

Preliminary Evaluation of Air- and Water-Cooled Heat Sinks for Free-Piston Stirling Engine using Radioisotope Source

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1. Introduction

Radioisotope power systems provide a reliable means of supplying electricity for space missions under harsh environmental conditions. KAERI has demonstrated a space radioisotope battery based on thermoelectric generators under conditions that simulate the space environment [1, 2]. Building on this achievement, KAERI is developing a radioisotope power conversion system that employs a free-piston Stirling engine (FPSE) to improve energy conversion performance for space nuclear applications.

FPSEs have been studied as promising power conversion devices because of their simple mechanical configuration and potential for high efficiency. Unlike conventional kinematic Stirling engines, the piston and displacer in an FPSE are not driven by a crank mechanism but oscillate freely within a hermetically sealed volume. Their motion is determined by the coupled effects of pressure oscillation, spring restoring force, fluid-induced damping, and external load characteristics.

The radioisotope source mounted on top of the FPSE housing supplies heat to the radioisotope power conversion system, as shown in Fig. 1. The supplied heat is transferred to the working fluid through the hot-region heat exchanger, while heat rejected from the working fluid is transferred to the heat sink through the cold-region heat exchanger. The resulting temperature difference between the hot and cold regions drives the oscillatory motion of the FPSE. In general, the heat sink can be configured for either water cooling or air cooling.

In this study, water-cooled and air-cooled heat sinks are compared for the FPSE being developed at KAERI during the preliminary design stage. The thermal performance of the two cooling concepts was evaluated using CFD simulations.

2. Methods and Results

2.1 System description

Fig. 1 shows the schematic of the FPSE and isometric views of the air-cooled and water-cooled heat sinks. The FPSE housing is filled with inert helium gas and contains the displacer piston and power piston in the upper and lower regions, respectively. Each piston is connected to its spring through a mechanical rod, forming a two-degree-of-freedom spring-mass system.

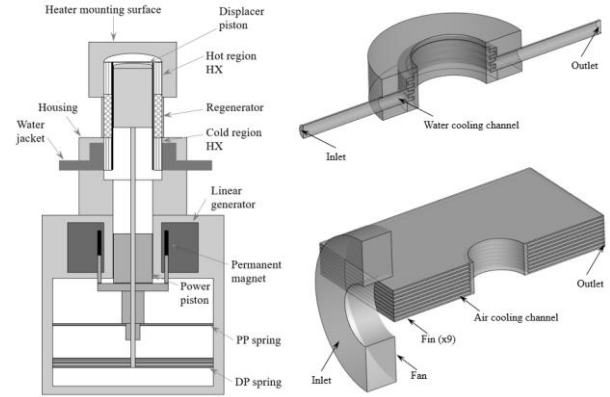


Fig. 1 Schematic of Stirling engine and isometric views of air-cooled and water-cooled heat sinks.

Heat from the radioisotope source mounted on top of the housing is transferred to the working fluid through the hot region heat exchanger and rejected through the cold region heat exchanger. The regenerator improves thermal efficiency by alternately storing and releasing heat, and the linear generator converts the oscillatory motion into electrical power.

In the water-cooled configuration, the finned cylindrical channel removes heat from the cold region heat exchanger. In contrast, the air-cooled heat sink is designed with larger plate fins to provide a greater heat transfer area, compensating for the relatively low convective heat transfer coefficient of air. A fan is directly attached to the end of the fin plates.

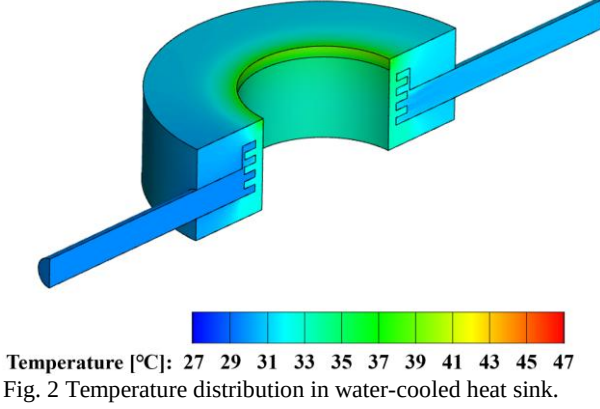
2.2 Numerical methodology

The flow fields in both cooling concepts were modeled as steady, three-dimensional, incompressible, and turbulent flows. Gravitational effects were neglected. The conservation equations of mass, momentum, and energy were solved under these assumptions, as follows:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]$$

$$\frac{\partial}{\partial t}(\rho C_p T) + \frac{\partial}{\partial x_j}(\rho C_p u_j T) = \frac{\partial}{\partial x_j} \left(k \frac{\partial T}{\partial x_j} \right)$$



The CFD simulations were performed using ANSYS Fluent 2019 R1 with the finite volume method. Pressure and velocity fields were coupled using the SIMPLE algorithm, and the convective fluxes were discretized with a second-order upwind scheme. A uniform inlet velocity was prescribed at the inlet channel, and a zero-gauge-pressure condition was imposed at the outlet channel. All solid surfaces were treated as no-slip walls. A convective boundary condition with an axially varying free-stream temperature was applied to the contact surface with the cold region heat exchanger ($h_{eff} = 2,500 \text{ W/m}^2\text{K}$; $T_{c,HX \text{ free stream}}$ linearly varies from $43.75 \text{ }^\circ\text{C}$ to $55.05 \text{ }^\circ\text{C}$), while the other walls were thermally insulated. Symmetry conditions were applied so that only half of each geometry was modeled, thereby improving computational efficiency. The numbers of cells in the water-cooled and air-cooled heat sinks was 4,799,995 and 1,306,300, respectively.

2.3 Results

The following assumptions were used for the CFD simulations of both heat sink types. The mass flow rate was set to 0.035 kg/s for both cases, while the inlet temperatures of water and air were $29.5 \text{ }^\circ\text{C}$ and $26 \text{ }^\circ\text{C}$, respectively.

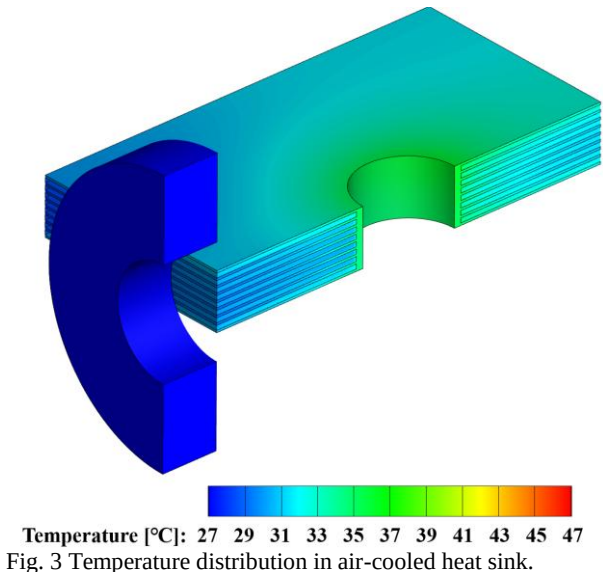


Table 1. Simulation results.

	Water-cooled	Air-cooled
Mass flow rate	0.035 kg/s	
$T_{out}-T_{in}$	$0.9 \text{ }^\circ\text{C}$	$3.3 \text{ }^\circ\text{C}$
Specific heat	4182 J/kg K	1006 J/kg K
$Q_{removal}$	134 W	115 W

Fig. 2 shows the temperature distribution of the water-cooled heat sink. Heat from the cold region heat exchanger is removed through the finned cylindrical cooling channel. The temperature is relatively high near the inner surface connected to the cold-region heat exchanger and gradually decreases toward the cooling channel and outlet region.

Fig. 3 shows the temperature distribution of the air-cooled heat sink. Heat is conducted from the cold region heat exchanger to the enlarged plate fins and then rejected to the forced airflow supplied by the fan. Compared with the water-cooled heat sink, the temperature variation is more widely distributed over the finned body because of the lower convective heat transfer coefficient of air.

The simulation results are summarized in Table 1. Although the mass flow rates and convective boundary conditions were identical for both CFD cases, the water-cooled case removed more heat than the air-cooled case. However, the difference in heat removal rate was within 15%.

3. Conclusions

This study performed a preliminary CFD evaluation of water-cooled and air-cooled heat sinks for the FPSE. The former showed better heat removal performance from the cold region heat exchanger. However, the difference between the two cooling concepts was within 15%. Therefore, the latter can also be considered as a candidate concept by optimizing fin numbers, thickness, and shape. Further research, including detailed design, manufacturing, and experimental testing remains as future work to realize KAERI's FPSE.

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