

Orientation Effects on Natural Convection and Temperature Field in Heat Pipe-Cooled Micro-MSR Comparing Triangular and Circular Configurations

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1. Introduction

Increasing energy demand driven by AI and concerns over carbon emissions has increased interest in non-fossil energy, and nuclear energy is highlighted as a carbon-free option. To develop safer and more economical next-generation reactors, GEN-4 concepts have been proposed, and molten salt reactor (MSR) is notable for low-pressure, high-temperature operation and strong inherent safety.

Westinghouse proposed a heat pipe-cooled MSR concept [1], where the fuel salt remains stagnant in the core while embedded heat pipes passively transport heat to the heat exchangers, avoiding mechanically driven heat removal components. Since MSR involves internal heat generation (IHG) and molten-salt experiments are challenging, high-fidelity CFD remains essential, despite surrogate fluid similarity analyses suggested by Abdellatif *et al.* [2].

Recent CFD studies have investigated MSR-relevant thermal-hydraulics under IHG and buoyancy-driven natural convection. Podila *et al.* [3] showed via 3D CFD that IHG can significantly modify natural-circulation flow structures, whereas Chen *et al.* [4] investigated the effect of heat pipe configuration on natural convection and concluded that a dense circular configuration yields a more uniform temperature distribution with fewer hot spots. However, their analysis was performed only for a horizontally oriented core. Therefore, this work compares vertical and horizontal orientations of a cylindrical heat pipe-cooled MSR core to examine orientation-dependent natural convection and temperature distribution.

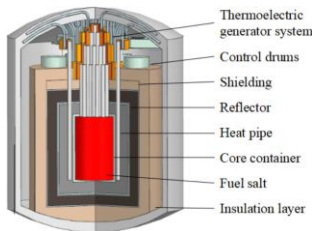


Fig. 1. Conceptual design of a heat pipe-cooled micro-MSR

Table I: Main design parameters of heat pipe-cooled micro-molten salt reactor

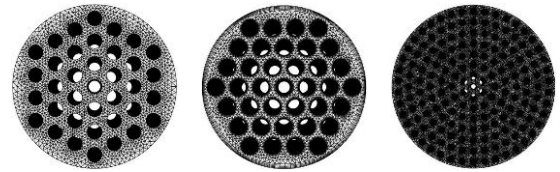
Parameter	Value
Diameter [mm]	350
Height [mm]	620
Thermal Power [kW]	50
Fuel composition [mol%]	72.5 LiF - 27.5 UF4
Working temperature of heat pipes [°C]	650

Core container material	Hastelloy N
System temperature limit [°C]	800

2. Modeling and Methodology

2.1 Configuration of the fluid domain

This work adopts a heat pipe-cooled micro-MSR concept originally proposed by Westinghouse and further developed by Cui *et al.* [5]. Since the reactor does not employ conventional, mechanically driven components, heat is removed in a purely passive way. Hence, numerical verification that natural convection can maintain a sufficiently uniform, hotspot-free temperature field would suggest that this purely passive concept offers enhanced passive safety margins. This reactor uses FLiU(72.5 mol% LiF - 27.5 mol% UF4) as a fuel, and removes the heat through the heat pipes with liquid sodium working fluid operating at 650°C. In this study, only the fuel region is modeled, neglecting surrounding structures. The heat pipes are represented as isothermal cylindrical boundaries and the outer wall is treated as adiabatic.



(a) Triangular 0° (b) Triangular 30° (c) Circular 0°
Fig. 2. Three Different heat pipe configurations

Since buoyancy-driven natural convection depends on both the heat pipe configuration and the core orientation with respect to gravity, three configurations (Triangular 0° / Triangular 30° / Circular 0°) are evaluated under two core orientations (vertical and horizontal) as shown in **Fig. 2**.

2.2 Analysis setup

Gravity is applied along -y (horizontal) or -z (vertical), IHG is uniform, and temperature-dependent FLiU properties (ex. $\rho = 6105 - 1.272T \left[\frac{kg}{m^3} \right]$) are used. Using the density correlation, the maximum density variation within the temperature range remained below 6%, which is sufficiently small for an engineering-level approximation while reducing computational cost. Hence, three-dimensional, steady, incompressible laminar natural convection is simulated using the Boussinesq approximation. It was treated as incompressible under the Boussinesq

approximation and the laminar assumption was adopted following Chen *et al.* [4], who reported that the present core operates in a low Rayleigh number regime.

Boundary conditions are defined on the outer core wall and heat pipe walls. The outer wall is treated as adiabatic, and the heat pipe walls are assumed isothermal at 650 °C. A uniform volumetric heat source of $q''' = 1.2 \text{ MW/m}^3$ is applied, corresponding to the designed thermal power of 50 kW and the fuel volume. A representative mesh-sensitive analysis for the best case configuration showed that the average heat transfer coefficient at the heat pipe wall approached an asymptotic value with mesh refinement.

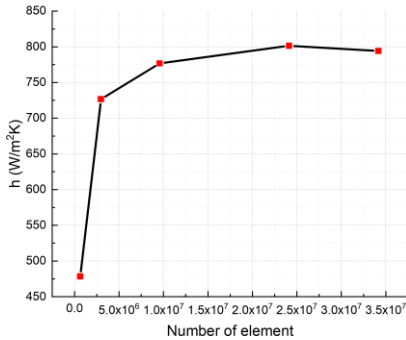


Fig. 3. Mesh-sensitivity analysis for the best case configuration

3. Results and Discussion

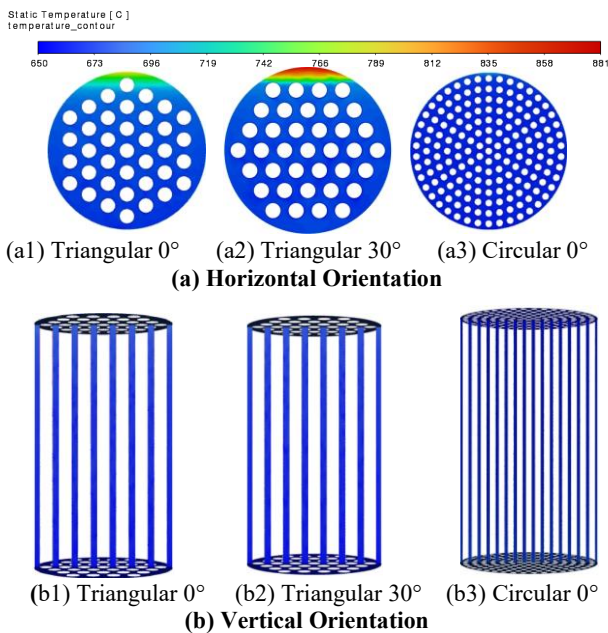


Fig. 4. Temperature field of the reactor core

Fig. 4 compares the steady-state temperature fields for the six cases. In the vertical orientations, rising hot salt repeatedly encounters heat pipes along the full height, yielding smooth cooling and no local hot spots. In the horizontal orientations, the reduced gravity length scale and misalignment between buoyant motion and the pipe array promote a stagnant hot layer near the upper boundary.

Table II: Temperature analysis results for the six simulation cases

	Triangular 0°	Triangular 30°	Circular 0°
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	T_{avg}	T_{max}	T_{avg}	T_{max}	T_{avg}	T_{max}
Horizontal	679	808	683	881	659	695
Vertical	663	680	665	683	657	677

*unit = °C

Table II shows that all vertical cases satisfy the 800 °C limit with negligible sensitivity to triangular rotation, whereas horizontal cases exhibit higher T_{max} due to the formation of an upper stagnant hot layer.

In the horizontal orientation, an upper stagnant hot layer limits mixing, whereas the vertical orientation enhances circulation by providing a longer buoyancy driving length scale and better alignment with the heat-pipe axes.

4. Conclusion and Future work

This work examined the effects of core orientation and heat-pipe configuration on buoyancy-driven natural convection and the resulting temperature field in a heat pipe-cooled MSR with stagnant fuel salt. The results show that the vertical orientation is the most favorable, since it consistently provides more effective passive cooling, yielding a more uniform temperature distribution and lower peak temperatures. In contrast, horizontal placement promotes hot-layer stagnation and higher T_{max} . Among the three layouts, the dense circular configuration is the most robust and remains a viable option even when horizontal placement is required.

Future work will extend the present model to include conjugate heat transfer with solid structures and more realistic heat-generation and fuel-salt effects relevant to long-term operation.

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