Preliminary Evaluation of the Conceptual Feasibility of a Cartridge-type Molten Salt Reactor Design

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***Keywords : molten salt reactor, cartridge, gas trap, computational fluid dynamics**

1. Introduction

Molten Salt Reactors (MSRs) have been proposed as one of the Generation IV reactor concepts. The concept of MSRs has shown safety, nuclear fuel utilization, economy, and nonproliferation. Recently, liquid-fueled molten salt reactor (MSR) research has focused on fast-spectrum MSRs, due to potential for efficient waste transmutation and extended fuel resource utilization. Nevertheless, graphite-moderated, thermal-spectrum MSRs employing fluoride salts enable near-term deployment, considering higher technology maturity and accumulated experimental experience. One of the major challenges in thermal-spectrum MSRs is the limited irradiation lifetime of graphite moderators. Graphite initially shrinks and then gradually expands beyond the original volume as it is exposed to a neutron flux. The dimensional instability is a key factor limiting the overall reactor lifetime [1-3].

Hence, two representative design strategies have been suggested to address the technical challenge. The first involves adopting a large core volume with low power density, as in the FUJI reactor concept, allowing for long-cycle operation with online fuel processing [4]. The second approach selects a more compact, high power density core that is designed for periodic replacement of graphite. For instance, the Integral Molten Salt Reactor (IMSR) by Terrestrial Energy and the Thorizon reactor developed by Thorizon.B.V. are designed for periodic cartridge replacement to facilitate maintenance [5]. The cartridge-type systems integrate the main components of the primary circuit, such as the graphite moderator, reactor vessel, and primary heat exchanger into a single replaceable unit.

The modular configuration enables simplified maintenance by minimizing on-site operations in high-radiation environments. Furthermore, it allows the used cartridge to function as a secure storage unit for spent fuel salt. A replaceable modular type approach offers a practical solution for managing the degradation of in-core materials and provides a design-oriented pathway to mitigate limitations associated with material lifetime.

In this study, the preliminary evaluation of the conceptual feasibility of a cartridge-type MSR design was conducted. The hydrodynamic stability of the internal cartridge geometry was investigated using computational fluid dynamics (CFD) to demonstrate the feasibility of the cartridge-type MSR. The proposed design can enhance passive safety through gravity-driven mechanisms during accident conditions.

2. Modeling and Methodology

2.1 System description

The MSR design proposed in this study is a modular cartridge-type design, in which the core components of the primary circuit are integrated into a single replaceable unit. The cartridge contains liquid salt and non-condensable gas (argon or helium), while the graphite moderator is located externally. Fig. 1 illustrates the cartridge-type MSR with the flow direction.

2.1.1. Normal operation

Under steady-state conditions, the primary pump induces forced circulation of the fuel salt. The salt (orange zone, Fig 1) flows upward through the annular channel of the cartridge and enters the active core region. As the fuel salt enters the active core (red zone, Fig. 1), the displaced gas moves downward through the downcomer and is accumulated in the lower region of the cartridge, forming a gas trap (green zone, Fig. 1). Each individual cartridge remains subcritical. However, system-wide criticality is achieved through neutron interaction with adjacent cartridges. The heated salt then descends through the downcomer, which contains an internal heat exchanger for transferring thermal energy to the secondary loop. Thereafter, the cooled salt is recirculated by the pump.

2.1.2. Loss of Flow Accident (LOFA)

In the event of a pump trip, the resulting pressure perturbation propagates upward through the thin pipe, and the gas trapped in the lower region simultaneously migrates to the upper region of the cartridge. As the upper region of the cartridge is gradually filled with gas, the fuel salt passively drains downward by gravity from the core to the lower region of the cartridge. The gravity-induced reconfiguration of the working fluid inherently drives the reactor into a subcritical state. The decay heat from the drained fuel salt is continuously removed through a primary heat exchanger located at the bottom of the cartridge.

2.2 Configuration of CFD

ANSYS was utilized as the integrated platform for pre-processing, solver execution, and post-processing of numerical simulations. ANSYS Fluent 2024 R2 was employed as the primary flow solver to simulate the multiphase flow behavior within the closed-loop system.

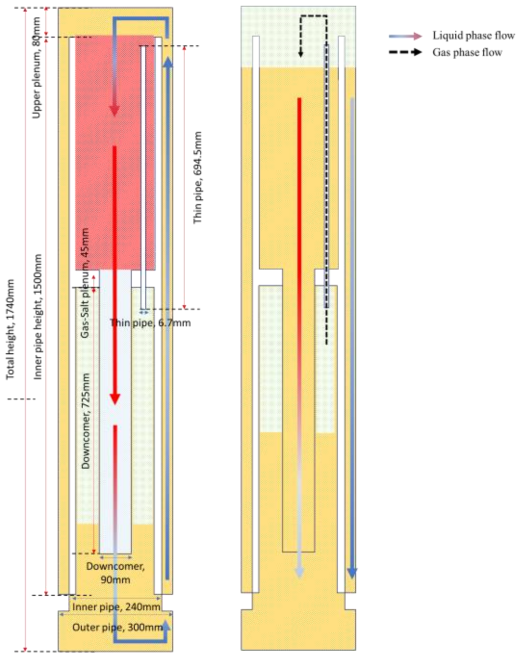

Fig. 1. Cartridge geometry and flow direction in steady state (Left), during LOFA (Right).

A three-dimensional model (diameter: 300 mm, height: 1740 mm) was developed to analyze fluid circulation within the cartridge. Boundary layer meshing was applied to accurately resolve near-wall flow, targeting a y^+ value close to 1. The simulation was conducted using water as a surrogate for molten salt. Heat sources were not modeled to focus on evaluating the hydraulic stability of the flow.

Due to the nature of a closed-loop system, direct application of conventional boundary conditions is not feasible. Therefore, the volume corresponding to the pump installation region was removed, utilizing two opposing faces as boundary conditions. The upper face was defined as a mass flow inlet with a flow rate of 25.4 kg/s, and the lower face was defined as a pressure outlet with a gauge pressure of 0 Pa, relative to an operating pressure of 0.1 MPa. To preserve gas mass conservation, a User-Defined Function (UDF) was implemented. Specifically, the UDF calculates the average volume fraction of water at the outlet boundary at each time step and imposes this value to the inlet. The method effectively coupled the physically separated boundaries in the numerical model, enabling the analysis of a closed loop with continuous flow field. Fig. 2 illustrates the schematic of the boundary condition configuration adopted in this study.

The Shear Stress Transport (SST) k–omega model was employed to resolve turbulence effects, while the Volume of Fluid (VOF) method was applied to capture liquid–gas interface dynamics. The detailed Fluent setup parameters are summarized in Table 1.

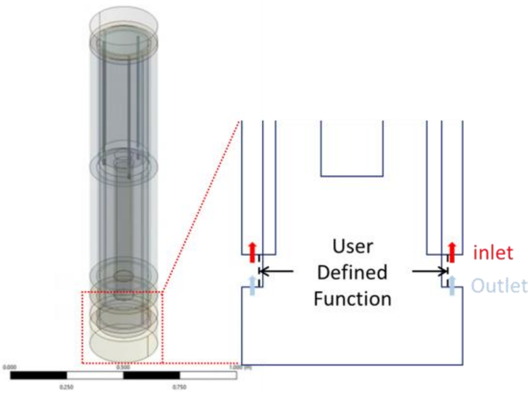

Fig. 2. Schematic of the applied boundary conditions.

Table. 1. Configuration of ANSYS Fluent Settings

Setting	Fluent	
Multiphase	VOF	-
	Volume Fraction Parameters	Implicit
	Interface modeling	Sharp
	Surface tension	-
Turbulent model	SST k-omega	-
Scheme	PISO	First order implicit

3. Results and Discussions

Fig. 3 illustrates the behavior of volume fraction distribution within the cartridge, where red represents the liquid phase and blue represents the gas phase. Fig. 3a shows the initial condition prior to pump startup. Gravitational forces induce phase separation based on density differences, establishing a distinct density-stratified interface. Fig. 3b shows pump startup. Liquid in the lower region is drawn upward through the annular flow channel, while liquid within the core simultaneously flows downward through the downcomer. Fig. 3c shows the ascending flow through the annular channel enters the active core, displacing the gas downward within the core region. The displaced gas is then discharged downward through the downcomer and accumulates in the lower annular region surrounding the downcomer. This transient phenomenon continues until the gas phase initially located in the upper region is fully transported to the lower annular zone, approaching a steady state. As shown in Fig. 3d, air remains trapped in lower region of the cartridge, while the fuel salt is circulated stably.

Fig. 4 presents the velocity vector distribution across the entire computational domain, including the thin pipe region not shown in Fig. 3, to capture the overall flow distribution. During the partially developed transient state, the gas trap region and the inlet/outlet sections of the thin pipe maintain relatively low velocities, ensuring flow stability. In the actual design configuration, the pump inlet is directly connected beneath a liquid pool that maintains a constant water level below the downcomer outlet. However, in the simplified numerical model, the pump is replaced with an inlet boundary condition, resulting in the formation of a recirculation zone in the lower section of the device. Despite the modeling simplification, the primary circulation flow remains stable while maintaining the gas trap. The proposed cartridge MSR configuration could integrate a lower pump layout with a gravity-based safety system.

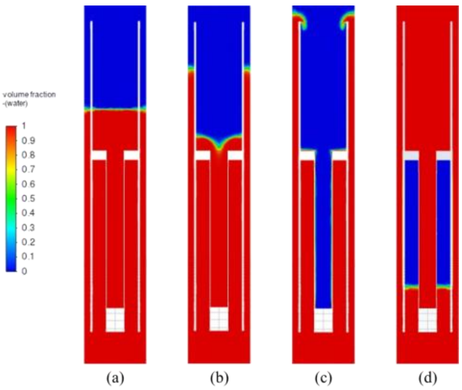

Fig. 3. Temporal variation of VOF distribution within the cartridge, progressing from left to right over time. (a) Initial condition before pump startup, (b) pump startup, (c) transition to steady state, (d) steady state after VOF redistribution

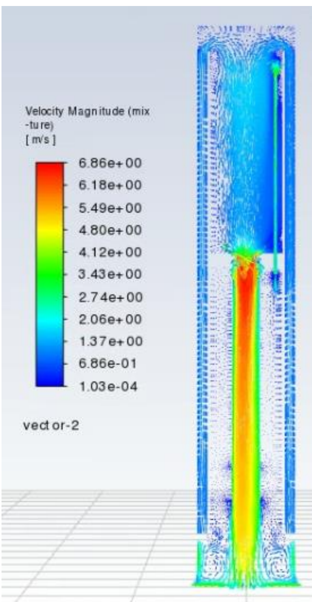

Fig. 4. Velocity vector distribution across the entire computational domain

4. Conclusion

This study presents a preliminary hydraulic analysis of a cartridge-type MSR that incorporates gravity-driven safety mechanisms. The CFD analysis was conducted to investigate two-phase circulation behavior within the cartridge without any heat source terms. The analysis demonstrates that a lower pump configuration enables stable primary circulation, maintaining a lower gas trap. The proposed configuration demonstrates the feasibility of gravity-assisted flow redistribution to enhance inherent safety in accident scenarios.

However, the CFD analysis was conducted with simplifications in both geometric representation and operating conditions due to modeling constraints. In addition, the feasibility of the proposed design was demonstrated solely through CFD analysis. Therefore, experimental investigation or code-to-code validation should be conducted. Despite the limitations, the results could contribute to the development of optimized cartridge-type MSR designs that could enhance safety, operational robustness, and lifecycle reliability.

ACKNOWLEDGMENTS

This work was supported by Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (RS-2024-00403194, Next-Generation Nuclear Technology Creation IP-R&D Talent (Human Resources) Development Project)

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