

Hydrodynamic Feasibility Test of Gravity-Driven Drainage in Cartridge-Type Molten Salt Reactor

Seolhui Kim, Ik Jae Jin, Doyeong Lim, In Cheol Bang*

Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gil, Ulsan, 44949, Republic of Korea

*Corresponding author: icbang@unist.ac.kr

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1. Introduction

Molten Salt Reactors (MSRs) are considered a promising Generation IV concept due to their high-temperature operation and inherent safety features. However, commercialization is challenged by structural material degradation under corrosive molten salt environments and neutron irradiation [1]. To mitigate long-term material constraints, cartridge-type MSR concepts have been proposed, in which major primary components, including the core, are integrated into a single unit that is periodically replaced, thereby reducing the material reliability requirements associated with long-term operation [2]. For practical deployment, such systems must ensure passive safety while maintaining ease of replacement. Accordingly, a cartridge-type MSR design incorporating an integrated gravity-driven drainage mechanism has been suggested [2–4].

The proposed concept remains at the conceptual stage, and the hydrodynamic feasibility of gravity-driven drainage following pump trip has not yet been sufficiently examined. Uncertainties remain regarding drainage rate, flow stability, and the capability of system-level models to represent coupled pressure and free-surface effects during the transient. This study evaluates the post-shutdown drainage behavior using the Multi-dimensional Analysis of Reactor Safety—KINS Standard (MARS-KS) code and compares the results with measurements from a scaled visualization experiment.

2. System description

The proposed cartridge-type molten salt reactor adopts a three-section configuration—upper, middle, and lower—as illustrated in Fig. 1(a). The upper section consists of a concentric double-pipe structure comprising the upper plenum, the active core, and part of the annular channel. The middle section forms a concentric triple-pipe arrangement: the innermost pipe serves as the downcomer, the outermost pipe corresponds to the annular channel, and the intermediate annular region is filled with cover gas during normal operation and functions as a drain tank by receiving fuel salt from the upper section under accident conditions. The lower section contains the heat exchanger and the primary pump. An equalization pipe connects the upper plenum

to the drain tank region, enabling pressure redistribution within the system.

A key safety feature of this concept is the formation of the active core inventory using the pump. When the pump trips, a portion of the fuel salt drains by gravity.

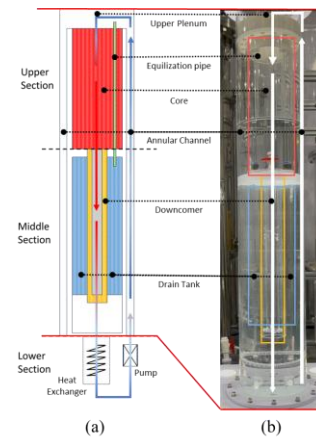


Fig. 1. (a) Schematic diagram of cartridge-type molten salt reactor system and (b) Experimental mock-up facility

3. Modeling and Methodology

3.1. Experimental setup

An acrylic mock-up facility was constructed to visualize the flow behavior of the proposed geometry, as shown in Fig. 1(b). Since the objective is to assess the functional feasibility of key safety features at the conceptual design stage, the facility dimensions and working fluids were selected for handling convenience rather than strict similarity with molten salt. The representative dimensions are summarized in Table 1.

Water and air were used as surrogates for molten salt and cover gas, respectively. The initial liquid inventory was set to 74.2% of the total volume, corresponding to an equivalent water level of 77.4 cm (≈ 78 cm). This volume ensures that the core and the primary flow paths are filled with liquid and that the downcomer outlet is submerged by approximately 0.18 m.

3.2 MARS-KS nodalization

The MARS-KS nodalization for the scaled experimental facility is shown on Fig. 2. (a). The domain was divided into the core, annular channels, downcomer,

drain tank, upper plenum, equalization pipe, and lower pool. Regions where a free surface forms after pump shutdown were modeled using PIPE components with the mixture level tracking model to capture gas-liquid interface behavior [5]. The initial phase distribution was specified to represent the expected configuration under normal operation (initial liquid level: 77.4 cm), and the fluid was assumed to be initially stagnant. Water and air were used as working fluids under atmospheric conditions (101,325 Pa, 293.15 K). All local form loss coefficients were set to zero so that the system response was governed by only frictional and area-change losses.

Table I: Component dimensions of experimental facility

Component	Outer Diameter (m)	Inner Diameter (m)	Length (m)
Upper plenum	0.17	0.17	0.075
Annular channel	0.17	0.13	0.985
Core		0.12	0.395
Downcomer	0.04	0.025	0.425
Drain tank	0.17	0.05	0.4
Low pool		0.17	0.155
Equalization pipe		0.008	0.4

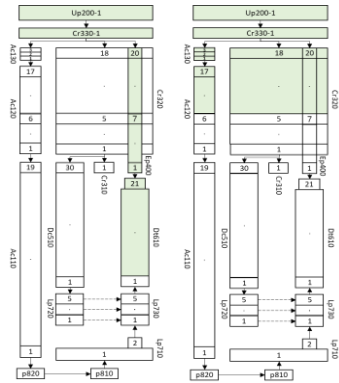


Fig. 2. Schematic nodalization of the scaled experimental facility depicted with (a) initial phase distribution and (b) final phase distribution (white: liquid, green: gas).

3. Results and Discussion

The MARS-KS analysis predicted annular-dominant drainage during the early transient following pump shutdown. As the drain tank reached capacity at approximately 6.7 s, inflow through the core is restricted by back pressure. Level equalization between two paths at 77.4 cm after an additional 24 s, as shown in Fig. 2(b).

In contrast, the scaled experiment exhibited core-dominated drainage with longer drain tank filling and level equalization times of approximately 10 s and 40 s, respectively. As shown in Fig. 3(b), the drain tank reached full capacity at approximately 10s. Subsequently, liquid discharged through the annular channel redirected into the core, progressively raising the core liquid level and reducing the level difference between the two pathways, as shown in Fig. 3(c). Level equalization was finally achieved at approximately 40 s after pump

shutdown, as shown in Fig. 3(d). This discrepancy is attributed to initial conditions not captured in the simulation: pump performance limitations reduced the initial static head in the core, and gas entrainment through the downcomer introduced two-phase flow resistance.

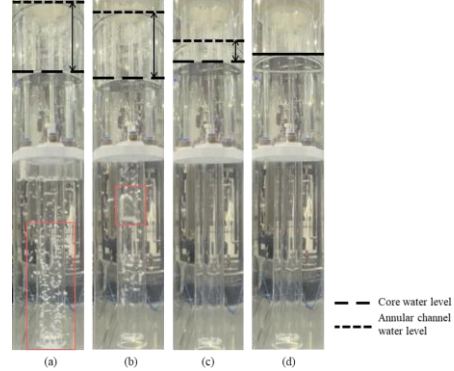


Fig. 3. Flow visualization obtained from the experiment: (a) 8 s, (b) 11 s, (c) 25 s, and (d) 40 s after pump shutdown.

4. Conclusion

The hydrodynamic feasibility of gravity-driven drainage in a cartridge-type molten salt reactor was evaluated using MARS-KS analysis and a scaled experiment. The results revealed differences in dominant discharge pathways and drainage timescales, attributed to initial conditions not represented in the MARS-KS simulation. The findings demonstrate that gravity-driven drainage can be initiated within the proposed configuration while highlighting sensitivity to internal hydraulic conditions. Future work will incorporate pump components to represent steady-state flow conditions and pump coastdown effects for improved predictive accuracy.

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