

Numerical Simulation of the Chlorine-based Molten Salt Forced Circulation Loop Using Simscape Fluids

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1. Introduction

The Molten Salt Reactor (MSR) is an innovative next-generation reactor design where the liquid fuel simultaneously serves as the primary coolant. The design and control of a forced circulation loop are essential for stable operation under normal conditions.

Globally, prominent institutions such as Oak Ridge National Laboratory (ORNL) and Texas A&M University have accumulated significant operational experience with forced circulation loops for various molten salt applications[1,2]. Building upon this international research context, this study focuses on a Chlorine (Cl)-based molten salt loop, which represents the first experimental attempt of its kind in South Korea. The primary objective is to acquire operational expertise and high-quality data. Although ultrasonic flow meters will be installed to measure temperature, pressure, and flow rates, verifying the accuracy of these measurements for high-temperature fluids is inherently challenging. Therefore, this paper utilizes Simscape Fluids, a Simulink-based tool, to perform thermal-hydraulic modeling and calculate flow information to validate the experimental results.

2. Methodology

2.1 Experimental Facility

The experimental facility is a forced circulation loop designed to simulate the physical behavior of Cl-based molten salts. As the first forced circulation loop experiment in Korea, it is equipped with ultrasonic flow meters to obtain precise data on flow rates in addition to temperature and pressure.

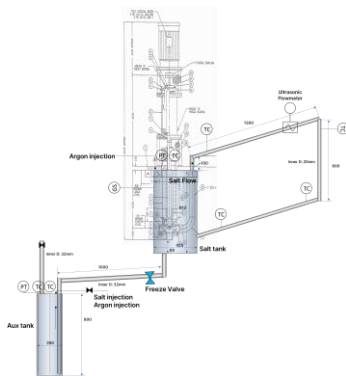


Fig 1. Diagram of the forced circulation molten salt loop

A cantilever-type molten salt pump is employed to circulate the high-temperature molten salt. The performance curves and specifications of this pump serve as critical input parameters for the numerical model.

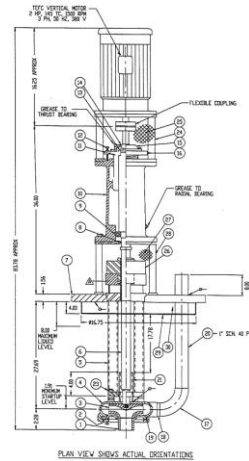


Fig 2. A cantilever-type molten salt pump

2.2 Simscape Fluids Model

The forced circulation system was modeled using Simscape Fluids that enables the construction of complex thermal-hydraulic networks through graphical, block-based components while maintaining high physical fidelity. In this study, the Isothermal Liquid domain was selected to simulate the single-phase incompressible flow of the molten salt.

- **Domain and Blocks:** The Isothermal Liquid domain was selected for single-phase incompressible flow modeling. Pipe(IL) and Tank(IL) blocks were utilized to represent the piping segments and storage tanks, respectively.

- **Pump Implementation:** The Centrifugal Pump block was used to simulate the cantilever pump. The input values were derived from the performance curve shown in Fig. 3.

- **Fluid Properties:** Thermophysical properties for the NaCl-KCl-MgCl₂ salt at 600°C were defined in the model. These properties are summarized in Table 2.

- **Piping Specifications:** The geometric details, including the diameter and length of the suction, discharge, and return lines, were implemented as listed in Table 3.

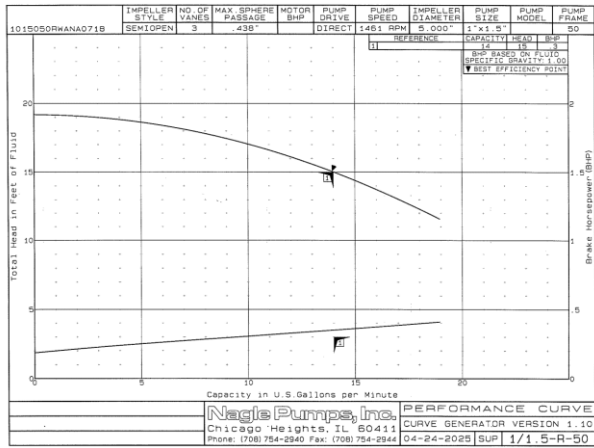


Fig 3. Pump Performance Curve

Table 1: Pump Parameters in Simscape Fluids model

Component	Value
Ref. capacity vector	[0, 5, 10, 14, 15, 19] gpm
Ref. vector	[19, 18.6, 17, 15, 14.5, 11.5] ft
Ref. brake power vector	[0.134, 0.1865, 0.2238, 0.2611, 0.2686, 0.2984] kW
Ref. shaft speed	1461 rpm
Ref. density	1706.7

Table 2: Thermophysical properties of molten salt at 600 °C

Component	Value
Density	1706.7 kg/m ³
Isothermal bulk modulus at atmospheric pressure	2.1791 e9 Pa
Kinematic viscosity at atmospheric pressure	1.0034 e-6 m ² /s
Atmospheric pressure	0.101325 Pa

For the hydraulic modeling of the piping segments, uniform input specifications were applied to ensure consistency across the simulation. The absolute roughness of the pipe walls was set to $1.5 \times 10^{-5} \text{ m}^3$. To define the transition between flow regimes, the upper Reynolds number limit for laminar flow and the lower Reynolds number limit for turbulent flow were assigned values of 2000 and 4000, respectively. These parameters allow the Simscape Fluids solver to accurately determine the friction factor and resultant pressure drop across various operating conditions.

Table 3: Pipe Parameters in Simscape Fluids model

Component	Length (cm)	Elevation (cm)	Block
DL-1	10	10	Pipe(IL)

Bend_1 (105°)	2	2.518	Pipe Bend(IL)
DL_2	130	33.6	Pipe(IL)
Bend_2 (75°)	2 (87°)	-1.482	Pipe Bend(IL)
DL_3	30	-30	Pipe(IL)
Bend_3 (105°)	2	-2.518	Pipe Bend(IL)
DL_4	130	-33.6	Pipe(IL)

The implemented block diagram for the Simscape Fluids nodalization of the forced circulation loop is presented in Fig. 4. This figure illustrates the actual arrangement and connectivity of the hydraulic blocks—including the Centrifugal Pump, Pipe(IL), and Tank(IL)—as specifically constructed within the simulation environment to replicate the experimental facility. Each block in this nodalization scheme corresponds directly to the physical components and connectivity of the CI-based loop, ensuring the physical fidelity of the thermal-hydraulic transient analysis.

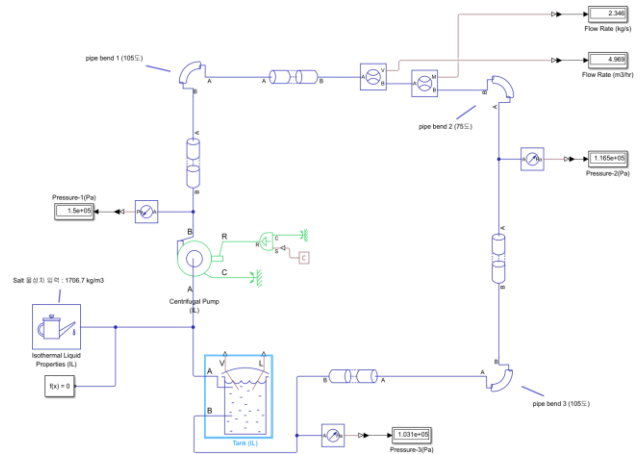


Fig 4. Nodalization for Simscape Fluids

2.2 Theoretical Background: Centrifugal Pump Modeling

The Centrifugal Pump (IL) block calculates the pressure increase within the isothermal liquid network based on the Pump Affinity Laws[3]. These laws allow the model to scale the reference performance data to the actual operating shaft speed ω . The pressure gain Δp is determined as follows:

$$\Delta p = \rho g \Delta H_{ref} \left(\frac{\omega}{\omega_{ref}} \right)^2$$

Where:

ΔH_{ref} is the reference head obtained from the manufacturer's H-Q (Head-Capacity) curve.
 ω and ω_{ref} are the actual and reference shaft speeds.
 ρ is the fluid density and g is the gravitational acceleration.

The simulation utilizes 1D Tabulated Data to interpolate the digitized head-capacity points from the pump's specification sheet. This approach enables a simplified yet accurate modeling process, providing the necessary flow information to validate experimental data within a block-diagram environment.

The mechanical power required by the pump, known as the brake power W_{brake} , is related to the shaft torque τ . The block computes the torque by considering the energy balance between mechanical input and hydraulic output.

Shaft Torque:

$$\tau = \frac{W_{brake}}{\omega}$$

Hydraulic Power:

$$P_{hydro} = \frac{\Delta p \dot{m}}{\rho}$$

For analytical parameterization, the reference brake power $W_{brake,ref}$ is derived from the nominal capacity, head, and efficiency. The pump efficiency curve is typically assumed to be quadratic, reaching its peak at the nominal operating point and falling to zero at shut-off or maximum capacity.

3. Results and Discussion

The thermal-hydraulic simulation of the NaCl-KCl-MgCl₂ forced circulation loop was executed using the Simscape Fluids nodalization scheme presented in Fig. 4. The hydraulic performance was determined by integrating the digitized H-Q curve of the Nagle pump and the thermophysical properties of the salt at 600°C.

The simulation achieved a steady-state mass flow rate of 2.346 kg/s, corresponding to a volumetric flow rate of 4.969 m³/hr. These results align with the operational range of the pump performance curve shown in Fig. 3, indicating that the loop's total hydraulic resistance is well-matched with the pump's driving head.

The analysis also provided a detailed pressure profile across the circulation loop. The calculated pressure at the pump discharge outlet was 1.5 x 10⁵ Pa, while the pressure at the bottom section of the loop was 1.03 x 10⁵ Pa. This pressure drop reflects the cumulative frictional losses calculated via the Haaland correlation and the elevation changes implemented in the Pipe(IL) blocks.

By utilizing Simscape Fluids, the modeling process was significantly streamlined compared to conventional system analysis codes while maintaining high physical fidelity. This numerical baseline is critical for the upcoming experimental phase, as it provides an independent means to verify the data acquired from the

ultrasonic flow meter, which can be difficult to calibrate directly in high-temperature molten salt environments.

4. Conclusions

In this study, a thermal-hydraulic model of the Chlorine-based molten salt forced circulation loop was successfully implemented using Simscape Fluids, facilitating the direct integration of manufacturer-provided pump performance data. This modeling approach allowed for the derivation of critical theoretical flow rate values—specifically a mass flow rate of 2.346 kg/s—prior to the actual experimental phase.

The accuracy and reliability of Simscape Fluids for MSR component analysis were previously verified in Reference [4], where simulation results showed good agreement with experimental data and conventional system analysis codes. Given that forced circulation experiments with molten salts involve high technical difficulty and significant measurement uncertainty, this pre-experimental modeling and validation work provides substantial strategic value.

Future Plans: The experimental facility is scheduled for construction and operation in the second half of 2026. The real-time data acquired from this facility will be compared with the current modeling results to further refine the numerical framework for future K-MSR development.

ACKNOWLEDGMENT

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