Impact of Reactor Height on Natural Circulation Performance and Thermal Characteristics in Passive Molten Salt Fast Reactors

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1. Introduction

In 2021, a research center (i-SAFE-MSR) established by KAIST, Gachon University, and Hanyang University initiated the development of a passive molten salt fast reactor (PMFR) targeting long-term operation exceeding 20 years without the need for refueling or pumps [1~2]. The PMFR is a unique molten salt reactor (MSR) relying on a fast neutron spectrum to produce fission power. By using chloride-based salt and uranium metal mixture as liquid fuel (NaCl-UCl3 or KCl-UCl3), the PMFR aims to achieve enhanced passive safety, thermal efficiency, and low operating pressure over the long term. Additionally, to enhance safety, the PMFR is designed to operate using natural circulation without pumps. This pump-free operation is expected to increase passive safety and system simplicity.

To evaluate the feasibility of natural circulation operation in the PMFR, various design aspects of the reactor are being considered [3]. Among these, the height of the reactor is the most critical factor. It affects the reactor's target power, temperature difference between the cool and hot sides, and flow rate of the primary system. Therefore, investigating the effect of reactor height is crucial for designing a natural circulation reactor. This paper aims to address this objective.

To investigate the height sensitivity of the PMFR, the OpenFOAM, an open-source computational fluid dynamics (CFD) library, was utilized. OpenFOAM provides various utilities and calculation solvers for thermal-hydraulics. Using OpenFOAM2312, natural circulation, including fission heat inside the primary system, was simulated for three different height designs. To simulate the primary system, a conceptual PMFR design was developed, and core power distribution was applied to the reactor core. A gradual increase in power was assumed over one hour to simulate the ideal power ramping scenario and analyze the behavior of the primary system over time. Through the simulation results, the sensitivity of height in the PMFR was evaluated.

2. Numerical method and conditions

2.1 Geometry and mesh generation

The geometry and mesh were generated using SALOME 9.7.0 [4], an open-source software that provides a generic platform for numerical simulation pre- and post-processing. Figure 1 depicts the conceptual design of the PMFR for the natural circulation simulation. Each case has external dimensions of 10 m, 15 m, and 20 m in height, respectively, with a cylinder radius of 1.75 m. To enhance natural circulation performance, flow guide shapes were incorporated into the upper and lower regions. The internal structure of the reactor comprises an active core, a long riser (R=0.3 m), a heat exchanger region, and a flow guide with 5×5 cm^2 rectangular channels for the core region. In this study, the heat exchanger region was modeled as a helical heat exchanger. However, to maintain a balance between heat generation and dissipation, heat removal was configured to occur from the entire heat exchanger region rather than solely from the heat exchanger walls.

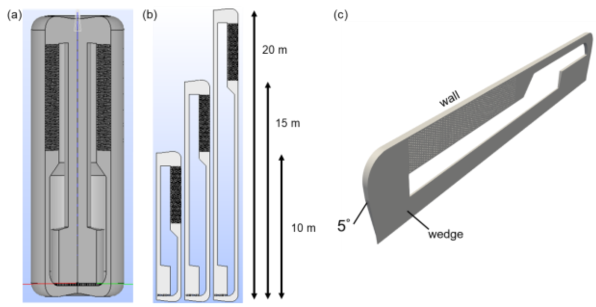

Fig. 1. A schematic of PMFR conceptual design (a) 3-Dimensional shape (b) 3 different height case (c) axisymmetric geometry for simulation.

2.2 Simulation condition

Table 1 provides a detailed overview of the calculation conditions used in the OpenFOAM simulation. The power distribution was computed using the Serpent code for reactor physics analysis of the PMFR. This distribution was then modeled within the active core region as a source term using fvOptions, which facilitates the addition of additional source/sink terms or the enforcement of constraints within user-defined regions. Similarly, heat removal in the heat exchanger region was simulated using a heat sink term.

To simulate the initial flow formation, the total power was incrementally increased from 0 MW to 295 MW over the course of 1 hour in the active core of the PMFR. The selected molten salt fuel was KCl-UCl3, representing a candidate for PMFR fuels, and its thermodynamic properties were applied to the input model. The internal temperature of the liquid fuel was set to 973 K. At the wall, a no-slip velocity condition was enforced, while an initial flow condition of 0 m/s was applied to the fluid. Turbulent flow was simulated using the k-epsilon turbulence model, with a time-step set to 1 second during the simulation.

Table 1: Numerical analysis condition for transident natural circulation of conceptual PMFR

	Value	Remarks
Solver	buoyantSimpleFoam	For buoyancy force
Turbulence model	RANS (k-epsilon)	
Time step	1 s	
Radiation Model	N/A	
Heat generation	0 ~ 295 MW	Only Core region
Heat sink	0 ~ 295 MW	Only Heat exchanger region
Liquid temperature	Initial Temp T = 973 K	
Velocity condition	No slip	All walls in the simulation
Density ($KaCl-UCl_3$)	ρ_0 = 3878 [kg/m^3] T_0 = 770 K β = 0.000237	Boussinesq approximation
Specific heat	657.22 [J/(kg-K)]	
viscosity	3.5 [cP]	

3. Results and discussions

Figure 2 displays the velocity magnitude and temperature contours of three different cases at 1 hour of simulation time. In the primary system, heat generated from the core elevates the temperature of the liquid fuel, causing it to ascend through the riser region. The heated liquid fuel then moves into the heat exchanger region, where it undergoes cooling. The cooled fluid subsequently descends back into the core, and just before entering the core region, it is evenly distributed by the guide channel.

In the riser of the shortest reactor (Case 1), the velocity was calculated as 1.85 m/s, compared to 2.3 m/s in Case 2 and 2.43 m/s in Case 3. The differing flow rates result in varying inlet and outlet temperatures between the core and the heat exchanger. In this simulation, the uniform heat sink condition in the heat exchanger (HX) region results in high temperature diffrence in the low flow velocity. Consequently, the temperature difference between the core and the heat exchanger outlet is 221.35 K for Case 1, 176.33 K for Case 2, and 163.79 K for Case 3. High-temperature operation in PMFRs can pose material corrosion and integrity risks due to thermal stress. Thus, for a 10 m tall reactor, long-term operational challenges may arise.

Figure 3 shows the outlet temperatures of the core and the heat exchanger over time. Since this study did not simulate the operating conditions of the secondary heat exchanger and the thermal feedback resulting from temperature changes, we assessed the impact of temperature variations in the core and the heat exchanger on the overall system. Over the 1-hour period of increasing power for all three cases, the core outlet temperature rose while the heat exchanger outlet temperature declined, leading to an increase in the system temperature difference. After 1 hour, the reactor power remained stable, and the temperatures and velocity stabilized, approaching steady-state operation.

In Case 1 (10 m) with slower flow, the larger temperature difference required for heat dissipation in the heat exchanger resulted in lower temperatures over time compared to the other two cases. This led to a larger temperature difference within the core. The lower core inlet temperature may induce thermal feedback, potentially increasing reactivity. Therefore, in a reactor with a 10 m height and slower flow, there may be a greater risk of instability due to excessive cooling in the heat exchanger. However, during the power increase process, Case 1 exhibited the least fluctuation compared to Cases 2 and 3, with Case 3 showing the greatest fluctuation. These temperature fluctuations also result from thermal feedback within the core, which can destabilize operation. Therefore, it is necessary to evaluate reactor design with considering temperature feedback.

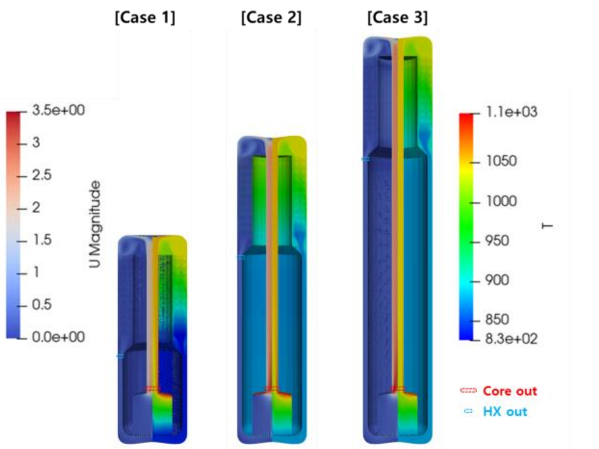

Fig. 2. Velocity magnitude contour and temperature of three different cases (case1: 10 m, case2: 15 m, case3: 20 m) at the 1 hour

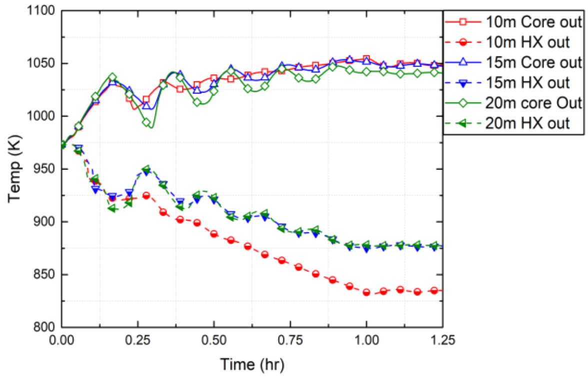

Fig. 3. Core outlet and HX outlet temperature over time in each case.

4. Conclusions

In this study, natural circulation in PMFRs of three different heights was simulated using OpenFOAM. The impact of reactor height on velocity and temperature profiles was assessed, and transient behavior was analyzed. The key findings can be summarized as follows.

- In the 10 m reactor, lower flow velocities and higher temperature differentials between the core and the heat exchanger outlet were observed compared to taller cases. Consequently, in 10 m height reactor, it is necessary to consider the corrosion and integrity issues more carefully by high temperature.
- Reactor configurations with slower flow rates, such as the 10 m case, displayed larger temperature discrepancies within the core, posing an increased risk of instability due to excessive cooling in the heat exchanger.
- Taller reactors demonstrated more unstable temperature profiles during the power increase process. Thus, it is needed to assess the temperature and velocity fluctuation effect in core region considering reactivity feedback effect.

This study provided insights into the flow characteristics of PMFRs based on height variations, but it did not consider the changes in reactivity due to temperature variations. Therefore, there is a need to further enhance the PMFR design through an analysis framework that incorporates these considerations.

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