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Numerical Simulation of the K-MSR Fuel Drain System Using Simscape Fluids

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1. Introduction

The molten salt reactor (MSR) is an advanced reactor design that has attracted significant global interest and research efforts in recent years. Unlike other reactor types, the MSR operates with nuclear fuel in a molten state, which simultaneously serves as the primary coolant. Due to this unique characteristic, the safety features of MSRs differ substantially from those of conventional pressurized water reactors (PWRs).

Among the key safety-related systems in MSRs is the drain tank, which plays a critical role in reactor shutdown. In the event of an emergency or planned shutdown, the molten fuel is passively transferred to the drain tank by gravity through a valve system, thereby achieving a subcritical condition [2].

Experimental validation and computational verification of this passive safety system are essential. Reference [1] presents a mock-up experiment simulating a drain tank, and analyzes the fuel drainage time using both the GAMMA+ and MARS codes. In this paper, we present an additional modeling and validation study using Simulink Fluids, independent of the two aforementioned codes. Simulink Fluids enables intuitive block-based modeling of thermal-hydraulic flow behavior, providing a useful tool for system-level transient analysis.

2. Methodology

2.1 Experimental Facility

The drain tank test facility was designed and constructed to simulate the fuel drainage system of the K-MSR, which is currently being co-developed with the Korea Atomic Energy Research Institute (KAERI). Initial experiments and code validation were conducted as reported in Reference [1], which confirmed that the experimentally measured drainage time was approximately 160 seconds—showing good agreement with the values predicted by system analysis codes.

Detailed specifications, functions, and operational objectives of the experimental facility are also described comprehensively in Reference [1].

2.2 Simscape Fluids Model

The drain system was modeled using Simscape Fluids, a MATLAB/Simulink toolbox that provides a library of pre-built components for simulating hydraulic and thermal-hydraulic systems. This environment allows for graphical, block-based modeling, enabling straightforward construction and visualization of complex piping networks while maintaining physical fidelity [3].

In the present study, the Isothermal Liquid domain was selected to model single-phase incompressible fluid behavior, consistent with the experimental conditions. For the water simulation, fluid properties were assigned using the Isothermal Liquid Predefined Properties option, ensuring accurate representation of density and viscosity over the relevant temperature range. For the molten salt case, a custom property set was defined based on representative NaCl-KCl-UCl_3 thermophysical data.

The system configuration included Tank, Pipe, and Pipe Bend blocks to represent the FSL tank, straight piping segments, and elbow connections, respectively. Each pipe element was assigned a length and diameter consistent with the scaled facility dimensions. Unless a change in slope or diameter occurred, a single pipe block was used to represent continuous piping runs, in order to simplify the model without compromising accuracy.

The layout and component arrangement in the Simscape Fluids model replicated the experimental facility described in Reference [1]. The complete block diagram of the Simscape Fluids model is shown in Fig. 2.

The specifications of the Fuel Salt Liquid (FSL) vessel, which corresponds to the reactor vessel, are identical to those described in Reference [1], and the input parameters for the Simscape Fluids model are listed in Table 1.

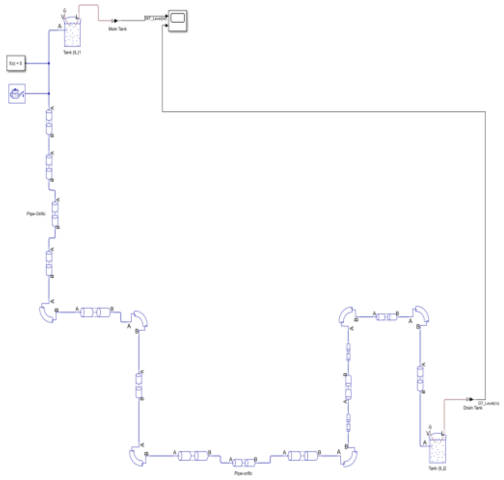

Fig 2. Nodalization for Simscape Fluids

Table I: FSL Tank Parameters in Simscape Fluids model

Parameter	Value
Block	Tank(IL)
Pressurization	Atmospheric pressure
Tank volume parameter	Constant cross-section area
Cross-sectional area	0.180956 m^2
Inlet cross-sectional area	0.000804 m^2
Gravitational acceleration	9.81 m/s^2
Liquid level	80 cm

The fluid in the FSL is discharged by gravity, passes through a siphon-configured piping system, and flows into the drain tank. The input parameters for this piping section are provided in Table 2. A uniform pipe roughness of 1.5 $\times 10^{-5}$ m was applied throughout the model. The pipe diameter was set uniformly to 0.032 m for all sections except FV_1-2 and SP_1-2. The diameters of FV-1 and FV-2, and SP-1 and SP-2, are 0.01952 m and 0.0125 m, respectively.

Table II: Pipe Parameters in Simscape Fluids model

Component	Length (m)	Elevation (m)	Block
DL-1	0.035	-0.035	Pipe(IL)
FV_1-1	0.063	-0.063	Pipe(IL)
FV_1-2 (Orifice)	0.014	-0.014	Pipe(IL)
FV_1-3	0.063	-0.063	Pipe(IL)
Bend_1 Radius (Angle)	0.0951 (87°)	-0.095-	Pipe Bend(IL)
DL_2	1.25	-0.06542	Pipe(IL)
Bend_2 Radius (Angle)	0.095 (87°)	-0.095	Pipe Bend(IL)
DL_3	0.2775	-0.2775	Pipe(IL)
Bend_3 Radius (Angle)	0.095 (90°)	-0.095	Pipe Bend(IL)
FV_2-1	0.063	0	Pipe(IL)
FV_2-2 (Orifice)	0.014	0	Pipe(IL)
FV_2-3	0.063	0	Pipe(IL)
Bend_4 Radius (Angle)	0.095 (90°)	0.095	Pipe Bend(IL)
SP_1-1	0.035	0.035	Pipe(IL)
SP_1-2	0.125	0.1125	Pipe(IL)
SP_1-3	0.035	0.035	Pipe(IL)
Bend_5 Radius (Angle)	0.095 (90°)	-0.095	Pipe Bend(IL
DL_4	0.3	0	Pipe(IL)
Bend_6 Radius (Angle)	0.095 (90°)	-0.095	Pipe Bend(IL)
DL_5	1.05	-1.05	Pipe(IL)

The specifications of the drain tank are given in Table III.

Table III: Drain Tank Parameters in Simscape Fluids model

Parameter	Value
Block	Tank(IL)
Pressurization	Atmospheric pressure
Tank volume parameter	Constant cross-section area
Cross-sectional area	0.384845 m^2
Inlet cross-sectional area	0.000804 m^2
Gravitational acceleration	9.81 m/s^2
Liquid level	0 cm

2.2 Implemented Hydraulic and Thermal-Hydraulic Models

The correlation for calculating the pressure loss due to friction in the pipe flow is given by the equation below [4, 5]. The upper Reynolds number limit for laminar flow and the lower Reynolds number limit for turbulent flow were set to 2000 and 4000, respectively.

Table IV. Pressure Loss due to friction correlation for Pipe(IL)

Pressure Loss Due to Friction	Correlation

Haaland Correlation (Laminar flow upper Reynolds number limit)	$\Delta p_{f,A} = \frac{\upsilon\lambda}{2D^2 S}\frac{L+L_{add}}{2}\dot{m}_A,$ $\Delta p_{f,B} = \frac{\upsilon\lambda}{2D^2 S}\frac{L+L_{add}}{2}\dot{m}_B,$
Haaland Correlation (Turbulent flow lower Reynolds number limit)	$\Delta p_{f,A} = \frac{f}{2\rho_I D S^2}\frac{L+L_{add}}{2}\dot{m}_A\lvert\dot{m}_A\rvert,$ $\Delta p_{f,B} = \frac{f}{2\rho_I D S^2}\frac{L+L_{add}}{2}\dot{m}_B\lvert\dot{m}_B\rvert,$
Surface roughness specification	$f = \left\{-1.8\log_{10}\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon}{3.7D_h}\right)^{1.11}\right]\right\}^{-2},$

The correlation used for the pipe bends is presented in Table V.

Table V. Bend Pipe Curvature Loss coefficient

Loss Coefficient	Correlation
Coefficient for Pressure loss due to factor C_{angle} and bend coefficient C_{bend}	$K_{loss} = C_{angle}C_{bend}.$
	$C_{angle} = 0.01480\theta - 3.9716 \cdot 10^{-5}\theta^2.$

3. Results and Discussion

The simulation results using Simscape Fluids, the experimental data, and the GAMMA code analysis for the fluid level in the FSL tank are presented in Figure 3. Since the Simscape model does not explicitly simulate the ball valve behavior, the simulation results were time-shifted by 5 seconds to account for the valve opening delay. According to the simulation, the time required for the water level to reach 4.5 cm was approximately 150.86 seconds, while the experimental result showed 156 seconds, and the GAMMA code predicted 157.2 seconds. The difference between the Simscape result and the experiment is 5.14 seconds, corresponding to an error of about 3%.

More importantly, the drainage rate—represented by the slope of the level-time curve—shows meaningful differences across the three methods. The average drainage rate was 0.5303 cm/s for Simscape, 0.5128 cm/s for the experiment, and 0.5089 cm/s for GAMMA, indicating a maximum deviation of approximately 3.4%. This suggests that Simscape Fluids is capable of capturing the overall transient behavior with reasonable accuracy, although minor discrepancies exist due to simplified valve modeling and numerical assumptions.

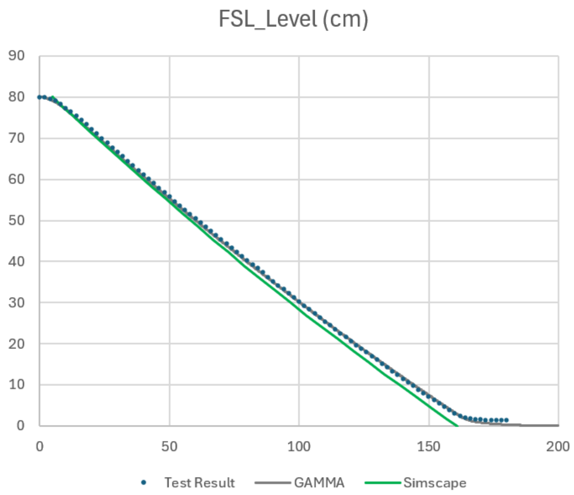

Figure 3. FSL Tank water lever through the time using Simscape Fluids, Test Results, GAMMA

4. Conclusions

These findings indicate that, compared with conventional nuclear system analysis codes such as MARS and GAMMA+, Simscape Fluids offers a much simpler modeling process, with the added benefit of block diagram visualization for enhanced user-friendliness. Furthermore, it achieves comparable accuracy in results, enabling rapid evaluation and design iteration by easily modifying material properties and input parameters. This makes Simscape Fluids a valuable tool for preliminary design and performance verification of various K-MSR components before prototype fabrication and testing.

ACKNOWLEDGMENT

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