1.

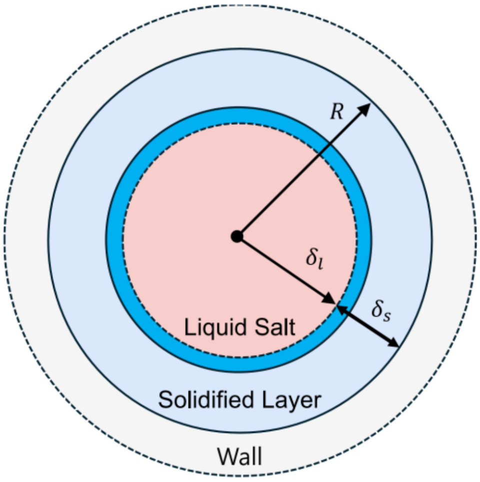

Fig. 1. Schematics of the freezing pipe model [1]

The governing equations for the liquid region are given in Eqs. (1)–(4), and those for the solid region are given in Eqs. (5)–(7).

$$(1)\ \frac{\partial}{\partial t}(\alpha_l \rho) + \frac{\partial}{\partial z}(\alpha_l \rho u) = -\frac{\sigma_A}{A_T}$$

$$(2)\ \frac{\partial}{\partial t}(\alpha_l)(\rho u) + \frac{\partial}{\partial z}(\alpha_l)(\rho u u) = -(\alpha_l)\frac{\partial p}{\partial z} - (\alpha_l)\rho u - (\alpha_l)\frac{f}{2D_h}\rho u|u| - \frac{\sigma_A u}{A_T}$$

$$(3)\ \frac{\partial}{\partial t}\left(\alpha_l \rho C_p T\right) + \frac{\partial}{\partial z}\left(\alpha_l \rho C_p T u\right) = -\frac{\sigma_A}{A_T} H_{l,T_m} - \frac{q_i'' P_{h,i}}{A_T} + \alpha_l \dot{Q}_d$$

$$(4)\ \rho = \rho(p, T)$$

$$(5)\ \frac{\partial}{\partial t}(\alpha_s \rho_s) = \frac{\sigma_A}{A_T}$$

$$(6)\ \frac{\partial}{\partial t}\left(\alpha_s \rho_s C_p T_s\right) = \frac{\sigma_A}{A_T} H_{l,T_m} + \frac{q_i'' p_{h,i}}{A_T} - \frac{q_w'' p_w}{A_T} + \alpha_s \dot{Q}_d$$

$$(7)\ \rho_s = \rho_s(p,T)$$

α_l and α_s denote the liquid and solid fractions defined on an area basis, respectively, and the freezing rate σ_A represents the mass that solidifies per unit length and per unit time. $\dot{Q}_d$ and H_{l,T_m} represent decay heat and saturated enthalpy of liquid, respectively.

In addition, by assuming a quasi-steady temperature distribution in the solidified layer governed by conductive heat transfer, the temperature profile within the solid layer is expressed as Eq. (8). The freezing rate is calculated by dividing the difference between the convective heat flux on the liquid side and the conductive heat flux on the solid side at the liquid–solid interface by the latent heat of fusion.

$$(8)\ T(r) = C \ln\left(\frac{r}{\delta_l}\right) + T_{frz} + \frac{1}{4k_s}\dot{Q}_d \delta_l^2 - \frac{1}{4k_s}\dot{Q}_d r^2$$

$$(9)\ C = \left[\frac{R^2-\delta_l^2}{R^2 \ln\left(\frac{R}{\delta_l}\right) - \frac{R^2-\delta_l^2}{2}}\right]\left[T_s - T_{frz} + \frac{\dot{Q}_d}{8k_s}\left(R^2 - \delta_l^2\right)\right]$$

The verification of the freezing model consists of two cases: (1) comparison against experimental results for a natural circulation loop under non-freezing conditions; and (2) comparison against an analytical solution for a freezing case in slab geometry.

2.2. Non-Freezing Natural Circulation Loop

For the first verification, a Modelica-based natural circulation loop model was designed to enable direct comparison with the experimental data reported by Swapnalee and Vijayan [2]. The loop has the heated and cooled sections arranged in the vertical legs; the left vertical pipe serves as the heater, and the right vertical pipe is modeled as a shell-and-tube type heat exchanger where cooling occurs. The freezing model was applied to the tube side of the heat exchanger model (HX), and water was used as the working fluid. The schematics of the loop model is shown in Fig. 2.

Simulations were performed by varying the heater power, and each case was run long enough to obtain steady-state responses.

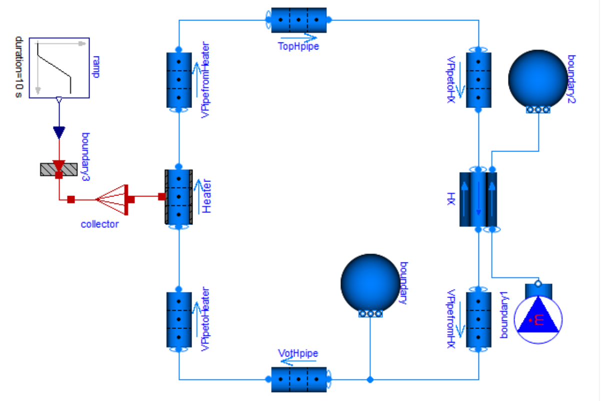

Fig. 2. Schematics of Modelica natural circulation loop

2.3. Slab-Geometry Freezing Verification

In the second verification, the steady-state solution derived by Zou et al. was used as the analytical soltuion [3]. In slab geometry, this analytical solution predicts the onset of freezing along the axial direction and provides closed-form, piecewise expressions for the axial liquid temperature distribution and axial solid fraction distribution.

Consistent with this benchmark setup, the Modelica freezing model was configured for slab geometry using KCl-UCl$_3$ molten salt as the working fluid, and cooling was imposed through convective heat transfer at the outer surface of the pipe. The comparison variables were the axial distributions of solid fraction and the temperature profile. The analytical solution was calculated using Python.

3. Results and Discussion

In the natural circulation loop comparison, increasing heater power increased the loop driving head, resulting in an increasing trend in the temperature difference between the inlet and the outlet of the heater component. This behavior was consistent with the experimental results. The relationship between mass flow rate and temperature difference (ΔT) from the simulations and experiments is shown in Fig. 3.

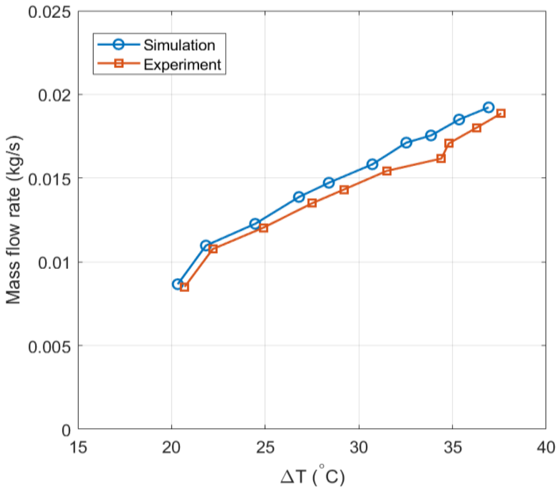

Fig. 3. Verification of the natural circulation loop model

These results confirm that the Modelica natural-circulation loop model developed in this study reproduces the literature benchmark behavior, and that including the freezing model did not distort the natural circulation response under non-freezing conditions.

The slab-geometry freezing comparison results are shown in Fig. 4 and Fig. 5. As the liquid temperature decreased along the axial direction, freezing initiated downstream of a certain location, and the solid fraction increased thereafter, showing a freezing development trend. When the liquid temperature profile and solid fraction profile obtained by the Modelica freezing model were compared with the analytical solution, the freezing onset location and the overall distribution shapes were found to be generally similar.

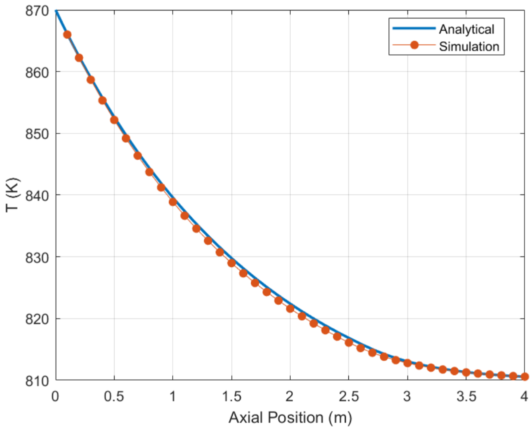

Fig. 4. Verification results of axial liquid temperature profile

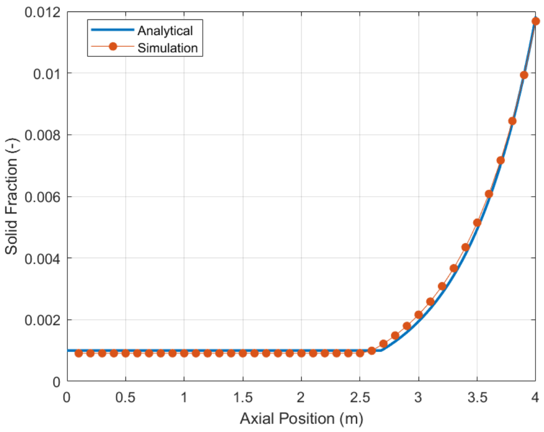

Fig. 5. Verification results of axial solid fraction profile

4. Conclusion

Building on the 1-D freezing model previously developed in the Modelica–TRANSFORM framework, this study strengthened its verification basis through two representative scenarios. First, the model was applied to a single-phase natural circulation loop under non-freezing conditions and verified against experimental data. Second, the model was verified for a slab-geometry freezing case by comparison with a steady-state analytical solution, showing generally consistent axial temperature and solid-fraction distributions. With these verification results, the previously developed Modelica freezing model is now supported for use in future MSR system-level transient and accident analyses where solidification may influence passive decay heat removal performance. In addition, because the model can account for volumetric internal heat generation, the same framework is expected to enable further analyses for fuel-salt systems including internal heat generation.

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