Thermal analysis of the KRUSTY experiment using OpenFOAM-PRAGMA coupled code with heat pipe thermal analysis module

Myung Jin Jeong [a], Jaeuk Im [a], San Lee [a], Hyoung Kyu Cho [a*]
[a] *Department of Nuclear Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826*
[*]*Corresponding author: chohk@snu.ac.kr*

Keywords: heat pipe, microreactor, multiphysics, thermal-structural analysis, KRUSTY

1. Introduction

Recently, research on microreactors for distributed power grids in remote areas has been actively conducted, and the heat pipe cooled microreactor (HPMR) is gaining attention. The HPMR uses heat pipes to remove heat passively from the reactor core. The HPMR core has a solid core structure called 'monolith', which contains multiple fuel rods and heat pipes. The HPMR has advantages such as good mobility due to its small size, enhanced system reliability and safety, and passive heat removal from the core. Various types of HPMR, such as MegaPower [1], eVinci [2], Aurora [3], and NUSTER-100 [4] are being actively researched.

However, there are some issues with the HPMR core design, such as high thermal stress and reactivity feedback due to the thermal expansion of the solid core. Hence, for the accurate safety analysis and design of the core, a high-fidelity multiphysics simulation tool is needed. In previous research, a coupled code was developed for the multiphysics analysis of the HPMR core, and the demonstration calculation was conducted [5].

In the present study, the analysis of the KRUSTY experiment is conducted for the validation of the OpenFOAM-PRAGMA coupled code with the heat pipe thermal analysis module.

This paper describes the coupled code briefly and presents the multiphysics analysis results of the KRUSTY experiment using the coupled code.

2. OpenFOAM-PRAGMA coupled code

This section describes the OpenFOAM-PRAGMA coupled code with the heat pipe thermal analysis module for the multiphysics analysis of the heat pipe cooled microreactor core.

2.1 Description of codes

OpenFOAM [6] is an open-source based CFD tool, and its official version provides a basic thermal-structural analysis solver. This solver calculates temperature, displacement, and the corresponding thermal stress based on linear elasticity assumption. This solver was modified for the analysis of the HPMR core in the previous research [5].

PRAGMA [7] is a GPU-accelerated continuous energy Monte Carlo neutronics code developed by Seoul National University. PRAGMA has advantages such as fast calculation speed with GPU parallelization and the capability to analyze irregular and complex geometry such as the HPMR core.

The heat pipe thermal analysis module (HP module) is developed based on ANLHTP [8]. ANLHTP is a steady-state heat pipe analysis code for a sodium heat pipe. ANLHTP predicts a heat transfer rate, temperature, and operation limit using a thermal resistance network. However, ANLHTP is written in FORTRAN language and has not been maintained for a long time. Hence, for better coupling with the OpenFOAM-PRAGMA, the HP module has been rewritten in C++ language.

2.2 Coupling strategy

The coupled code used the coupling interface provided by OpenFOAM for external coupling. OpenFOAM sends the heat transfer rate at the boundary to the HP module and the HP module calculates the corresponding temperature. These data are exchanged at the wick-vapor interface of the heat pipe, as shown in Fig. 1. Using this method, the axial temperature distribution of the heat pipe wall could be considered.

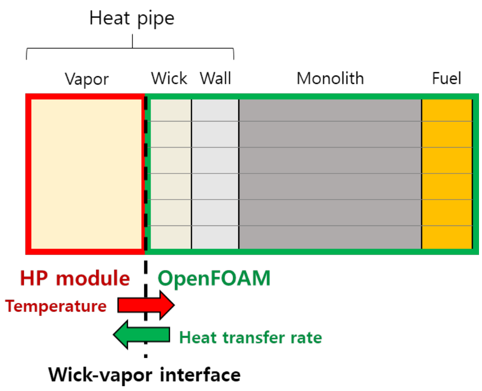

Fig. 1. Data exchange at the wick-vapor interface of heat pipe.

OpenFOAM and PRAGMA perform data exchange for the reactivity feedback due to the thermal expansion. The OpenFOAM sends temperature and density data, and the PRAGMA calculates the power from the received data and sends it to OpenFOAM.

The OpenFOAM-PRAGMA coupled code was established using the Manager-Worker method as shown in Fig. 2 [9]. PRAGMA and OpenFOAM are connected to the worker as a dynamic library, and each worker performs variable exchange through the manager. The wrapper script for the coupling of the OpenFOAM and the HP module is executed in the background by the manager.

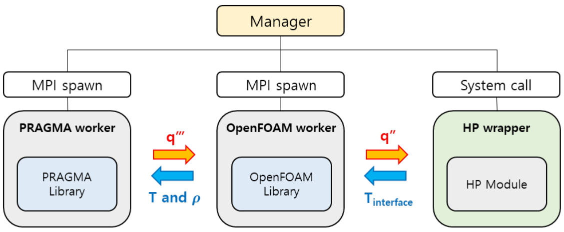

Fig. 2. Manager-worker method of coupled code.

3. Analysis of the KRUSTY experiment

For the validation of the OpenFOAM-PRAGMA coupled code with the HP module, a steady-state analysis of the KRUSTY experiment was performed.

3.1 KRUSTY experiment

The KRUSTY experiment [10] is a reactor design, development, and test program to demonstrate the operation of the Kilopower reactor. The Kilopower system is intended to provide 1-10 kW(e) in space, and KRUSTY is a 1 kW(e) prototype with highly enriched uranium. In March 2018, KRUSTY was successfully operated as a fission power system, with 29 hours of steady-state and various transient operations. The detailed geometry and specifications of the test device are shown in Fig. 3 and Table I below.

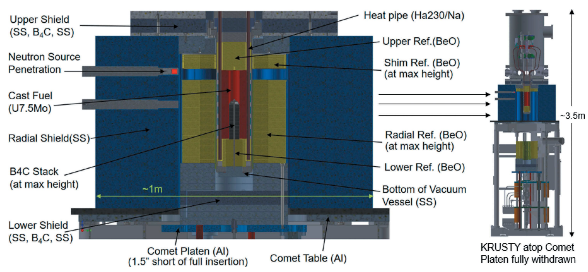

Fig. 3. Geometry of KRUSTY experiment [10].

Table I: Specifications of the KRUSTY experiment

Thermal power	5 kW(th)	HP working fluid	Sodium
Fuel material	U-7.5Mo	# of HPs in core	8
U-235 enrichment	93.1 %	Fuel height	25.0 cm
Fuel OD	11.0 cm	Fuel ID	3.98 cm
Power conversion system	Stirling	Reflector material	BeO

3.2 Analysis conditions

The KRUSTY experiment was modeled as shown in Fig. 4. If only the top/bottom reflector and radial reflector are modeled, the neutron leakage occurs at the height where the radial reflector is not filled. Therefore, all external structures outside the core were modeled to enable accurate neutron tracking. Fig. 5 shows the mesh used in the coupled analysis. For the U-Mo fuel, which is the part most affected by coupled calculation, the average mesh size is 1 mm. In the previous study, the mesh size did not make a significant difference in the simulation results when using 0.5 mm ~ 2 mm size meshes [5].

The heat pipe used in the KRUSTY experiment has a wick only in the evaporator region, and the rest of the heat pipe operates as a thermosyphon. Furthermore, only limited information about the heat pipe is publicly available. Therefore, for the analysis using the HP module, based on the heat pipe performance presented in the reference [11], a heat pipe with similar performance in the corresponding operating temperature range was assumed and simulated. The specifications of the heat pipes are shown in Table II.

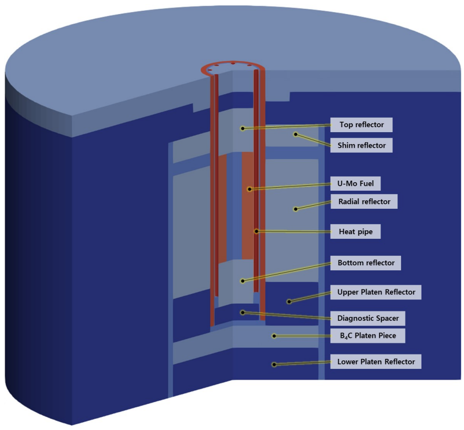

Fig. 4. Modeling of the KRUSTY experiment.

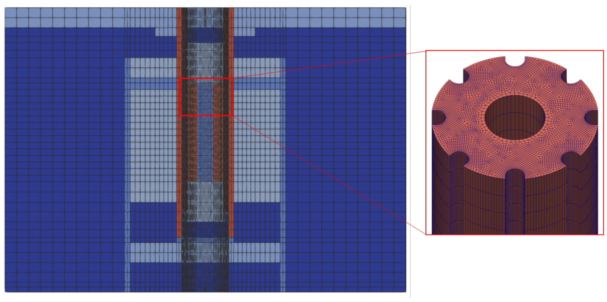

Fig. 5. Calculation mesh of the KRUSTY experiment.

Table II: Specifications of the modeled heat pipe

Working fluid	Sodium	Wall material	Haynes 230
Length	1.0 m	OD	1.27 cm
ID	1.092 cm	Wick type	Screen mesh
Mesh number	#625	Sink temperature	775.0 °C

Steady-state analysis was conducted for the normal operating state of the KRUSTY experiment (7.5 to 8.0 h of experiment), and for the boundary conditions, adiabatic conditions were applied to all boundaries except the heat pipe wall.

3.3 Analysis results

Fig. 6 shows the power and temperature distributions calculated using OpenFOAM-PRAGMA. As shown in the figure, the outer surface of the fuel has a high power density due to the radial reflector. The axial power distribution shows a higher power at the bottom of the fuel. Fig. 7 shows the radial temperature distribution in the mid-plane of the fuel between the reference [10] and this study. The graph is plotted along the black dashed line in Fig. 6, and the temperature prediction result of the OpenFOAM-PRAGMA shows good agreement with the reference.

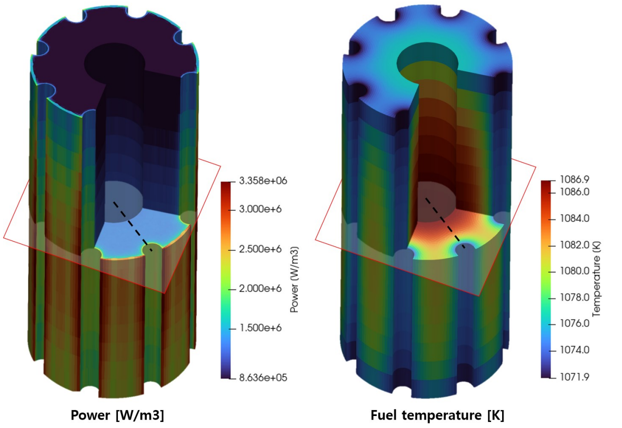

Fig. 6. Calculated power and temperature distribution of the U-Mo fuel.

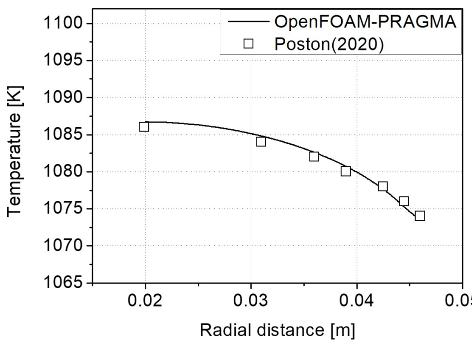

Fig. 7. Radial temperature distribution of the U-Mo fuel at the mid-plane.

4. Conclusions

In this study, the KRUSTY experiment was analyzed to validate the OpenFOAM-PRAGMA coupled code. In the modeling, the outer structures of the KRUSTY experiment were included, and the thermosyphon-operated heat pipes were modeled for the heat pipe analysis module. For the steady-state analysis, the 2.4kW normal operation state of the KRUSTY experiment was analyzed. The analysis results showed the axially bottom peak power distribution and the temperature distribution which is in good agreement with the reference. These results confirm that the OpenFOAM-PRAGMA code has adequate capability for HPMR core analysis. In the future, further validation of the coupled code and development of transient analysis capability will be conducted.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. 2020M2D2A1A0206631723) and the National Research Council of Science & Technology (NST) grant by the Korea government (MSIT) (No. CAP23061-000).

REFERENCES

[1] P. R. Mcclure et al., Design of Megawatt Power Level Heat Pipe Reactors, LA-UR-15-28840, 2015.

[2] M. M. Swartz et al., Westinghouse eVinci™ Heat Pipe Micro Reactor Technology Development, Proceedings of the 2021 28th International Conference on Nuclear Engineering, Virtual, Online, August 4-6, Vol. 85246, p. V001T04A018 (2021).

[3] OKLO Inc., Part II: Final Safety Analysis Report, https://www.nrc.gov/docs/ML2007/ML20075A003.pdf (2020).

[4] S. Tang et al., Thermal-electrical coupling characteristic analysis of the heat pipe cooled reactor with static thermoelectric conversion, Annals of Nuclear Energy (2022).

[5] M. J. Jeong et al., Multiphysics analysis of heat pipe cooled microreactor core with adjusted heat sink temperature for thermal stress reduction using OpenFOAM coupled with neutronics and heat pipe code, Front. Energy Res. 11:1213000, DOI: 10.3389/fenrg.2023.1213000 (2023).

[6] The OpenFOAM Foundation Ltd., OpenFOAM and The OpenFOAM Foundation, OpenFOAM, last modified Dec 4, 2023, accessed Feb 28, 2024, https://openfoam.org.

[7] N. Choi, K. M. Kin, and H. G. Joo, Optimization of Neutron Tracking Algorithms for GPU-based Continuous Energy Monte Carlo Calculation, Annals of Nuclear Energy, 162, no. 108508 (2021).

[8] G. A. McLennan, ANL/HTP: A Computer Code for The Simulation of Heat Pipe Operation, ANL-83-108 (1983), https://digital.library.unt.edu/ark:/67531/metadc283626.

[9] J. Im et al., Multiphysics Analysis System for Heat Pipe Cooled Micro Reactors Employing PRAGMA-OpenFOAM-ANLHTP, Nuclear Science and Engineering, DOI: 10.1080/00295639.2022.2143209 (2023).

[10] D. I. Poston et al., KRUSTY Reactor Design, Nuclear Technology, volume 206, S13-S30, DOI: 10.1080/00295450.2020.1725382, (2020).

[11] D. I. Poston et al., Results of the KRUSTY Nuclear System Test, Nuclear Technology, 206:sup1, S89-S117, DOI: 10.1080/00295450.2020.1730673, (2020).