

Preliminary Evaluation of Heat Exchanger in Hot Region inside Free-Piston Stirling Engine using Radioisotope Source

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has successfully developed a space radioisotope battery based on thermoelectric generators and demonstrated its operation in a space environment [1]. Furthermore, KAERI has been developing a new radioisotope-based energy conversion system using a free-piston Stirling engine (FPSE), aiming to become one of the global leaders in space nuclear battery technology.

FPSEs have attracted considerable attention as power conversion systems over the past decades [2]. Unlike conventional kinematic Stirling engines, FPSEs do not require a crank mechanism. Instead, the piston and displacer move within a hermetically sealed control volume. Their dynamic behavior is governed by the coupled effects of pressure forces, spring forces, fluid damping, and external load characteristics.

Heat exchangers are installed in the upper hot region and the lower cold region of the FPSE, respectively. In particular, the hot region heat exchanger plays an important role in transferring heat from the radioisotope source to the working fluid while inducing pressure loss in the flow path. Therefore, its design directly affects the heat transfer performance and dynamic characteristics of the FPSE.

In this study, a preliminary design of the hot region heat exchanger for an FPSE is proposed, and its heat transfer performance and pressure loss characteristics are evaluated using computational fluid dynamics (CFD).

2. Methods and Results

2.1 System description

Fig. 1 shows a schematic of the Stirling engine and a magnified view of the hot region heat exchanger. Inert helium gas fills the hermetically sealed FPSE housing. The displacer piston and power piston (DP and PP) are located in the upper and lower regions of the FPSE, respectively. The DP and PP are connected to their respective springs through mechanical rods. The upper surface of the housing is in direct contact with the radioisotope heat source, which transfers heat into hot region heat exchanger. The heat is then rejected to the water jacket through the cold region heat exchanger. The regenerator improves thermal efficiency by

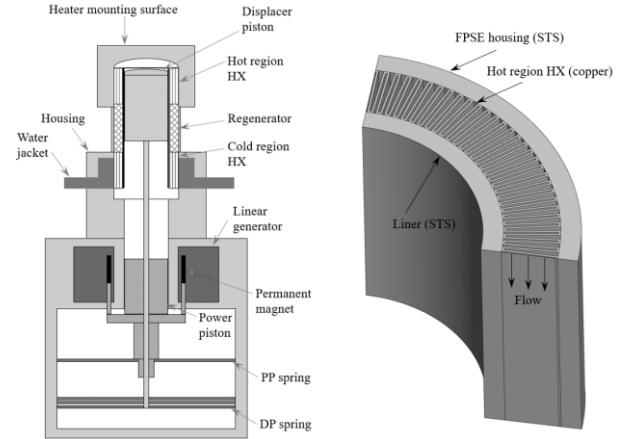


Fig. 1 Schematic of Stirling engine and magnified view of hot region heat exchanger.

alternately absorbing and releasing heat during the cycle. The permanent magnet and linear generator convert mechanical energy into electrical energy. The fluid system provides damping to the two-degree-of-freedom (DOF) spring-mass systems.

2.2 Numerical methodology

The governing equations for the hot-region heat exchanger are formulated by assuming steady, three-dimensional, incompressible, and laminar flow (turbulent model is not used because of low Reynolds number of 1,200 in this problem; Prandtl number is 0.66), while neglecting gravitational effects, 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 finite volume method was used to solve the governing equations. The semi-implicit method for pressure linked equations (SIMPLE) algorithm was adopted to couple pressure and momentum. A second-order linear upwind scheme was used for the convective terms. ANSYS Fluent 2019R1 was used to solve the governing equation set. Uniform and constant velocity

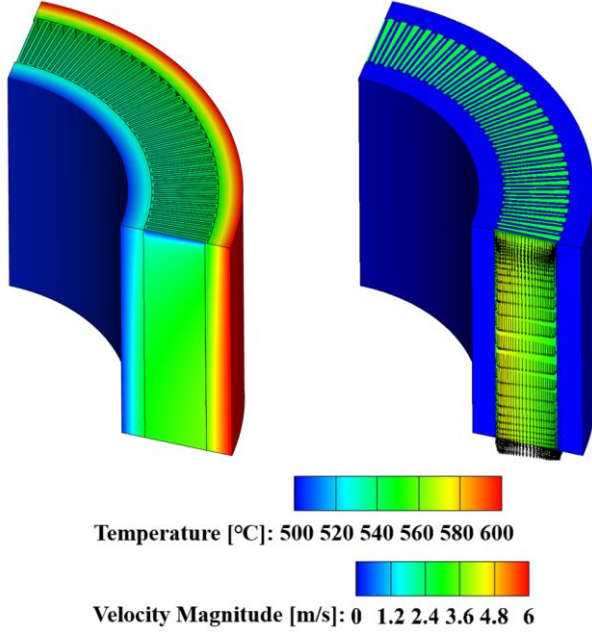


Fig. 2 Temperature and velocity distribution in hot region heat exchanger.

conditions were applied at the top of the inlet channel, while a zero absolute pressure condition was applied at the bottom of the outlet channel. The no-slip condition was applied to all other boundaries. The outer and inner walls were assumed to have constant temperatures. A one-quarter partial geometry was used to reduce the computational cost, and the number of nodes was 1,329,254 (N3 grid was selected after testing dependency among N1(node: 758,086; T_{out} : 558.02), N2(node: 1,126,744; T_{out} : 553.91), and N3(node: 1,329,254; T_{out} : 553.92).

2.3 Results

The following assumptions were used for the CFD simulations of the FPSE. The fluid pressure in the FPSE was maintained at 2.8 MPa. The outer wall of the FPSE housing was maintained at 600 °C, while the inner wall of the liner was maintained at 500 °C. The mass flow rate was 0.00161 kg/s. The working fluid flows downward from the top face. The hot region heat exchanger employs corrugated plate fins with a zigzag-folded geometry. The corrugated plate fin consists of 120 corrugation periods, with each period comprising two inclined fin segments. The fin thickness is 0.2 mm.

Fig. 2 shows the temperature and velocity distributions in the hot region heat exchanger. The flow is evenly distributed in the corrugated plate-fin channels and is heated as it moves toward the outlet. At the outlet, the fluid temperature almost reaches the average temperature of the inlet and outlet walls. The velocity distribution shows that the flow is not uniform over the channel cross-sectional area but is concentrated near the diverging-edge region, which is relatively wider than the narrow region near the converging edge, owing to the imbalance in flow resistance. The local peak in the flow speed can produce a larger pressure drop than

uniform flow because the dynamic pressure drop is proportional to the square of the flow speed. The

Table 1. Temperature comparison of CFD simulation and 0D heat balance at liner and housing surfaces.

Temperature [°C]	CFD	0D	Error [%]
$T_{Liner,in}$	500 (boundary)		-
$T_{Liner,out}$	539.3	546.2	1.3
$T_{Housing,in}$	554.5	556.5	0.4
$T_{Housing,out}$	600 (boundary)		-

pressure drop is 352.7 Pa, which is relatively small compared with the operating pressure of 2.8 MPa.

The spatially averaged temperatures predicted by the CFD simulation were in good agreement with those obtained from the 0D heat-balance within approximately 1.3%, as shown in Table 1.

Heat exchanger effectiveness, as one of the indicators of thermal performance, is defined as the ratio of the actual heat transfer to the maximum theoretically possible heat transfer. Assuming the identical mass flow rate and specific heat capacity, the effectiveness of the hot region heat exchanger was evaluated using the CFD results for the hot region heat exchanger, as follows.

$$HX \text{ effectiveness} = \frac{T_{out} - T_{in}}{T_{Housing,out} - T_{in}} = \frac{553.9 - 500}{600 - 500} = 0.54$$

3. Conclusions

This study conducted CFD simulations to preliminary evaluate the hot region heat exchanger. The CFD simulation results shows the temperature and velocity distributions inside the hot region heat exchanger. The pressure drop is relatively small compared with the operating pressure despite the existence of a local peak in the flow speed. The CFD results show good agreement with the 0D heat balance. Heat exchanger effectiveness is evaluated as 0.53, which is higher than the requirement for the hot region heat exchanger. Detailed design, manufacturing, and testing will be conducted as future work to successfully develop the FPSE using a radioisotope source.

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