

Enhancing Radiative Heat Transfer in a Double-Walled MSR Containment Vessel Using Interlocking Fins

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***Keywords:** MSR / passive safety system / interlocking fin / OpenFOAM / radiation heat transfer

1. Introduction

Molten salt reactors (MSRs) are being actively investigated as advanced nuclear systems, and many design concepts emphasize passive and robust safety functions [1]. One representative feature is the drain tank approach, in which the fuel salt can be relocated by gravity to a passively cooled configuration under off normal conditions [2]. In parallel, non-light-water reactor designs often consider air-based passive heat removal concepts that aim to cool the reactor cavity or the containment vessel by using the external atmosphere as the ultimate heat sink [3]. For MSR configurations in which the containment vessel accommodates both the reactor and the drain tank and interfaces with an air-cooling path, the vessel wall must provide both containment integrity and adequate heat-transfer capability.

Adopting a double-wall structure can ensure barrier redundancy and reliably isolate the internal salt containing volume from the external environment. However, the inter-wall gap introduces additional thermal resistance, degrading heat-transfer performance compared with a single-wall reference design. Considering the MSR operating temperature range, radiative heat transfer across the gap is expected to be a dominant mechanism [4]; therefore, enhancing radiative heat exchange is an effective means to recover the degraded performance. This paper proposes an interlocking fin configuration in which fins mounted on both walls are arranged in an alternating (interlocking) manner to increase the effective radiating area and the view factor toward the opposing wall surfaces. Conjugate heat-transfer simulations are conducted using OpenFOAM to evaluate heat-transfer performance as a function of fin thickness, fin-to-fin clearance, and inter-wall spacing. Based on these results, we propose a structure that achieves better heat-transfer performance while preserving the advantages of a double-wall barrier.

2. Methods

2.1 Computational domain and geometry

A double-walled MSR containment vessel concept that encloses both the reactor and drain tank regions was modeled. To compensate for the reduced heat transfer capability caused by the inter-wall gap, interlocking fins were attached to the opposing walls and arranged to

interleave without mechanical contact. Because detailed plant design information and absolute dimensions of the MSR containment vessel are not yet finalized and the present work focuses on a proof-of-concept evaluation, the simulations were conducted for a fixed base area.

Since the analysis is performed per unit base area, an infinitely extended fin array must be represented. Therefore, symmetry boundary conditions were applied on the lateral boundaries (left/right and top/bottom), if both the geometry and the thermal field repeat indefinitely in the two in-plane directions.

A parametric study was conducted for the key geometric variables affecting radiative heat exchange, namely fin thickness, fin-to-fin clearance, and inter-wall spacing. The fin length was fixed at 90% of the inter-wall spacing throughout the study.

The assumed geometric values were selected to provide a representative parametric space for a proof-of-concept study. Therefore, the present results should be interpreted primarily in terms of relative performance trends rather than the absolute physical significance of each numerical value.

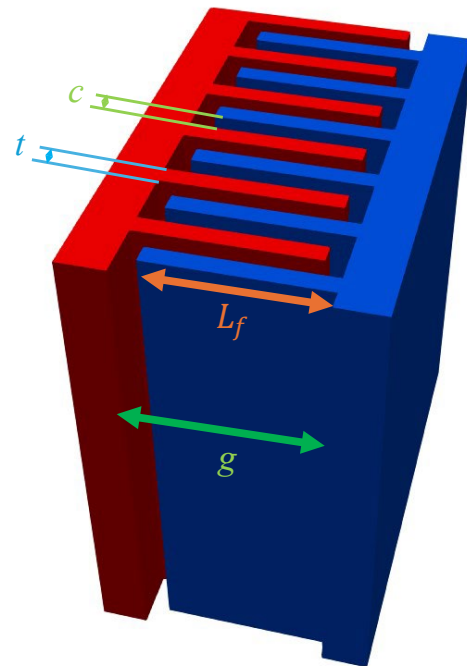


Fig. 1 Schematic of the interlocking fin configuration and key geometric parameters

Table I: Geometric variables and fixed parameters

Parameter	Symbol	Value	Note
Varied parameters			
Inter-wall spacing	g	100, 200, 500 mm	Gap between the two base walls
Fin thickness	t	10, 20, 50 mm	Thickness of each fin (hot and cold fins)
Fin-to-fin clearance	c	10, 20, 50 mm	Minimum clearance between hot and cold fins
Fixed parameters			
Fin length	L_f	$L_f = 0.9 g$	Derived from the inter-wall spacing
Base wall thickness	t_w	5 mm	Constant for all cases
Base area	A_{base}	0.25 m ²	Constant normalization area

2.2 Solver and physical models

All computations were performed using OpenFOAM with the steady-state conjugate heat transfer solver chtMultiRegionSimpleFoam [5], which couples heat conduction in solids with a fluid region. In this study, the primary focus was placed on radiative heat transfer.

Accordingly, the inter-wall region was modeled as a non-participating, quiescent medium with convection disabled (zero velocity and no buoyancy forcing). Conduction through the gap was suppressed by assigning a negligibly small thermal conductivity to the gap region, such that heat transfer across the gap is dominated by surface radiation.

Radiative heat transfer across the inter-wall region was computed using the finite-volume discrete ordinates method (fvDOM) [6], which solves the radiative transfer equation along discretized angular directions. The fvDOM model was selected to maintain consistency with potential future extensions to participating media (e.g., gas-filled gaps). In addition, because the present unit-cell model employs symmetry boundaries, the OpenFOAM surface-to-surface (S2S) radiation approach was not suitable for reflecting symmetry effects in the current configuration; therefore, fvDOM was adopted.

2.3 Boundary conditions and performance metrics

A uniform heat flux boundary condition ($q''_{in} = 7500 W/m^2$) was imposed on the hot-side wall, while the cold-side wall was prescribed as an isothermal boundary ($T_{cold} = 500 K$). Accordingly, the total heat input to the system was kept constant for all cases. To

prevent the total heat input from being affected by fin geometry, the heat-flux boundary condition was applied only to the base wall surface, not to the fin surfaces. The heat-transfer performance of the double-wall configuration was evaluated by the temperature difference between the hot and cold sides under the same heat input. The performance metrics, the temperature difference and thermal resistance are defined as.

$$\Delta T = \bar{T}_{hot,base} - T_{cold}$$

$$R_{th} = \frac{\Delta T}{Q_{in}}$$

Here, $\bar{T}_{hot,base}$ is the area-averaged temperature of the hot-side base wall. Smaller ΔT (or R_{th}) indicates improved heat-transfer capability under an identical thermal load.

3. Results

Table II lists the area-averaged hot-base temperature ($\bar{T}_{hot,base}$) for the interlocking-fin configuration. Because the total heat input and the cold-side temperature are identical for all cases, lower $\bar{T}_{hot,base}$ indicates improved heat-transfer performance. In the tested range ($g = 100-500$, $c = 10-50$, $t = 10-50$), $\bar{T}_{hot,base}$ varies from 592.28 K at $(g,c,t)=(200,10,10)$ to 766.14 K at $(g,c,t)=(500,50,10)$. Clearance is the dominant factor: the mean temperature increases from 615.74 K ($c=10$) to 688.00 K ($c=50$). An intermediate spacing $g=200$ shows the lowest mean value (632.96 K), suggesting a trade-off between fin length (fixed at 0.9g) and radiative coupling with separation. Figure 2 summarizes the clearance trend using, for each g , the best-performing thickness at each clearance (Table III).

Table II(a): $\bar{T}_{hot,base}$ [K] at $g = 100$

$c \setminus t$ (mm)	10	20	50
10	595.56	608.52	644.66
20	626.64	634.95	654.26
50	679.05	673.13	681.16

Table II(b): $\bar{T}_{hot,base}$ [K] at $g = 200$

$c \setminus t$ (mm)	10	20	50
10	592.28	593.57	621.52
20	625.51	620.25	629.45
50	688.84	663.87	661.34

Table II(c): $\bar{T}_{hot,base}$ [K] at $g = 500$

$c \setminus t$ (mm)	10	20	50
10	640.72	619.29	625.52
20	690.94	655.69	632.84
50	766.14	709.16	669.33

Table III: Minimum $\bar{T}_{hot,base}$ [K] over t at each (g, c) , with the corresponding t in parentheses

c (mm)	$g=100$	$g=200$	$g=500$
10	595.56 ($t=10$)	592.28 ($t=10$)	619.29 ($t=20$)
20	626.64 ($t=10$)	620.25 ($t=20$)	632.84 ($t=50$)
50	673.13 ($t=20$)	661.34 ($t=50$)	669.33 ($t=50$)

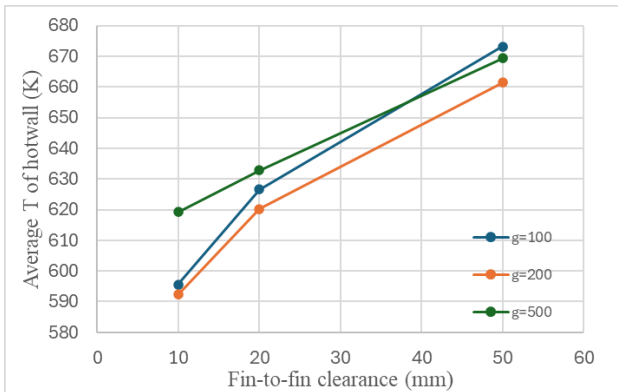


Fig. 2 Clearance effect using the best-performing thickness at each clearance

4. Conclusions

This study evaluated a double-walled MSR containment concept equipped with interlocking fins to enhance barrier redundancy while partially recovering the heat-transfer capability degraded by the inter-wall gap. Under identical total heat input and cold-side temperature, and within the present simplified radiation-dominant model for a vacuum-like inter-wall region, the interlocking fin arrangement produced area-averaged hot-base temperatures in the range of approximately 592–766 K over the tested geometric space (g, c, t) .

Within this parametric space, the lowest hot-base temperature was obtained at $(g, c, t) = (200, 10, 10)$, yielding $\bar{T}_{hot,base} \approx 592$ K. In contrast, larger fin clearance and larger inter-wall spacing generally resulted in significant performance degradation. Among the geometric parameters, the fin clearance c was the dominant factor; increasing c from 10 to 50 increased the mean hot-base temperature by about 72 K. A moderate inter-wall spacing generally provided the most favorable performance, suggesting a trade-off between increased fin length/radiating area with increasing spacing and reduced radiative effectiveness due to weakened radiative coupling and conduction limitations toward the fin tips. These results indicate that the proposed interlocking-fin concept can improve radiative heat-transfer performance under the present idealized conditions and may serve as a useful thermal design option for double-walled containment configurations.

However, the present results should be interpreted as a thermal proof-of-concept based on simplified geometric and boundary assumptions, rather than as a finalized

engineering design recommendation. In particular, the practical feasibility of narrow fin clearances should be further assessed in terms of fabrication tolerance, thermal expansion allowance, assembly feasibility, and structural integration under high-temperature conditions. Future work will therefore extend the present model to gas-filled gaps (including convection and participating-media radiation), quantify surface emissivity sensitivity, perform mesh and angular-resolution verification, and further examine the manufacturability and practical applicability of the proposed interlocking-fin design.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. RS-2025-02653098)

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