# Flow characteristics of molten salt natural circulation in non-uniform heat flux condition using OpenFOAM

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## 1. Introduction

Since the Fukushima NPP accident in 2011, the importance of the reactor's passive cooling system and its inherent safety has increased. Various fluids have been studied for removing decay heat without electricity. Among them, Molten salt has great advantages in terms of heat capacity, high boiling point and heat transfer, which is drawing attention as a fluid of the future nuclear reactor [1]. The Molten Salt Reactor (MSR) which uses molten salts based on fluorine or chloride as fuel or coolant has advantages in terms of passive cooling system, so research is being conducted as a Gen-IV reactor [2].

Various MSR design studies were performed to ensure that the passive safety system provides enough cooling of decay heat. In terms of passive cooling, natural circulation is a key phenomenon caused by density differences due to local temperature distribution. The thermal physical properties of fluid or geometry of the system have significant effects on the performance of natural circulation [3]. For the application of MSR, predicting the performance of the natural circulation of the molten salt is important to design the passive decay heat removal system for securing safety.

Since the molten salt have higher Prandtl (Pr) number much more than unity as shown in Table I, properties and thermal performance of molten salt is required to be studied for the design of MSR. From previous studies, the performance of molten salt natural circulation to heat transfer capability varies depending on Pr range [4]. Especially, high-Pr is the key parameter for analysis of natural circulation heat transfer, thus single phase momentum and natural heat transfer are approximately acceptable for molten salt with similar Pr range [5].

In this paper, natural circulation flow of molten salt according to variations of thermophysical properties depending on temperature and heat input condition is studied by computational fluid dynamics (CFD) simulation with open source CFD toolkit, OpenFOAM. The simulation results are compared with the experimental data on the molten salt natural circulation loop (NuHOPE-pre) by Seo [5] using HITEC; a kind of heat transfer salt. By CFD analysis of molten salt are conducted to understand the single-phase flow characteristics of natural circulation in the high-Pr fluid by changing the conditions to contribute to the strategy of MSR system design.

Table I: Thermal physical properties of molten salt.

| | k (W/m-K) | $C_p$ (kJ/kg-K) | ν (m2/s×10$^6$) | Pr |
|---|---|---|---|---|
| $LiF\text{-}BeF_2\text{-}NaF$ at 873K [8] | 0.829 | 2.090 | 3.830 | 21 |
| $2LiF\text{-}BeF_2$ at 873K [9,10] | 1.1 | 2.385 | 4.309 | 19 |
| HITEC at 573K [11] | 0.383 | 1.160 | 1.879 | 11 |
| $LiF\text{-}ThF_4$ at 973K [12] | 1.010 | 1.594 | 2.460 | 16 |

## 2. CFD simulation

In the present work, OpenFOAM is selected, an open source-based CFD package that can be modified solver to further modify various dynamics. Simulation is done in the same geometry of experiment as shown in Fig. 1 and Table II. For the modeling simplification, the loop is divided by a heater, hot leg, cooler and cold leg. The figure 2 shows the simulation domain of the single-phase natural circulation filled with molten salt.

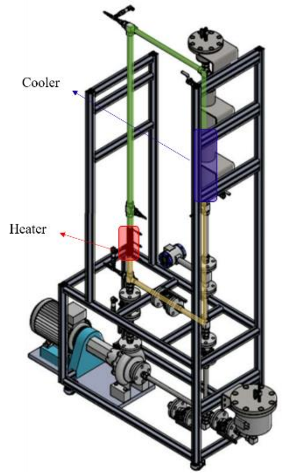


Fig. 1. NuHOPE-pre for high-Pr molten salt natural circulation rectangular loop in UNIST [5]

Table II: Dimensions of the experimental facility

| (m) | Value |
|---|---|
| Loop height/width | 2.6/0.6 |
| Inner/outer diameter | 0.023/0.0254 |
| Heating section length | 0.193 |
| Cooling section length | 0.74 |

### *2.1 OpenFOAM solver*

In the present study, two kinds of the OpenFOAM solvers are considered on the natural circulation flow; The buoyantBoussinesqSimpleFoam solver and the buoyantSimpleFoam solver. Both are a steady-state solver for buoyant and turbulent flow with a pressure-velocity SIMPLE corrector [6]. Former only considers density variation by temperature to adopt Boussinesq approximation as shown in equation (1). And, later considers the properties variation with temperature.

$$\rho = \rho_0[1-\beta(T-T_0)] \text{ (if } (\beta(T-T_0)/\rho_0 \ll 1)) \quad (1)$$

In steady state, governing equations for the mass, momentum, energy analysis could be written as (2), (3), (4):

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

$$\nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \rho \mathbf{g} + \nabla \cdot \left(2\mu_{eff} D(\mathbf{u})\right) - \nabla\left(\frac{2}{3}\mu_{eff}(\nabla \cdot \mathbf{u})\right) \quad (3)$$

$$\text{where } D(\mathbf{u}) = \frac{1}{2}\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right)$$

$$\nabla \cdot (\rho \mathbf{u} h) + \nabla \cdot (\rho \mathbf{u} K) = \nabla \cdot (\alpha_{eff} \nabla h) + \rho \mathbf{u} \cdot \mathbf{g} \quad (4)$$

$$\text{where } \alpha_{eff} = \frac{\rho \nu_t}{\Pr_t} + \frac{\mu}{\Pr}$$

Where **u** is the velocity field, $\rho$ is the density [kg/m$^3$],**g** is the gravitational acceleration [m/s$^2$], $p$ is the pressure [Pa], $\mu_{eff}$ is the sum of the molecular and turbulent viscosity [Pa·s], $D(\mathbf{u})$ is the rate of strain tensor, $h$ is the sum of internal energy per unit mass, $K$ is kinetic energy per unit mass, $\alpha_{eff}$ is the sum of laminar and turbulent thermal diffusivities, $\nu_t$ is the turbulent kinematic viscosity, Pr is the Prandtl number and $\Pr_t$ is the turbulent Prandtl number.

### *2.2 CFD modeling*

The simulation results are compared with the experimental data of Seo [5] to validate the modeling. The parameters to be used for comparison is the Grashof number (Gr), Prandtl number (Pr) and Rayleigh Number (Ra), temperature and mass flow rate as shown in equation (5), (6), (7). Those are important dimensionless numbers in natural circulation.

$$\Pr = \frac{c_p \mu}{k} = \frac{\nu}{\alpha} \quad (5)$$

$$Gr = \frac{L_c g \beta \Delta T}{\nu^2} \quad (6)$$

$$Ra = Gr \Pr = \frac{g \beta \Delta T L_c^{\,3}}{\nu \alpha} \quad (7)$$

Where $c_p$ is the volumetric heat capacity [J/kg·K], $\mu$ is the fluid viscosity [Pa·s], $k$ is the thermal conductivity, ν is the kinematic viscosity [m$^2$/s] and α is the thermal diffusivity [m$^2$/s], g is gravitational acceleration [m/s$^2$], β is the thermal expansion coefficient [1/K], ΔT is the temperature differences between wall and fluid [K], $L_c$ is the characteristic length [m].

To analyze the natural circulation filled with molten salt, the simulation domain is set Vertical Heater Vertical Cooler type for its greatest of flow stability [13]. The initial temperature is designated as 573K, which is higher than the melting point temperature of HITEC(~415K). And adiabatic boundary condition at the walls except heater and cooler is applied. Various values of heat flux and condition for properties variation are set as shown in Fig. 2 and Table III test matrix for analysis. Uniform and non-uniform external input condition are set for comparison as shown in Fig. 3.

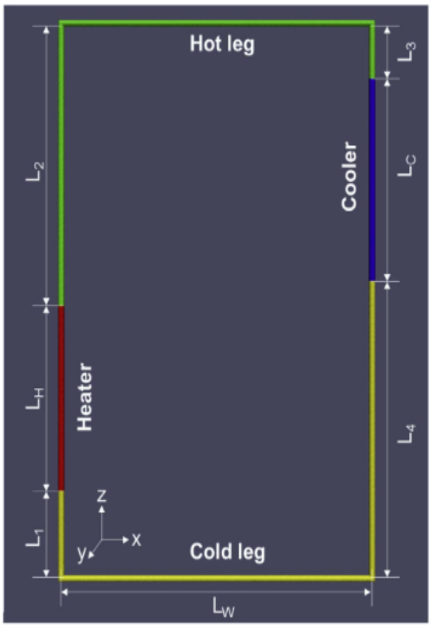


Fig. 2. Domain of OpenFOAM modeling [13]

Table III: Test matrix for natural circulation loop

| Parameter | Value |
|---|---|
| Working fluid | HITEC |
| Heater | External uniform heat input/<br>External nonuniform heat input |
| Heat input | 500 – 2200W |
| Cooler | Fixed value |

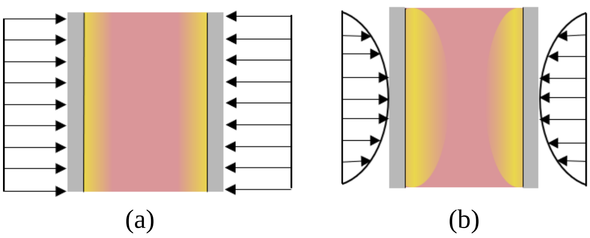


Fig. 3. Schematic of heat input condition (a) uniform heat flux (b) non-uniform heat flux

## 3. Results and Discussions

The variation of velocity and temperature at the heater inlet, outlet and intermediate region along radial position at 1250W is represented in Fig. 4. Typical molten salt like FLiBe, which is a high Pr fluid has a thin thermal boundary layer and high-temperature gradient near the heated wall. Fluid near the wall have local density variety, and this can be a key phenomenon of the natural circulation behavior for the molten salt. It means that bulk fluid cannot represent the overall behavior of natural convection, but the variety of the property changes should be considered. In the middle section, the temperature change is observed to be extremely small. So, optimization will be performed to observe the flow characteristic of the bulk fluid in detail.

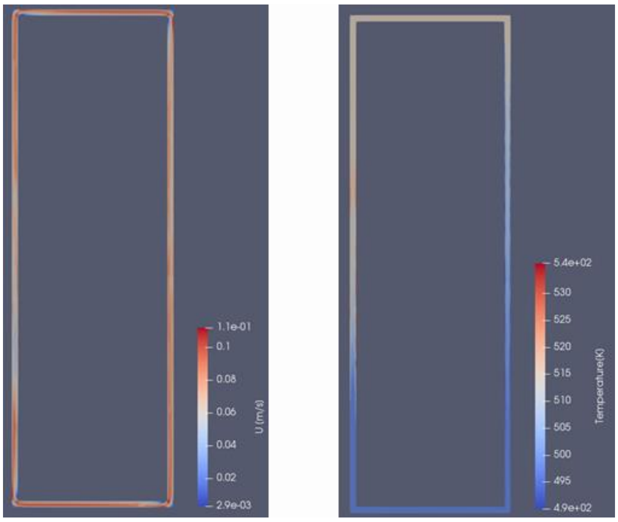


Fig4. Temperature and velocity distribution under 1250W

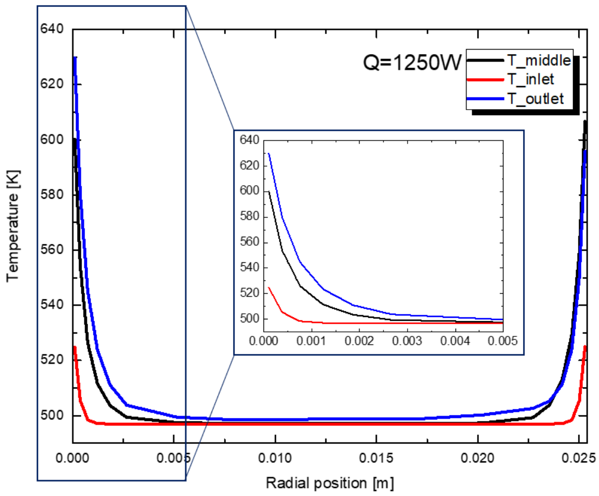


Fig. 5. Temperature distribution in the heater at 1250W heater power.

## 4. Summary and Further work

The mass flow rate and temperature in both the experimental data and the CFD simulations will compare to estimate the reliability of modeling. Then, the simulation will conduct the changing conditions such as temperature, heat input condition for determining flow characteristics when high-Pr molten salts. Later, the solver will be modified to conduct more complex condition like actual MSR with CFD modeling in situations where internal heat sources are added to help design the actual MSR.

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