Gap Assessment on the Moderator Temperature Distribution in a Space Reactor

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1. Introduction

Since humans began exploring outer space, various technologies related to space missions have been researched and developed. Among them, developing a power supply suitable for use in space has become challenging. Solar panels can provide electricity for satellites near Earth; however, solar power declines with distance from the Sun. Radioisotope power systems offer a sustainable alternative energy supply of less than 1 kWth (used, for example, in the vehicle Curiosity [1], now on Mars). However, the use of radioisotopes with ^{238}Pu has been decreasing, so the USA started research to provide simpler space reactors using heat-pipes [2]. The Kilopower reactor that resulted from those studies arose from the philosophy to make a simple and reliable reactor. A space reactor will be installed in a space launch vehicle, which means that its weight (mass) should be as small as possible. Moreover, reactor maintenance in the space environment is almost impossible. Therefore, the number of components should also be as few as possible to reduce unexpected accidents. Thus, Kilopower uses heat-pipes to transport heat without a pump. Korea also started research on space reactors (prompted by the success of the USA) via the Korea Atomic Energy Research Institute (KAERI). However, in contrast to the US approach, the space reactor researched and developed by KAERI uses low enriched uranium (LEU). This makes control of the reactor weight much more challenging. In this report, we present results from the preliminary study of heat transfer in the candidate cores.

2. Methods and Results

The core power is derived from the results of the neutronics code calculation. The geometry and meshes are generated using the ANSYS CFD S/W [3]. For simplicity, the heat-pipe was modeled as a solid pipe with high thermal conductivity. Figs. 1 and 2 show the reactor cores considered in the present study.

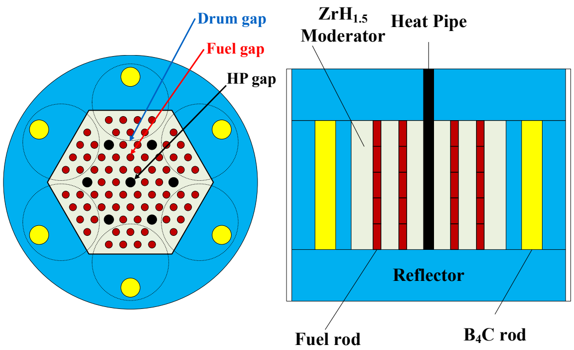


Fig. 1. Monolith type reactor [4]

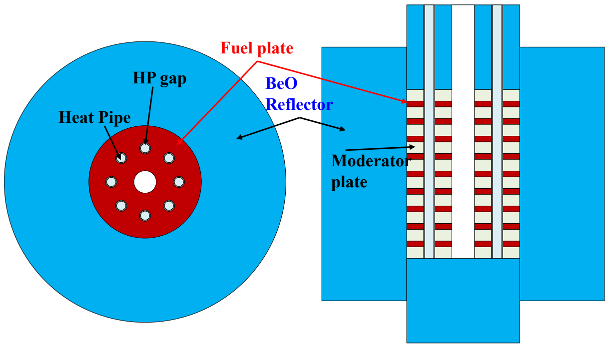


Fig. 2. Plate type reactor

The fuel pins in Fig. 1 are inserted in the $ZrH_{1.5}$ moderator block. The heat-pipe and fuel compact in Fig. 1 is designed to be installed in the block. Therefore, there exist three vacuum gaps from the heat-pipe to the fuel compact through the moderator, including the drum region in Fig. 1. The fuel plates are shown stacked vertically together with the moderator plates in Fig. 2. The heat-pipe is shown installed directly in the fuel plate in Fig. 2 to reduce the number of gaps. In this case, there is only one gap between the heat-pipe and the fuel plate.

The power was fixed at 5 kWth. The boundary condition of the cooling region uses a fixed temperature condition of 700 °C. The surface-to-surface radiation model was used to calculate heat transfer in the gaps with very low thermal conductivity. The momentum model in the gap fluid was deactivated in order to solve only the heat transfer in the CFX calculation.

In the space environment, the existence of the gap prevents heat transfer within the component. This causes unexpected temperature increase; therefore, gap analysis is important for accurate prediction of the operating temperature of the heat-pipe and the moderator block under normal operating conditions.

2.1 Modeling

Table 1 shows the calculation cases used in the present study. The gap size in Table 1 represents the gap between the heat-pipe and the moderator block in Fig. 1 and the gap between the heat-pipe and the fuel plate in Fig. 2. The cross gap between the vertical blocks is not considered in the present study. A helium filled gap is considered in cases 4 and 6 to assess heat conduction across the gap. An air-filled gap (Case 7) is also considered to estimate the heat transfer for a reactor used on Earth.

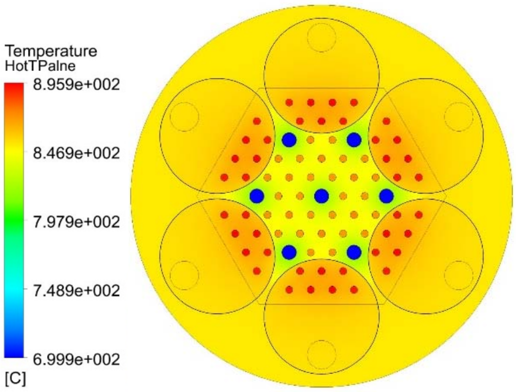
It was assumed that the power density in the fuel compact is uniform over the whole core.

Table 1: Calculation cases

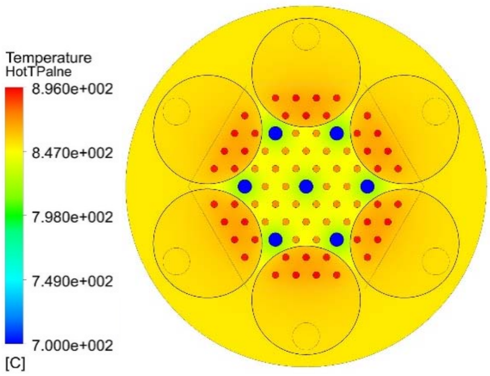
Case	Core	HP Gap size [mm]	Gap fluid
1	Monolith	0.1	Vacuum
2	Monolith	0.2	Vacuum
3	Monolith	0.4	Vacuum
4	Monolith	0.1	He
5	Plate	0.1	Vacuum
6	Plate	0.1	He
7	Plate	0.1	Air

2.2 Results

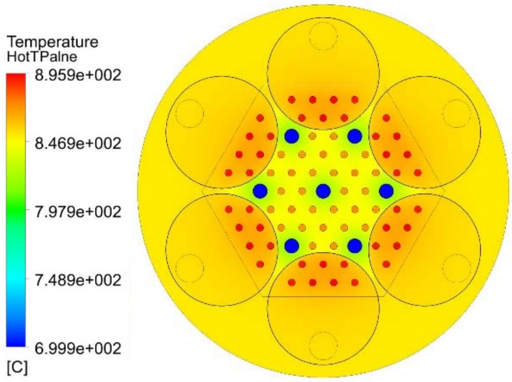
Fig. 3 shows temperature distributions in which hot spots are found in the block. The maximum temperature in the monolith type reactor is about 50 °C higher than that in the plate type reactor because the monolith type reactor has more gaps that prevent heat transfer in the block. Moreover, the 1 mm gap used to rotate a control drum also interrupts the heat transfer between the fuel compact and the heat-pipe. However, if the gap is filled with helium, the maximum temperatures decrease substantially for both reactor types, as shown in Fig. 3 (d) and (f).



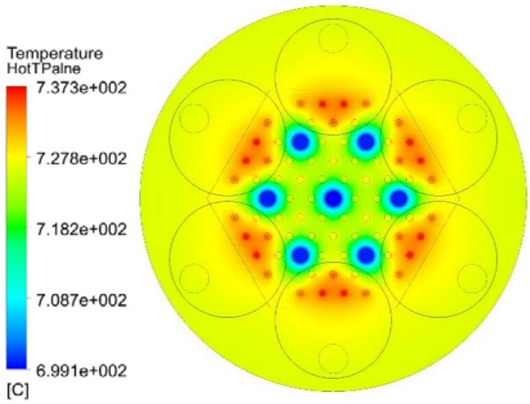
a) Case 1 temperature distribution



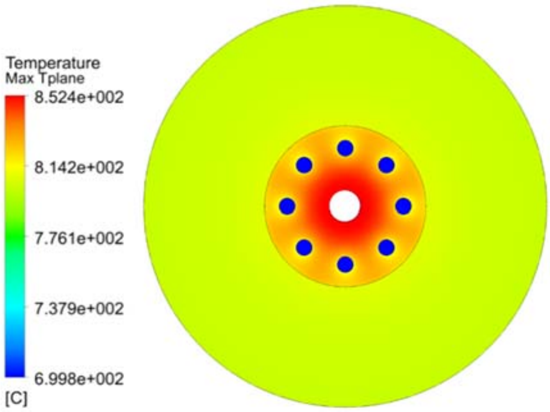
b) Case 2 temperature distribution



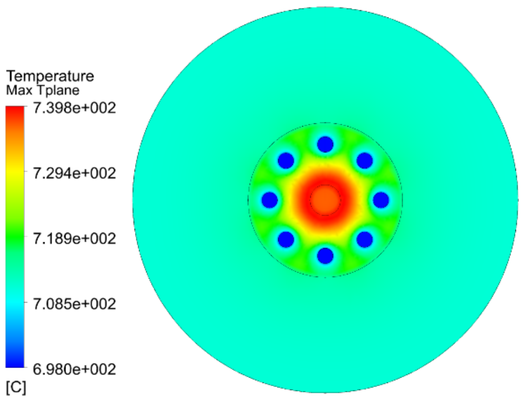
c) Case 3 temperature distribution



d) Case 4 temperature distribution



e) Case 5 temperature distribution



f) Case 6 temperature distribution

Fig. 3. Temperature distribution in the hot-spot plane

Table 2 presents the maximum fuel temperatures and average moderator block temperatures. There is better thermal performance in the plate type reactor with a vacuum gap.

Table 2: Temperature in the core

Case	Max. Fuel [℃]	Avg. Moderator [℃]
1	896	837
2	896	837
3	896	838
4	737	719
5	853	817
6	740	716
7	780	750

Fig. 4 indicates the plot position used to examine the temperature profile in the block axially and radially. The temperature profiles are plotted in Fig. 5. In these graphs, an additional case with an air-filled gap was examined to consider the possibility that the reactor is used on Earth.

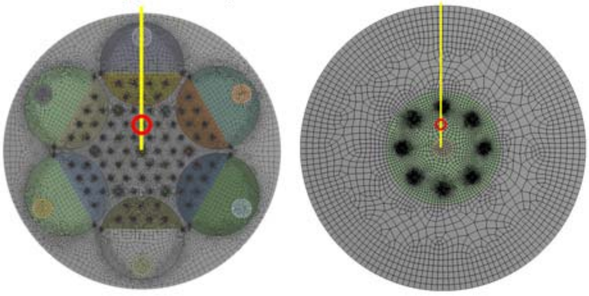
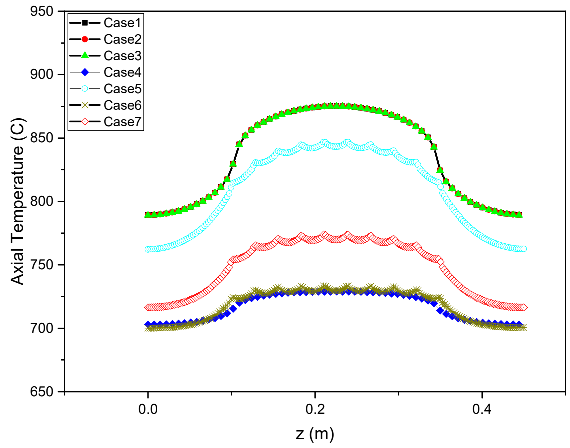
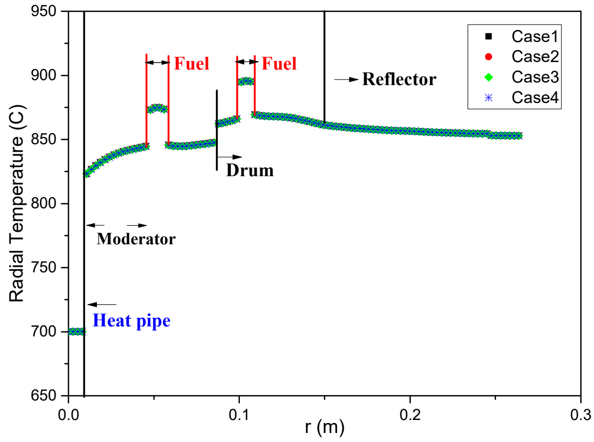


Fig. 4. Temperature plot position

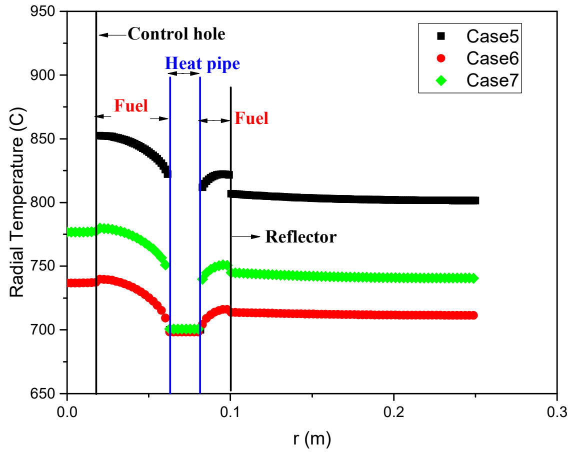
Fig. 5 presents the temperature profile at the position indicated in Fig. 4. The radiative heat transfer depends on the temperature and the distance. However, the gap effect in the present study is negligible due to the very short distance. The existence of a fluid decreases the core maximum temperature more than 150 °C due to thermal conduction. If the gap is filled with air, higher temperature occurs than with helium due to its lower conductivity. The moderator considered in this study is $ZrH_{1.5}$. The hydrogen in the moderator dissociates above 800 °C. Therefore, gap filling would be one solution for operating a space reactor. Alternatively, another material (like ZrY) could be considered as the moderator.



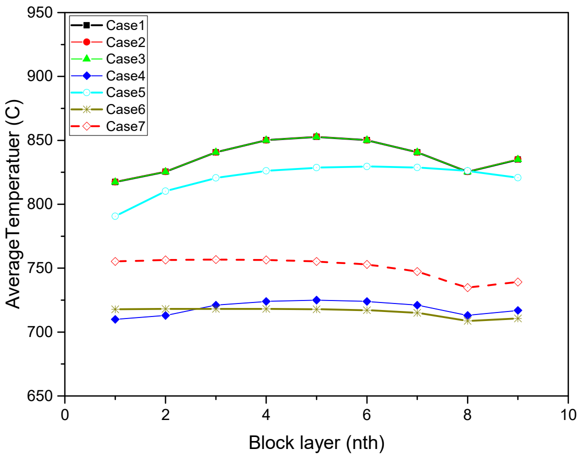
a) Block axial temperature



b) Monolith type radial temperature



c) Plate type radial temperature



d) Moderator block average temperature

Fig. 5. Temperature profile for each case

3. Conclusions

Thermal analysis of several options for a heat-pipe cooled space reactor was conducted in the present study. The core compositions are from calculations based on the neutronics code. Because of the existence of the gap in the block, the heat transfer from the fuel to the heat-pipe is interrupted by a vacuum space. As a result, the moderator temperature approaches the dissociation limit of the moderator material. Filling the gap with a fluid medium reduces the block temperature. If filling with the medium in the space environment is too difficult, an alternative material for the moderator should be considered to operate the reactor safely in space.

Acknowledgements

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