

Effect of Ship Motion on the Opening Time of the MSRE Freeze Valve Using OpenFOAM

Dowon Lee^a, Juhyeong Lee^a, Seungmin Lee^a, Joon-Eon Yang^a, Sung Joong Kim^{*a,b}

^aDepartment of Nuclear Engineering, Hanyang University
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

^bInstitute of Nano Science and Technology, Hanyang University
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

*Corresponding author: sungkim@hanyang.ac.kr

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1. Introduction

Molten salt reactors (MSRs) use a liquid salt as both fuel and coolant. This liquid fuel enables a passive safety strategy that solid-fuel reactors cannot adopt. In an emergency, the fuel itself is removed from the core. The fuel salt drains by gravity into criticality-safe and passively cooled drain tanks. The drain path is blocked during normal operation, so the blocking element must open reliably and passively on demand.

The freeze valve serves this role by using cooling gas to keep a salt plug frozen inside a short flattened section of the drain line. When a drain is required, the cooling gas is shut off. The plug is thawed by the surrounding heat alone, and the drain path opens without any mechanical action. The Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL) operated the main fuel-drain freeze valve FV-103 throughout its operating life [1]. The design required a thaw time of less than 15 minutes. The normal thaw time without power was measured at 9 to 11 minutes [1].

MSRs are also being considered for marine applications such as nuclear-propelled ships, floating power plants, and moored offshore units. On these platforms, the reactor experiences continuous six-degree-of-freedom (6-DoF) ship motion. Rotational motions tilt the gravity vector, and translational motions add oscillating inertial accelerations. Thawing of a freeze valve is driven by conduction and natural convection, and natural convection depends directly on the gravity vector. Ship motion therefore acts directly on the thawing time of the plug, and the resulting change affects the passive drain safety function.

However, the effect of ship motion on freeze valve opening has not been quantified. In this study, a computational fluid dynamics (CFD) model of MSRE freeze valve FV-103 was validated against the thaw time reported by ORNL [1]. The validated base case was then subjected to 6-DoF motions, and the resulting change in opening time was evaluated.

2. Numerical Methodology

2.1 Geometry and Computational Domain

FV-103 is a flattened section of a 1.5-in. schedule-40 INOR-8 pipe. The inner diameter is 40.9 mm and the

wall thickness is 3.68 mm. The flat section has an internal gap of 12.7 mm, a width of 57.15 mm, and a length of 50.8 mm [2]. The shoulders connect the flat section to the round pipe at about 30° to the pipe axis [3]. The flat faces are horizontal, so the narrow gap is vertical. The line slopes 3° downward toward the drain tank. The computational domain spans 0.38 m along the pipe axis and covers the reactor-side pipe, the valve section, and the drain-side pipe (Fig. 1). A block-structured O-grid mesh with about 149,760 cells was used.

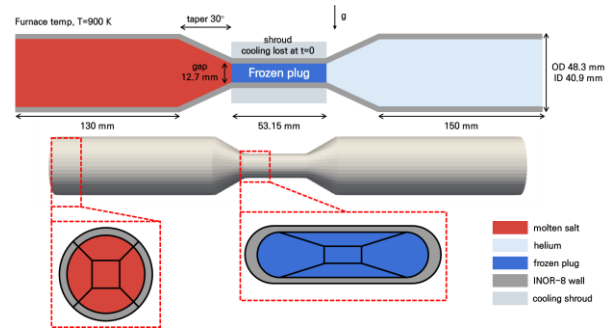


Fig. 1. Geometry and computational domain of the freeze valve FV-103

2.2 Numerical Model

The analysis was performed with OpenFOAM v2406 and its icoReactingMultiphaseInterFoam solver. The solver captures multiple incompressible phases with the volume-of-fluid method and solves a single energy equation for the phase mixture. Four phases were defined in this work, namely the molten fuel salt, the helium cover gas, the frozen salt, and the INOR-8 structure. Melting of the frozen plug is tracked with a local liquid-fraction field. Partially molten cells receive a momentum sink of the Carman-Kozeny form, given in Eq. (1).

$$S = -C \cdot \frac{(1-f)^2}{f^3 + \epsilon} \cdot U \quad (1)$$

where f is the local liquid fraction, C is a mushy-zone constant set to 10^8 in this work, and ϵ is a small number for numerical stability. Fully frozen cells are therefore immobilized, and the flow resistance vanishes as melting completes. This treatment follows the enthalpy-porosity method [4]. Thermophysical properties at phase interfaces are harmonically interpolated. The salt melts at 707 K. The latent heat is 4.4×10^5 J/kg and the density

is 2,240 kg/m³ [5]. The remaining thermophysical properties of the salt and the structure follow the ORNL property report [5].

2.3 Initial and Boundary Conditions

The initial temperature field follows the ORNL benchmark condition [1]. ORNL reported the axial temperature profile of FV-103 for a normal freeze with no salt on the drain-tank side, and the thaw time of 9 to 11 minutes corresponds to this condition. The reported profile and the mapped initial temperature field are shown in Fig. 2. The initial frozen plug length from this profile is 55.5 mm.

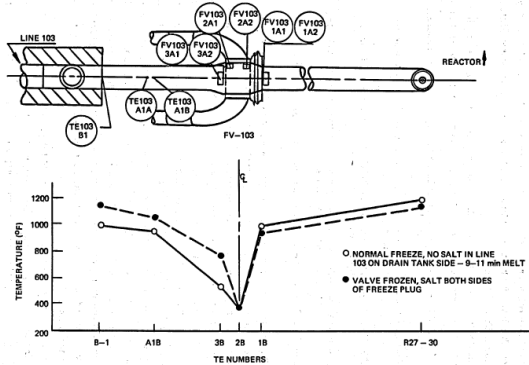


Fig. 2. Reported and mapped initial axial temperature profiles of FV-103 [1]

The boundary conditions are listed in Table I. The thaw scenario assumes a failure of the component cooling pump. The cooling gas supply stops at $t = 0$, and the plug is thawed by the furnace heat and by axial conduction from the hot salt. The furnace side stays near the operating temperature during the short thaw transient because of the thermal inertia of the furnace structures. The upstream static head of the drain line is not included in this analysis. Seal loss is defined as the time at which the liquid fraction of the thinnest plug slab crosses 1 %. Outflow onset is defined as the time at which the cumulative outflow to the drain side crosses 0.1 cm³. The seal loss time is taken as the opening time of the valve, and the ORNL thaw time of 9 to 11 minutes serves as its reference window. Drainage after opening is outside the scope of this paper.

Table I: Boundary Conditions

Boundary	Velocity	Pressure	Temperature
Reactor end	No slip	Zero gradient	Adiabatic
Drain end	Pressure inlet-outlet	Fixed, 0 gauge	Inlet-outlet 576 K
Furnace-side wall	No slip	Zero gradient	Convection, $h = 3.2$ W/m ² ·K, $T^\infty = 900$ K
Shroud-side wall	No slip	Zero gradient	Convection, $h = 10.0$ W/m ² ·K, $T^\infty = 900$ K

2.4 Ship Motion Modeling

Ship motion was imposed with the built-in tabulatedAccelerationSource of OpenFOAM. This source applies a tabulated acceleration as a body force and adds the Coriolis, centrifugal, and Euler terms for rotations. The source does not reorient gravity for rotational motions, so the reorientation was encoded in the acceleration table as Eq. (2).

$$a(t) = g_0 - R(t)^T \cdot g_0 \quad (2)$$

where g_0 is the gravity vector at rest and $R(t)$ is the rotation matrix of the ship tilt at time t . The effective gravity in the solver is $g_0 - a(t)$, which equals the tilted gravity $R(t)^T g_0$. The rotation center is set at the center of the valve flat section.

Each DoF was imposed individually as a harmonic motion with a period of 10 s. This period corresponds to the natural roll period of cargo ships [6] and to the mean wave period of the target sea area [7]. Realistic amplitudes were based on ERA5 sea statistics of Southeast Asian waters [7]. The realistic roll range is 6° to 21°, and the significant wave height is about 2.5 m with local peaks above 4 m. The bounding translation amplitudes of 2.5 to 4.0 m follow these observed wave heights. The bounding rotation amplitude of 40° matches the upper angle of the intact stability assessment in the International Maritime Organization (IMO) criteria [8], so it represents an extreme condition. Roll was examined at four amplitudes from the realistic range to the bounding value to resolve the amplitude dependence. For yaw, gravity is parallel to the rotation axis, so the effective gravity does not change. The yaw case was therefore excluded. Table II lists the case matrix.

Table II: Case Matrix (period 10 s for all motion cases)

Group	DoF	Amplitude
Base case	No motion	-
Rotation	Roll	10°/20°/30°/40°
	Pitch	40°
	Yaw	excluded
Translation	Surge	2.5 m/4.0 m
	Sway	2.5 m
	Heave	2.5 m

All cases share the same mesh, boundary conditions, and time controls. Only the motion differs between cases. Motion effects are reported as relative changes from the no-motion base case.

3. Results and Discussion

3.1 Base Case Validation

The base case has no ship motion. Seal loss occurs at 614.5 s, so the opening time of the valve is 10.2 minutes. This value falls inside the ORNL reference window of 9 to 11 minutes. Outflow onset follows at 684.0 s, and the plug melts completely at about 810 s. The model therefore reproduces the reported thaw behavior of FV-103. This case serves as the reference for all motion cases.

Fig. 3 shows the frozen plug at the start of the transient and before seal loss. Melting starts at both hot ends of the plug and proceeds toward the center. The reactor side melts faster. The narrow vertical gap suppresses natural convection at rest. The thaw time of the base case is thus driven mostly by conduction. Ship motion acts on this suppressed convection.

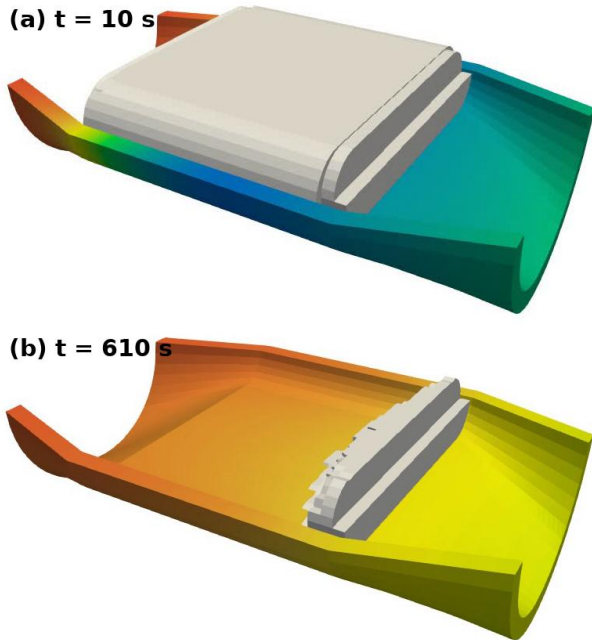


Fig. 3. Frozen plug (white) and wall temperature of the base case at (a) $t = 10$ s and (b) $t = 610$ s, before seal loss

3.2 Effect of Ship Motion

Table III and Fig. 4 summarize the motion effects on the opening time. The rotational motions dominate. Roll at 40° advances the opening from 614.5 s to 508.2 s, a change of 17.3 %. Pitch at 40° advances the opening by 11.0 %. All three translations change the opening time by less than 2 % and show no significant effect.

No motion delays the opening by more than 2 %. Every significant effect is an advance, and the valve opened fully in every case. Ship motion therefore does not degrade the passive drain function of the freeze valve.

In the flat section, the salt layer is only 12.7 mm high and 57.15 mm wide. At rest, gravity acts along the short 12.7 mm direction, and buoyant circulation cannot develop in such a thin layer. Thus, the base case melts almost by conduction. However, roll tilts the valve, and a gravity component then appears along the 57.15 mm width. Buoyant circulation develops in the wide direction and carries hot salt to the melt front. This enhanced convection accelerates the opening under roll. Under pitch, the gravity component appears along the pipe axis, and the melt front sweeps axially. Translational accelerations only shake the enclosed salt as a rigid body and do not change the heat transfer at the melt front.

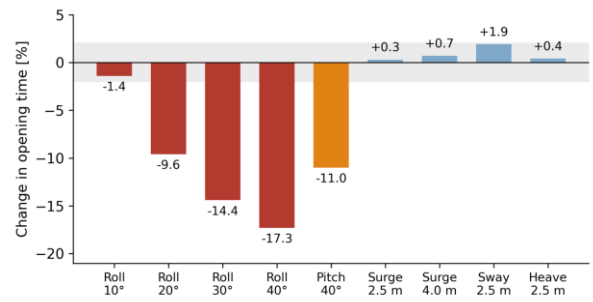


Fig. 4. Relative change in opening time for each ship motion

Table III: Opening times and relative changes

Case	Seal loss [s]	Drain initiation [s]	Δ Seal loss	Δ Drain initiation
Base case	614.5	684.0	-	-
Roll 10°	606.2	664.3	-1.4 %	-2.9 %
Roll 20°	555.7	601.8	-9.6 %	-12.0 %
Roll 30°	526.0	566.2	-14.4 %	-17.2 %
Roll 40°	508.2	543.1	-17.3 %	-20.6 %
Pitch 40°	546.9	590.0	-11.0 %	-13.7 %
Surge 2.5 m	616.3	684.1	+0.3 %	+0.0 %
Surge 4.0 m	618.9	685.9	+0.7 %	+0.3 %
Sway 2.5 m	626.4	691.2	+1.9 %	+1.1 %
Heave 2.5 m	616.7	684.0	+0.4 %	+0.0 %

3.3 Roll Amplitude Sensitivity

Fig. 5 shows the change in opening time over the roll amplitude. The advance is 1.4 % at 10° , 9.6 % at 20° , 14.4 % at 30° and 17.3 % at 40° . The curve rises steeply up to about 20° and flattens above it. The upper end of the realistic sea range is 21° , and this places the steep part of the curve inside the realistic range. The effect over the realistic range is about 1 to 10 %. The advance at the bounding 40° is only 1.8 times the advance at 20° . The opening time is insensitive to the assumed bounding amplitude.

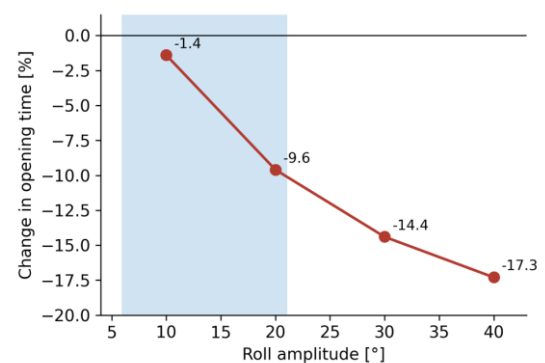


Fig. 5. Change in opening time over the roll amplitudes. The shaded band is the realistic sea range of 6° to 21°

4. Conclusions

A four-phase CFD model of the MSRE freeze valve FV-103 was built with OpenFOAM and validated against the ORNL benchmark. The opening time of the base case is 10.2 minutes and falls inside the reported thaw window of 9 to 11 minutes. The 6-DoF ship

motions were then imposed on the validated base case. Key findings include:

- ✓ Opening safety: No ship motion delays the opening by more than 2 %. Every significant effect advances the opening, and the valve opened fully in every case. The passive drain function of the freeze valve is preserved under ship motion.
- ✓ Dominant motion: The rotational motions dominate. Roll at 40° advances the opening by 17.3 %, and pitch at 40° by 11.0 %. The three translations show no significant effect. Rotation restores the suppressed convection in the flat section by redirecting buoyancy along the wide direction.
- ✓ Amplitude sensitivity: The roll effect rises steeply inside the realistic sea range of 6° to 21° and saturates above about 20°. The effect is 1 to 10 % over the realistic range, and the conclusion is insensitive to the assumed bounding amplitude.

Overall, ship motion does not degrade the opening performance of the MSRE freeze valve, and the results support the freeze valve as a passive drain device for marine MSR applications in the opening phase. The present results were obtained for single-DoF harmonic motions with a fixed period of 10 s, and it should be regarded as a screening of the individual motion effects. Future work will evaluate the sensitivity to the motion period over the range of wave periods and natural roll periods of candidate ships, and will impose combined multi-DoF motions such as simultaneous roll, pitch, and heave. The upstream static head will also be included in a full drain simulation, and a formal grid convergence study of the absolute opening time will be performed.

Acknowledgements

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