Adjustment of Heat Sink Temperature Distribution to Reduce the Thermal Stress in a Heat Pipe Cooled Microreactor Core

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1. Introduction

The heat pipe cooled microreactor is a reactor that passively removes heat from the core using heat pipes. It has a solid core called 'monolith,' which consists of multiple fuel rods and heat pipes. Heat pipe cooled microreactor's advantages are mobility due to their small size, high system reliability, and safety. Research on heat pipe cooled microreactors such as MegaPower[1], eVinci[2], and Aurora[3] is being actively pursued.

Major concerns of the core design of a heat pipe cooled microreactor are the high thermal stress of monolith and the reactivity feedback due to volume expansion. For the safety analysis and design of the core, a high-fidelity multi-physics simulation tool is needed. Especially, a heat-pipe-thermal-structural coupled analysis code is required.

In the present study, the thermal-structural analysis solver of OpenFOAM and heat pipe thermal analysis code ANLHTP were used for code coupling. Using the coupled code, thermal-structural analysis of heat pipe cooled microreactor core was conducted.

This paper describes the coupled code system and presents the thermal-structural analysis results of the heat pipe cooled microreactor core using the coupled code.

2. OpenFOAM-ANLHTP coupled code system

This section describes each code used for coupling and the coupled code system.

2.1 OpenFOAM

OpenFOAM[4] is an open-source CFD code and provides a basic thermal-structural analysis solver. This solver could calculate temperature, displacement, and the corresponding thermal stress. The governing equations of the thermal-structural analysis solver are shown below.

Momentum equation

$$\frac{\partial^2(\rho u)}{\partial t^2} - \nabla \cdot [\mu \nabla u + \mu(\nabla u)^T + \lambda I tr(\nabla u)] - \nabla(3K\alpha T) = 0 \quad (1)$$

Heat conduction equation

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + q''' \quad (2)$$

This solver has been verified only for simple structural analysis problem that does not consider thermal analysis within the OpenFOAM manual[5]. Therefore, verification was performed on the problem without thermal analysis, confirming that the solver could predict the thermal-structural analysis results well[6].

However, this thermal-structural analysis solver is only applied for a single material, and material properties are used as a constant. For the heat pipe cooled microreactor core analysis, new scalar fields were defined in the solver to classify materials for each cell and to use physical properties as a function of temperature.

The OpenFOAM provides a file-based external coupling boundary condition. However, this boundary condition was only available at the fluid boundary. Therefore, for the coupled code system to analyze the heat pipe cooled microreactor, the boundary condition was modified to be usable at the solid boundary.

2.2 Code coupling system

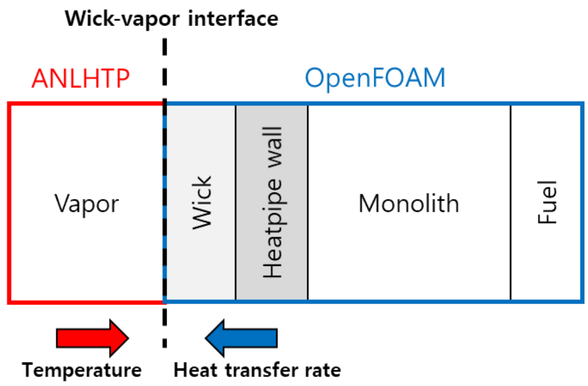

Fig. 1. Data exchange strategy at the wick-vapor interface of heat pipe for the OpenFOAM-ANLHTP code coupling

For the multi-physics analysis of the heat pipe cooled microreactor core, the coupled code system OpenFOAM-ANLHTP was established. OpenFOAM and ANLHTP are externally coupled using a file-based data exchange boundary condition. To analyze the heat pipe cooled microreactor core, the coupled code system must be capable of transient calculation. However, ANLHTP is a steady-state heat pipe analysis code. Moreover, ANLHTP cannot consider axial heat conduction at the heat pipe wall. Therefore, Data exchange was performed at the heat pipe wick-vapor interface to compensate for these shortcomings. Specifically, OpenFOAM provides the heat transfer rate at the interface, and ANLHTP calculates the corresponding temperature with the given heat transfer rate, as shown in Fig. 1. With this methodology, ANLHTP could be used for transient calculation with the 1-D quasi-steady-state[7]. In addition, the temperature of the wick-vapor interface is expected to be the saturation temperature of the heat pipe working fluid, and axial heat conduction at the heat pipe wall is calculated by OpenFOAM.

However, verification of coupled code system is challenging due to the absence of verification data. Therefore, the verification of coupled code system is not included in this paper, and a single heat pipe experiment is being prepared to produce data for code verification.

3. Thermal-structural analysis of the Minicore

This section describes the Minicore and thermal-structural analysis results of the Minicore are described.

3.1 Problem specifications and modeling

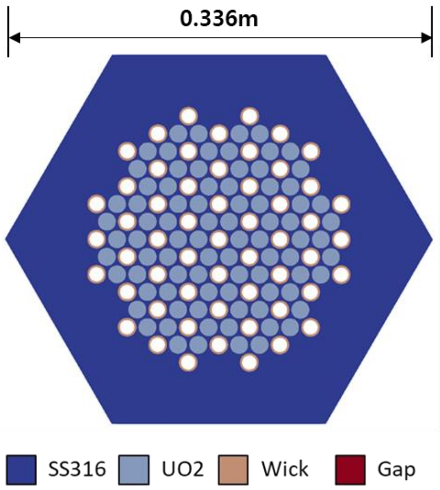

Fig. 2. Geometry of the Minicore

The Minicore was designed by Argonne National Laboratory to perform thermal-neutronics analysis of the heat pipe cooled microreactor core. The height of the Minicore is 1m, and the width is 0.336m. It consists of 84 fuel rods and 55 heat pipes. The geometry of the Minicore is shown in Fig. 2. Specifications such as material composition, fuel enrichment, and size of fuel rods and heat pipes are the same as the MegaPower reactor. However, since ANLHTP could only calculate sodium heat pipe, a sodium heat pipe is assumed.

In terms of reactor core criticality, the Minicore is a subcritical core. Nevertheless, the Minicore could be analyzed with the same thermal-structural arrangement as a critical core of the MegaPower.

For the thermal analysis, constant volumetric heat generation was assumed, and the shape and heat transfer characteristics such as heat sink temperature of all heat pipes are the same. All boundaries except heat pipe wick-vapor interface are adiabatic conditions. The thermal analysis result and free expansion condition were used for the structural analysis.

3.2 Thermal-structural analysis results

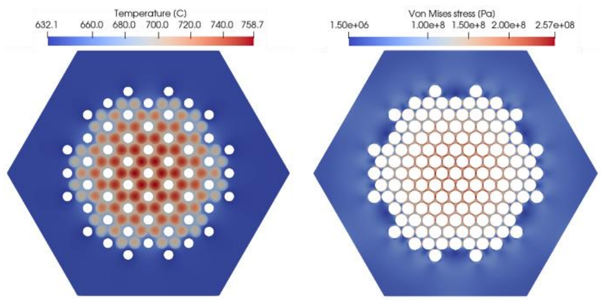

Fig. 3. Thermal-structural analysis results of the Minicore

Fig. 3. shows a thermal-structural analysis result of the Minicore. As a thermal-structural analysis result, the high thermal stress of about 260 MPa appears at the center of the core and exceeds the yield stress of 100MPa of SS316. This is because the Minicore problem was designed only for thermal-neutronics analysis, and structural integrity and thermal stress were not considered during the design process. Specifically, since the extra peripheral monolith has a low temperature compared to the central region, it is estimated that the peripheral monolith obstructs thermal expansion of the central region and induces high thermal stress.

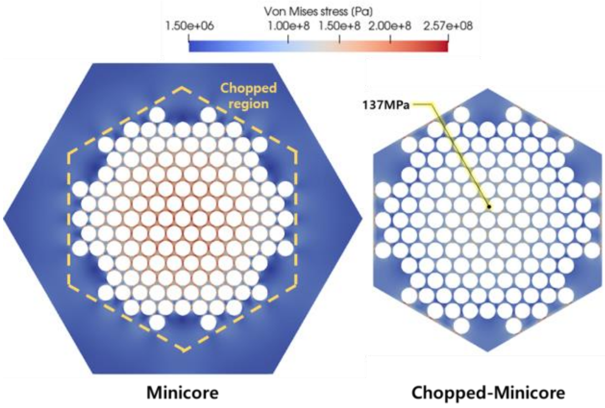

Fig. 4. Comparison of the structural analysis result of the Minicore and the chopped-Minicore

To reduce the excessively high thermal stress, two approaches were taken. The first approach is to remove the peripheral monolith that obstructs thermal expansion. The geometry with the peripheral monolith removed was named ‘chopped-Minicore.’ Then, the same thermal-structural conditions with the Minicore were used to analyze the chopped-Minicore.

Fig. 4. shows the comparison of the structural analysis result of the Minicore and the chopped-Minicore. The peak stress at the central region of the core was reduced to 137 MPa by removing the peripheral monolith. However, this peak stress still exceeds the yield stress of SS316, and additional effort is needed to reduce the stress.

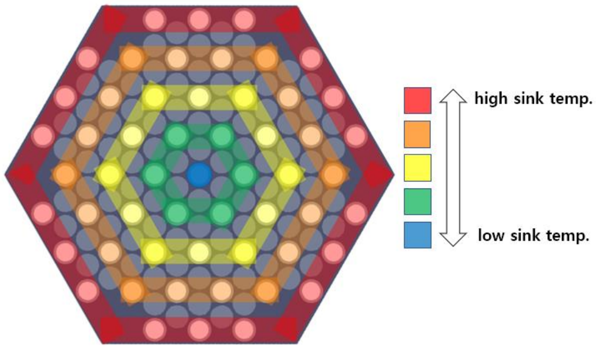

Fig. 5. Heat pipe grouping for adjusting heat sink temperature

The second approach is to control the temperature distribution across the monolith as uniform as possible. For this, the heat pipes were divided into five groups according to their locations, as shown in Fig. 5. The heat pipe sink temperature of each group, corresponding to the heat-pipe-to-heat-exchanger temperature, was set differently. This calculation assumes that the sink temperature of the heat pipes in the peripheral region is higher than in the central region.

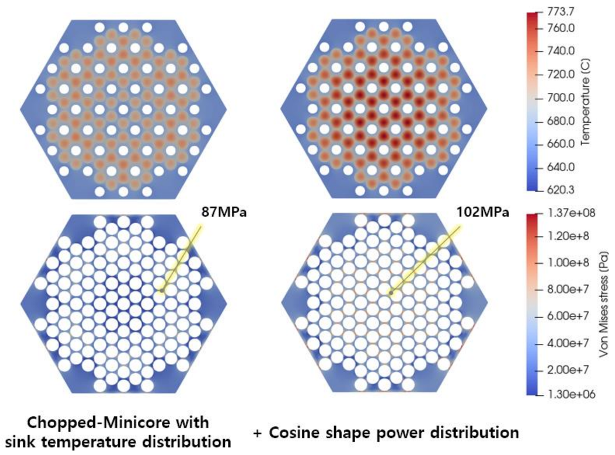

Fig. 6. Thermal-structural analysis of the chopped-Minicore with different heat pipe sink temperature and power distribution

As shown in Fig. 6, the temperature distribution across the monolith is flattened when the sink temperature is adjusted. As a result, the peak stress in the central region is reduced to 87 MPa. In addition, even when the cosine shape power distribution in the axial and lateral direction is applied, which is expected to increase the temperature gradient in the real microreactor, the peak stress of the central region is 102 MPa. It was confirmed that the heat sink of the heat pipe, corresponding to the condition of the microreactor power conversion system, affects the thermal stress of the core. Hence, a multi-physics analysis of the entire microreactor system is necessary to calculate the thermal stress of the core and to optimize the configuration of the heat pipe cooled microreactor core.

4. Conclusions

In this study, the OpenFOAM-ANLHTP code coupling system was established to develop a high-fidelity multi-physics simulation of the heat pipe cooled microreactor. In this process, the OpenFOAM structural analysis solver was improved, and a coupling strategy to compensate for the limitations of ANLHTP was set. Thermal-structural analysis was performed on the Minicore using a coupled code system, and high thermal stress in the core was calculated. A method to reduce thermal stress was proposed by adjusting the geometric shape and controlling the heat sink temperature. In the future, a more accurate multi-physics analysis of the heat pipe cooled microreactor core, including neutronics analysis, will be performed.

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