Optimizing Thermal Distributors in Heat Pipe-Cooled Micro Reactors using Generative Design

Ju Hyeong Lee[a], Eung Soo Kim[a]*
[a] *Department of Nuclear Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, South Korea*
**Corresponding author: kes7741@snu.ac.kr*

Keywords : Heat pipe-cooled micro reactor, lightweight thermal distributor, generative design, topology optimization

1. Introduction

The Heat Pipe-Cooled Micro Reactor (HPR) features its compact and simple design, offering a prolonged operating time and high power capacity compared to conventional chemical-based energy supply systems[1, 2]. This nuclear power supply technology, when integrated with a static power conversion system like Thermoelectric Generators(TEG), presents significant advantages in terms of flexibility, reliability, and transportability with fewer moving parts. These attributes suit a wide range of applications, such as military use, space exploration, and emergency relief energy supply[3].

The lightweight design of HPR not only contributes to enhanced system mobility, making it more adaptable to diverse environments with various constraints but also improving manufacturability in factories reducing material costs economically[4]. Accordingly, our research aims to optimize the HPR's thermal distributor to achieve optimal thermal resistance and mass reduction, targeting a more lightweight and efficient design.

Based on previous research, the HPR system depicted in fig. 1 was selected as the target design[1]. We have developed the generative design code using topology optimization method based on Solid Isotropic Material with Penalization(SIMP) and introduced Smoothed Particle Hydrodynamics (SPH) for thermal analysis to derive an optimized thermal distributor design.

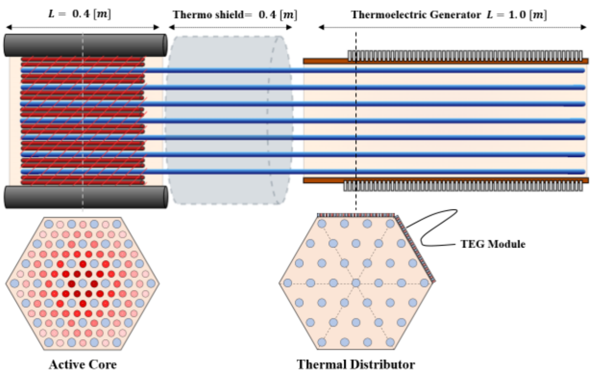


Fig. 1. Conceptual design of HPR and thermal distributor with TEG

2. Generative design method

2.1 Topology optimization of heat conduction problem

Topology optimization is a design optimization method aimed at maximizing performance by strategically arranging materials within a given space. It evaluates the fitness of each design numerically, based on its steady solution. Then it updates design based on local element sensitivity or other optimization algorithms.

Generally, the optimal design under heat conduction problem means to find the optimal arrangement of limited amount of conductive materials within design domain Ω_D that ensures efficient heat distribution connecting the heat source area Ω_q to heat sink zone Ω_c (Fig. 2).

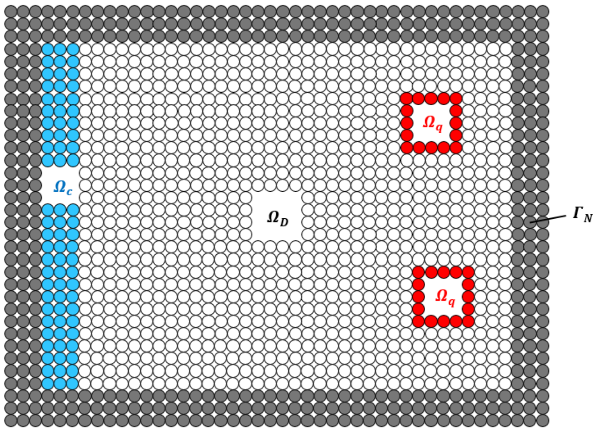


Fig. 2. Conceptual configuration of design domain and boundaries for thermal resistance optimization problem

Then, the topology optimization problem can be mathematically stated as equations (1) as below.

$$\text{Find}: \quad \mathrm{X}_i = [\mathrm{x}_1, \mathrm{x}_2, \dots, \mathrm{x}_N] \qquad \mathrm{x}_i = \begin{cases} 0 & void \\ 1 & solid \end{cases}$$

$$\text{Min}: \quad \mathrm{C} = \frac{1}{n}\sum_{i=1}^{n} T_i \qquad \Omega_c \in HeatPipe$$

$$\text{s.t.}: \quad \mathrm{A}(\mathrm{x}_i)\mathrm{T} = \mathrm{F} \Leftrightarrow \nabla \cdot (k\nabla T) = -q$$

$$\frac{\mathrm{V}}{\mathrm{V_t}} = \overline{\mathrm{V_f}} \quad \mathrm{V}_t = \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{V_i} \quad \mathrm{V} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{V_i} \times \mathrm{x_i} \qquad (1)$$

In equations (1), x_i is the binary design variable determining the absence or presence of material. Governing system equation can be described by AT=F where T and F denotes the temperature and the thermal load vector of predefined space.

Our goal is to minimize temperature of heat pipes in thermal distributor. It is equivalent to minimizing the effective thermal resistance of thermal distributor, as the temperature of heat sink and power distribution of heat pipes are given with specific values. The specific dimensions, powers required in the system optimization were obtained from the preceding paper [1].

2.2 SIMP method and sensitivity analysis

The solid isotropic material with penalization (SIMP) method is devised to adopt gradient descent optimization algorithm in the process of deriving better design.

As for SIMP, solid and void indicating the presence or absence of conductive material, are connected by continuous value ρ with a range of 0 to 1 and it determines local conductivity as shown in equation (2). Here κ_{min} and κ_{max} mean conductivity of void and solid separately.

$$\kappa_i = \kappa_{min} + (\kappa_{max} - \kappa_{min})\rho^3 \qquad (2)$$

Under the above modeling scheme, one can decide whether to increase or decrease local ρ based on sensitivity which determines where to increase conduction capability for better fitness.

The sensitivity can be calculated effectively with adjoint method summarized by equations (3), (4). Also, popular optimality criteria (OC) method[5] is employed as optimization algorithm to update design satisfying limited volume constraints.

Adjoint : $$\nabla \cdot (k\nabla\phi) = -C \qquad C_i \begin{cases} 1 & i \in HP \\ 0 & \text{else} \end{cases} \qquad (3)$$

Sensitivity : $$-\nabla\phi\nabla T = \frac{\partial F}{\partial k}\Big|_i \qquad (4)$$

The SIMP method can result in unclear boundaries for the optimized design due to continuous values for gradient descent algorithm. Thus, we included design binarization process calculating design connectivity directly. So it can handle boundary of design clearly. Plus, as part of the generative approach, this framework has been designed pursuing the integration of various meta-heuristic optimization methods in the future.

3. Smoothed Particle Hydrodynamics(SPH) for steady heat conduction problem

As for the topology optimization code, there are widely recognized papers and commercial programs using FEM method. Many papers have extended topology optimization from FEM to other methods, offering advantages in solution analysis. We extended topology optimization using smoothed particle hydrodynamics (SPH), particle-based CFD code.

The SPH is based on numerical integration using approximated delta function which is called kernel function. Estimated physical property at position r_i and the first derivative of the property field is expressed as below in equations (5), (6) where f is a physical quantity, W_{ij} is a kernel function and j is an index for neighboring particle which of its volume is V_j.

$$f(r_i) = \sum_j f_j W_{ij} V_j \qquad (5)$$

$$\nabla f(r_i) = \sum_j f_j \nabla W_{ij} V_j \qquad (6)$$

From the above basic principle, the heat conduction equation is well known as (7). The steady solution for the representative 2D heat sink design example where heat is emitted from the entire space was also shown in Fig.3.

$$\sum_j^N 2V_j\left(\frac{2k_ik_j}{k_i + k_j}\right)\left(T_i^n - T_j^n\right)\frac{r_{ij}}{|r_{ij}^2|} \cdot \nabla W_{ij} = -q_i \qquad (7)$$

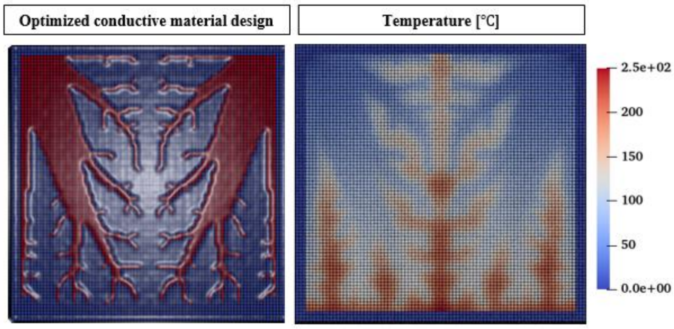


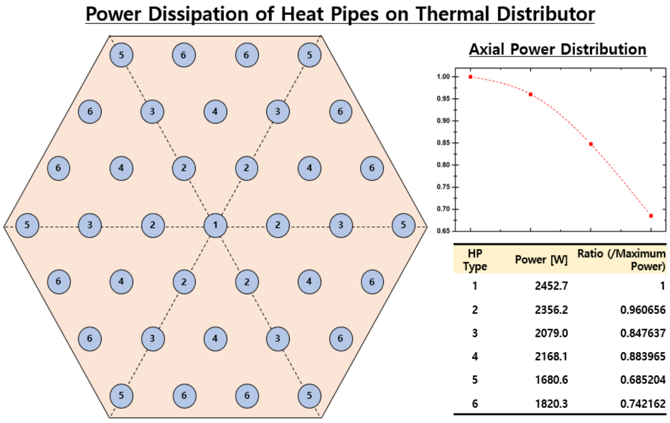
Fig. 3. Representative 2D heat sink design example and steady temperature solution of system.

The conjunctive gradient method accelerated by GPU-based parallelism was used with jacobian preconditioner to obtain steady solution of the equation (7) quickly. It is confirmed that converged solution can be calculated at similar residual levels about 25 times faster than the widely known jacobian iteration method.

4. Optimized design results of thermal distributor in heat pipe-cooled micro reactors

The thermal distributor, depicted in fig. 4 with a diameter of 0.4 m and a height of 1 m, was selected as the target for optimization. Leveraging symmetry, 1/8 of the domain was discretized for the simulation by utilizing 12 million particles, each with a diameter of 1.19 mm. The blue circular area represents the space occupied by the heat pipe connected through the thermal distributor.

The estimated power distribution emitted from each heat pipe to the thermal distributor was calculated based on reactor neutronic analysis and simple thermal resistance modeling. Fig. 5 illustrates the temperature calculated in the thermal distributor of reference design with conductive material placed throughout the entire space, with considerations regarding the heat dissipation distribution from fig. 4.



HP Type	Power [W]	Ratio (/Maximum Power)
1	2452.7	1
2	2356.2	0.960656
3	2079.0	0.847637
4	2168.1	0.883965
5	1680.6	0.685204
6	1820.3	0.742162

Fig. 4. Radial power distribution from heat pipes on thermal distributor

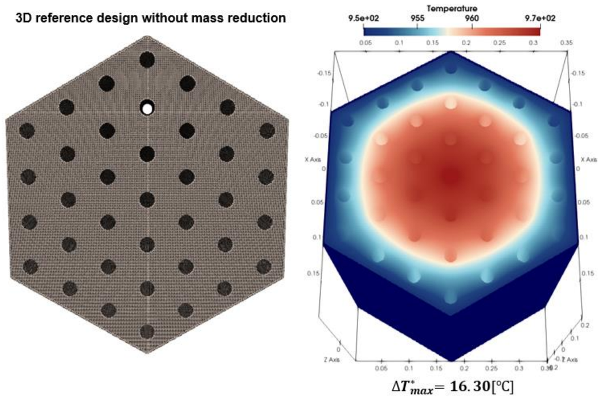


Fig. 5. Calculated temperature for thermal distributor with reference design

Fig. 6 shows the derived optimum shapes of a TEG thermal distributor using the developed generative design method. Aligned with the application's objectives, the reduction of the system's mass enhancing portability and manufacturability concurrently augments the void space within the thermal distributor, thereby effectuating a decrease in material costs. This modification, however, incurs an increase in effective thermal resistance as an adverse repercussion. Effective thermal resistance refers to a relative value derived from the temperature difference between the heat pipe and the TEG high temperature side part. The reference temperature difference between the heat sink and heat pipes, in the scenario without material reduction, is defined as 100. Subsequent increment of thermal resistance along material reduction is expressed relatively to this base. Leveraging the developed code, the increase in thermal resistance was minimized, ensuring the maintenance of maximum efficiency. The outcomes are presented in Figure 6.

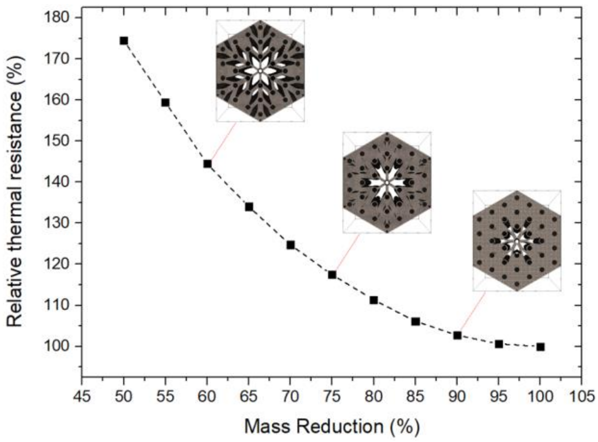


Fig. 6. Optimized design of TEG thermal distributor as respect of thermal resistance for mass reduction

Furthermore, considering the total thermal resistance of heat transfer path starting with fuel and passing through the heat pipe, the thermal conductivity value of the materials like UN, Zr_2H_3 which constitute the other paths is around 10% of that for a copper. Therefore, this relative increase trend in fig. 6 will lead to much smaller impact on total energy conversion efficiency as the thermal resistance of the TEG heat distributor accounts for a small percentage overall.

Consequently, selecting a design from around the pareto-optimal front in Fig 6 can result in a design with high utility for a lightweight system.

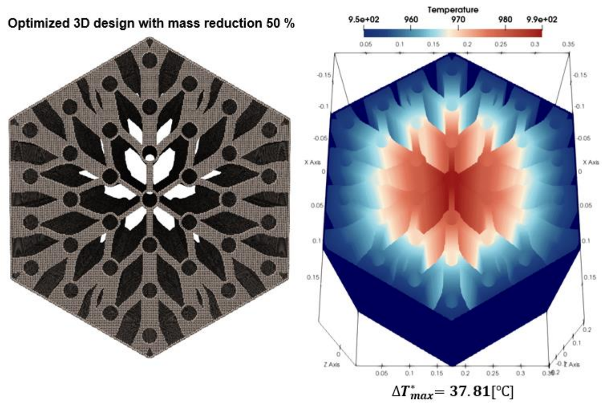


Fig. 7. Calculated temperature for thermal distributor with optimized design in case of mass reduction 50%

For example, using the design shown in Figure 7, which cuts the weight by 50%, would also cut the amount of copper needed in half, whilst engendering increment in thermal resistance by a factor of 1.75. This increase is expected to be minor when compared to the overall thermal resistance of the system, with the anticipation based on the thermal conductivity of the constituent materials, suggesting an increase of less than 10% in the total thermal resistance.

Meanwhile, as mass reduction progresses up to 50%, it is observed that the increment of thermal resistance leads to 2.3 times increase in the difference between the temperature of the heat sink and the system's maximum temperature. Additionally, it is noted that structures resembling spider webs emerge in fig. 7. In this scenario, thermal stress increases and it can potentially compromise the integrity of the system. Therefore, to derive the optimal reliable design, a quantitative analysis of the increase in thermal stress is necessary, and this would be addressed in future research.

5. SUMMARY

In this study we developed generative design method based on SIMP method and SPH for design optimization. Using the developed code, the lightweight design of the thermal distributor located in the energy conversion system of the HPR was pursued, and shapes with optimized thermal resistance in various mass reduction case were explored. Through this process, some designs around Pareto front for two opposing objectives were obtained as a result. These results can contribute in the decision-making process for determining the optimal shape during lightweighting of HPR when a ratio of importance for thermal resistance, weight, and cost is provided. During the optimization, structural features leading to increased thermal stress emerged. This highlights the need for future research to analyze these features and integrate them into the optimization process to derive reliable shapes.

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