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Analysis of natural circulation characteristics of passive molten salt fast reactor by using OpenFOAM simulation

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1. Introduction

In 2021, a research center (i-SAFE-MSR) teamed up by KAIST, Gachon University, and Hanyang University initiated development of a passive molten salt fast reactor (PMFR) targeting longer than 20 years long-term operation without refueling and pump [1~2]. The PMFR is a unique molten salt reactor (MSR) relying on the fast neutron spectrum to produce fission heat. By using the chloride-based salt and uranium metal mixture as liquid fuel (NaCl-UCl_3 or KCl-UCl_3), the PMFR pursues enhanced passive safety, thermal efficiency, and low operating pressure with the long-term operation. In addition, to increase the safety the PMFR is designed to operate by natural circulation without pumps. The operation without pump is expected to increase the passive safety and system simplicity while achieving improved operational stability.

However, unlike the coolant of conventional heterogenous reactor core, whose heat sources and coolant fluid are separated, the heat generation and flow formation occur simultaneously in the molten salt fuel. Additionally, the thermodynamic properties of molten salt such as viscosity, density, specific heat are quite different with ordinary water coolant. Thus, it is expected that the natural circulation of the PMFR significantly different with natural circulation characteristics by water coolant.. So the object of this study is to develop a proper analysis method for the natural circulation of PMFR.

To develop the PMFR natural circulation method, OpenFOAM code, which is open-source computational fluid dynamics (CFD) library was applied. The OpenFOAM code provides various utilities and calculation solvers for flow analysis. By using OpenFOAM v8 [3], the natural circulation including the decay heat inside the primary system was simulated. To simulate the primary system, a conceptual PMFR design was generated, and core power distribution was applied for the reactor core. The heat generation of liquid fuel in the core was applied as simulation condition by using OpenFOAM heat generation utility. Through the simulation results, the characteristics of natural circulation such as velocity and temperature were evaluated.

2. Numerical method and conditions

2.1 Geometry and mesh generation

The SALOME 9.7.0 [4], which is an open-source software providing a generic pre- and post- processing platform for numerical simulation was used to generate geometry and mesh. **Figure 1** illustrates the conceptual PMFR design for the natural circulation simulation. The external dimension of the reactor is 10.5 m height and 1.75 m radius cylinder. To increase the natural circulation performance, the upper and lower regions were designed as flow guide shape. The internal structure of the reactor consists of an active core, a long riser (R=0.5 m), a region reserved for heat exchangers, and flow distributor of 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 balance the heat generation and heat sink, the heat removal was set to occur from the whole heat exchanger region not from the heat exchanger walls.

The mesh was generated for a quarter of the PMFR and the resulting number of cells is 42,900,036. The overall value of mesh satisfied the criteria of checkMesh, which is the OpenFOAM function for checking mesh quality.

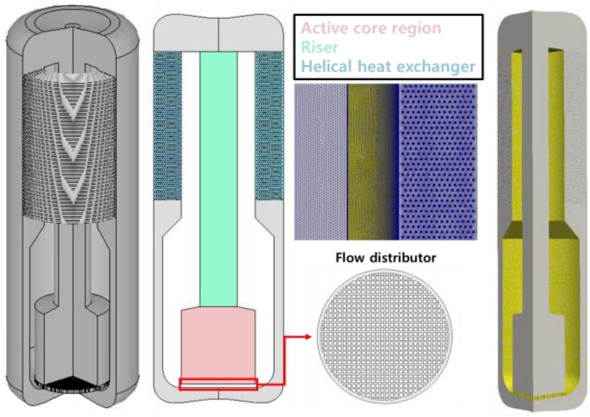

Fig. 1. A schematic of PMFR conceptual design (a) 3-Dimensional shape (b) cross section (c) generated mesh for simulation

2.2 Analysis code

The OpenFOAM is free C++ library and toolbox for the solution of various numerical problems. To solve the various numerical problems, the OpenFOAM provides numerical solvers developed to simulate particular thermal-hydraulic phenomena and utilities for pre-/post- processing. Additionally, the OpenFOAM is available in the GNU general public license, which allows users to access the OpenFOAM libraries and to modify the source code. Because of its freedom and flexibility, the OpenFOAM has been used in variety of research and development for new finding.

2.3 Simulation condition

Table 1 shows detailed calculation condition of the OpenFOAM simulation. The power distribution was calculated by the serpent code of reactor physics analysis for the PMFR and was modeled in the active core region as a source term by using fvOptions, which provides additional source/sink terms, or enforces constraints to the user defined region. Similarly, in the heat exchanger region, heat removal was simulated by using a heat sink term. To simulate initial flow formation, the total power was set to increase linearly from 0 MW to 92.5 MW for 1 simulation hours in the quarter core of the PMFR. $NaCl\text{-}UCl_3$ was selected as the molten salt fuel, which is a candidate of the PMFR fuels, and its thermodynamic properties were applied to the input model [5]. The internal liquid fuel temperature was set at 900 ^{o}K. No slip velocity condition was applied at the wall and 0 m/s was applied as initial flow condition of the fluid. To simulate the turbulent flow, k-ω SST turbulence model was employed. During the simulation, time-step was set as 1 s.

Table 1: Numerical analysis condition for natural circulation of quarter PMFR

	Value	Remarks
Solver	buoyantSimpleFoam	OpenFOAM solver for buoyancy force
Turbulence model	RANS (SST k-ω)	For natural circulation
Time step	1 s	
Radiation Model	N/A	
Heat generation	0 ~ 92.5 MW	Only Core region
Heat sink	0 ~ 92.5 MW	Only Heat exchanger region
Liquid temperature	Initial Temp T = 900 K	
Velocity condition	No slip	All walls in the simulation
Density [2] ($NaCl\text{-}UCl_3$)	ρ = 3860.4 -0.8371T [kg/m^3]	Linear approximation
Specific heat	550 [J/(kg-K)]	
viscosity	3.9 [cP]	

3. Results and discussions

Figure 2 shows z-axis velocity and temperature contour of a cross section along x-axis at 5 hour as simulation time. In the primary system, the generated heat from the core increased the temperature of liquid fuel, and it formed upper flow through riser region. The heated liquid fuel moved into heat exchanger region and cooled in the heat exchanger region. In the exit of riser region, which is 9 m height, the mean flow Z-velocity was 1.18 m/s, and temperature was 944.6 K. On the other hand, the heat exchanger outlet, which is 4 m height, the mean flow Z-velocity was -0.34 m/s, and temperature was 777.16 K. The velocity difference of each region was shown by the area difference of riser and heat exchanger region. In terms of mass flow rate, each region was calculated as 701.22 kg/s and 706.165 kg/s respectively. Consequently, a natural circulation with a mass flow rate of about 700 kg/s was formed in the primary system.

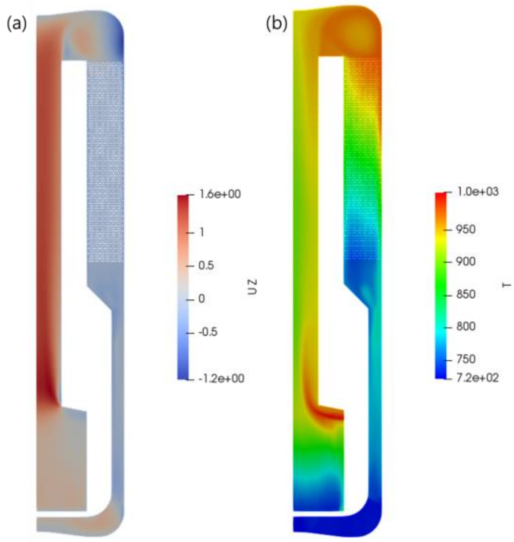

Fig. 2. Z-velocity contour (a) and temperature (b) of cross section along x-axis at the 5 hours.

Figure 3 shows the velocity vector of the PMFR upper region. The flow from the riser moved along the top wall to the outer wall. During the process, most of the flow was injected into the heat exchanger region along the outer wall. However, some of the flow formed a mixing zone at the top of the heat exchanger. Thus, the high flow rate was formed on the outer wall side while passing near the inlet of the heat exchanger. Under this circumstance, the heat may be concentrated in a specific region of the heat exchanger. To stabilize the flow for the effective heat removal, it is necessary to modify the upper region and heat exchanger inlet design.

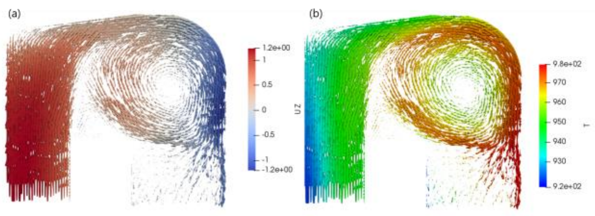

Fig. 3. Z-velocity vector (a) and temperature of vectors (b) in the upper region of PMFR.

An unintentional flow also occurred in the core region. **Figure 4** shows the velocity vector in the downcomer, core, and riser inlet. The flow from the downcomer was injected into the core through the flow distributor, and Z-axis uniform flow was formed in the core region. However, because of sudden contraction from the core to the riser, the flow in the core upper region was accelerated and became unstable. As a result, a stagnation zone was formed near the upper wall of the core, and the temperature was increased in the stagnation zone. The increased temperature was about 1000 ºK, which is 150 ºK higher than the core mean temperature. Such temperature increase by stagnation zone may affect the core wall integrity and reactivity of the core due to density difference. Thus, to eliminate the stagnation zone in the core region, it is needed to modify the design of the core and riser region.

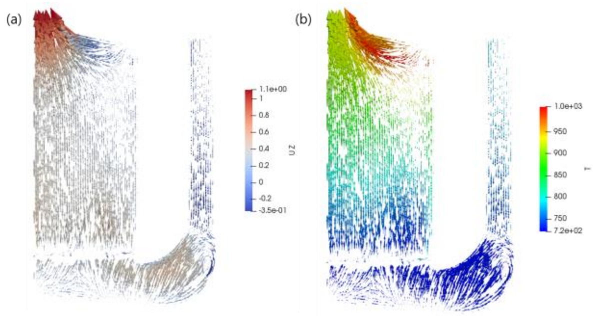

Fig. 4. Down-comer to core, riser region vector Z-velocity (a), and temperature of vectors (b)

4. Conclusions

In this study, natural circulation for the quarter shape of the PMFR was simulated through the OpenFOAM. By using fvOptions function, the power distribution obtained from the serpent code could be applied in the core region and the same power was removed in the helical heat exchanger region. The major results can be summarized as follows.

- In the 370 MW condition, the 10 m PMFR formed natural circulation, which had 700 kg/s mass flow rate, and about 170 ºK temperature difference.
- In the upper region of the reactor, because of high flow velocity along the wall, the flow of the heat exchanger inlet was dominant near the wall. Thus, design modifying is needed to improve the heat exchanger.
- The flow distributor successfully uniformed the flow as Z-axis dominant. However, because of sudden contraction at the riser inlet, the stagnation zone was formed in the core region. The stagnation zone raised the core temperature locally, and it was expected to affect the core integrity and reactivity. Thus, it is necessary to reduce the stagnation zone in the core region.

As such, the natural circulation characteristic of the PMFR could be simulated, which provides critical consideration for the further design improvements. To achieve a uniform inlet condition in the heat exchanger and to reduce the stagnation zone in the core, more improved structural design of the PMFR will be proposed in the future.

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