Preliminary Thermal Analysis of Heat Pipe Cooled Reactor Core using Stress Analysis Solver in OpenFOAM

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1. Introduction

Recently, various concepts of micro reactors were proposed and a heat pipe cooled reactor has been considered as a promising candidate. MegaPower [1], Kilopower [2], eVinci [3], etc. are examples of the heat pipe cooled micro reactors. In this type of a reactor, the fission power is transferred to the power conversion system by heat pipes installed in the monolith core. KRUSTY experiment tested this concept for the space reactor development and its performance was investigated under steady-state and transient conditions [4].

In order to realize this concept of the micro reactor, its performance and safety need to be assured based on a series of experiments and high-fidelity computational tools. In particular, thermo-mechanical analysis is of great importance as the monolith core is operated at high temperature (~1000 K) and the volume expansion of it exerts the reactivity feedback to the core.

In the present study, a preliminary calculation was conducted for the thermo-mechanical analysis of the unit cell of the heat pipe cooled reactor core. The structure analysis solver in OpenFOAM, solidDisplacementFoam, was used and the heat pipe was analyzed using a heat pipe performance analysis code, ANLHTP. The coupling of the OpenFOAM and ANLHTP was established for the simulation.

This paper describes the coupling method between two codes and presents the preliminary analysis results using the OpenFOAM structure solver.

2. Structure analysis solver of OpenFOAM

Open-source software OpenFOAM has become one of the most popular packages in the realm of CFD and multi-physics simulations. The official version of OpenFOAM includes the computational solid mechanics solver named solidDisplacementFoam and more advanced solvers have been developed and opened by its user community [5]. The stress analysis solver in the official versions is the most basic solid mechanics tools, which is restricted to Hookean solids undergoing small strains and rotations. It is a transient segregated finite-volume solver with optional thermal diffusion and thermal stresses. In the present work, the solidDisplacementFoam was selected for the thermo-mechanical analysis because the monolith is expected to show small displacement under normal operating conditions. Using this solver, the temperature distribution and displacement vector were calculated. The governing equations of the thermo-mechanical analysis were shown as below,

<u>Momentum equation</u>

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

<u>Heat conduction equation</u>

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

3. ANLHTP

For thermal analysis of a heat pipe cooled reactor core, a heat pipe code is required, which can evaluate the amount of the heat removed by heat pipes for given conditions. In this study, we selected ANLHTP, which is a one-dimensional heat pipe analysis code developed at ANL in the 1980s. The code was developed to simulate a sodium heat pipe based on theory, analysis, and experimental data presented by Chi [6] and Dunn and Reay [7]. For the simplification, it was assumed that the evaporator and condenser are nearly isothermal (at uniform temperatures) and there is negligible axial heat conduction along the pipe wall or wick. These assumptions allowed the code to calculate the heat transfer rate without solving differential equations of fluid and solid structures.

The simplified calculation procedure of the code is plotted in Fig. 1. In this procedure, the code calculates the thermal resistances at each part of the heat pipe as illustrated in Fig. 2. For the operational limits, empirical correlations for the limiting criteria were implemented and details of the models are summarized in Reference [8].

As ANLHTP was developed to predict heat pipe performance and temperature distributions during steady-state operation, its validity is limited to the steady-state conditions and possibly slow transient conditions. Moreover, it assumes a uniform heat flux distribution in calculating the pressure drops and it may cause errors if the non-uniformity of the heat flux is significant and the pressure drop in the vapor core is considerable with compressibility. Therefore, quantitative analyses for the errors caused by these assumptions are required and further improvements are necessary for the future.

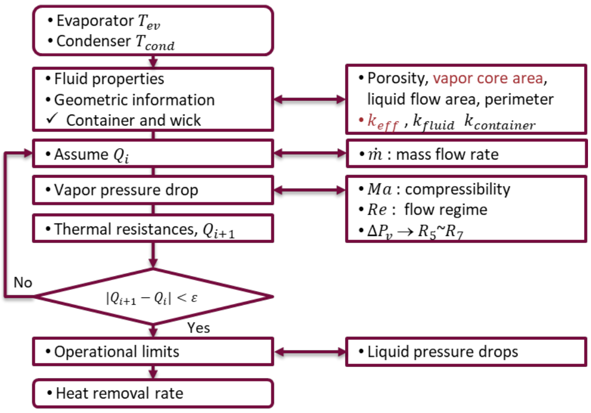


Fig. 1. Simplified calculation procedure of the ANLHTP code.

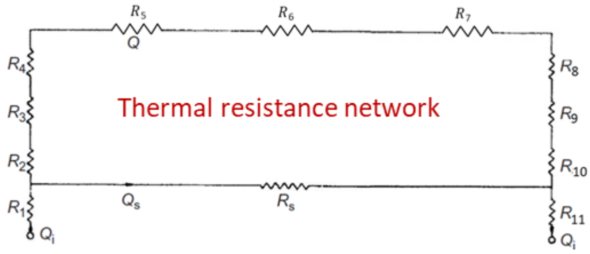


Fig. 2. Thermal resistance network of the ANLHTP code.

4. Coupling of OpenFOAM and ANLHTP

For a thermo-mechanical simulation of micro reactors, OpenFOAM and ANLHTP were coupled together as shown in Fig. 3. These two codes exchange the wall heat flux and wall temperature information. OpenFOAM runs with the wall temperature boundary condition and returns the wall heat flux. ANLHTP receives the wall heat flux and predicts the wall temperature. This exchange is continued until the Picard iteration converges at every time step.

OpenFOAM provides a file-based communication interface to transfer data to and from external codes. The externalCoupled function was applied after customization for the stress analysis solver and the boundary condition on the coupling boundary is updated at every iteration. The data transfer is supervised by a python code. The supervisor code transfers the data between two codes and checks the convergence of the iteration.

The coupling was confirmed using a simple single heat pipe problem. The solid region was modeled as stainless steel and the heat pipe had sodium as a working fluid and a screen wick. Fig. 4 was the geometry of the test problem and the heat pipe had 1.5 m, 1.0 m, and 1.0 m lengths for the evaporator, adiabatic section and the condenser, respectively. The imposed boundary conditions were the constant heat flux condition for the outer face of the solid and the condenser coolant temperature (624.2 K) and its heat transfer coefficient (250 W/K·m^2).

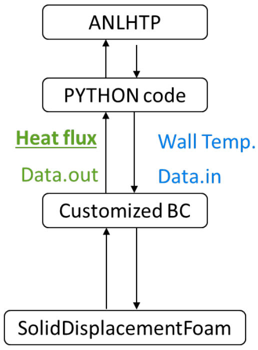


Fig. 3. Data transfer procedure of the ANLHTP-OpenFOAM coupled code.

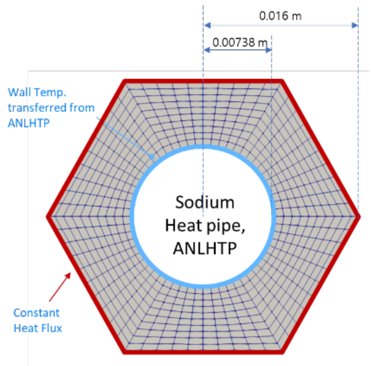
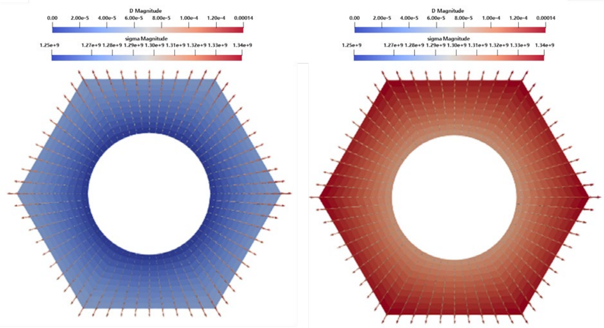


Fig. 4. The Geometry of the test problem.

A transient calculation was conducted using the coupled code. The wall heat flux boundary condition was modified from 32.5 kW/m^2 to 35.0 kW/m^2 after 20 sec. and the calculation was continued until a new steady-state reached. Fig. 5. shows the thermal stress and the displacement vector before and after the heat flux increase. Fig. 6. shows the heat pipe wall temperature during the transient at each Picard iteration. The red lines indicate the end of the Picard iteration after the convergence check. As shown in the figure, the Picard iteration converged about several iterations and the predicted value for the next iteration was determined using a secant method.



Before the transient After the transient

Fig. 5. Thermal stress and displacement vector in the coupled calculation.

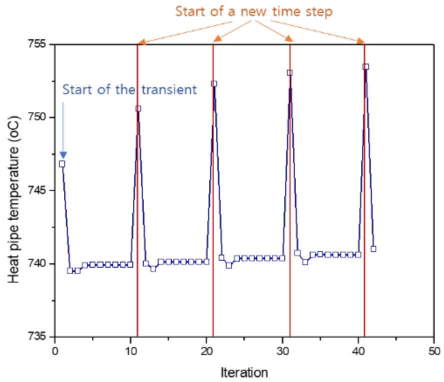


Fig. 6. Heat pipe wall temperature (during the transient) at each Picard iteration.

5. Stand-alone OpenFOAM analysis for a unit cell problem

A preliminary analysis for a unit cell of the heat pipe cooled micro reactor using the stand-alone OpenFOAM solver. Fig. 7 shows the unit cell geometry and mesh for this calculation. It includes six fuel rods and 7 heat pipes. 33,400 prism meshes were used. In this calculation, the heat pipe code was not coupled so that the constant temperature boundary condition of 750°C was imposed. The objective of this stand-alone calculation was to customize the OpenFOAM solver for the micro reactor core simulation. The volumetric heat source of 9.75 MW/m^3 was imposed on the fuel location and a file interface was newly added for this. The material property calculation routine was implemented into the customized code as well.

Fig. 8 and Fig. 9 show the calculation result of the temperature, thermal stress, and displacement vector. It was concluded that the customized OpenFOAM stress analysis solver can be used for the core thermal analysis by confirming the higher temperature in the fuel region and higher thermal stress near the heat pipe where the temperature gradient is large. Moreover, the calculated displacement vector caused by the thermal expansion can be used to estimate the reactivity feedback in a coupled simulation with a reactor physics code.

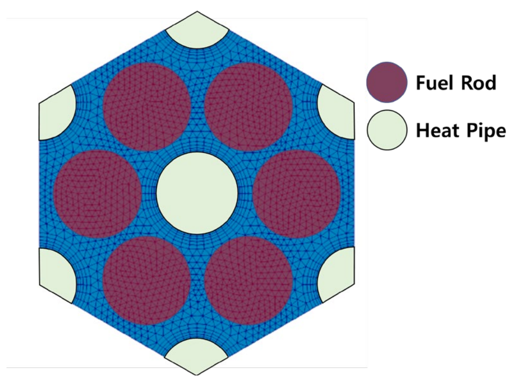


Fig. 7. Unit cell geometry and mesh of the OpenFOAM solver.

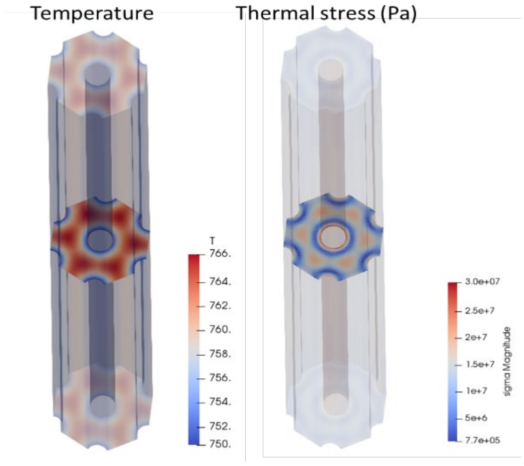


Fig. 8. Calculation result of the temperature and thermal stress for the unit cell problem.

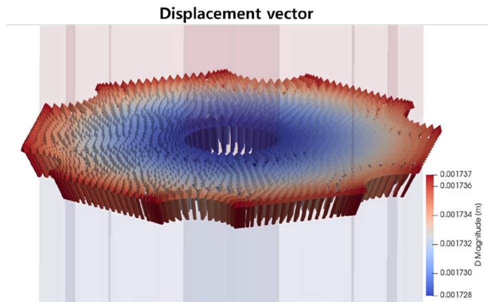


Fig. 9. Calculation result of the displacement vector for the unit cell problem.

6. Conclusion

In this study, a preliminary thermo-mechanical analysis of heat pipe cooled reactor core was performed using an OpenFOAM-ANLHTP coupled code. To confirm the coupled code, the analysis for the single heat pipe test problem was performed. The analysis results showed that the transient calculation using the coupled code was successful. In addition, to customize the OpenFOAM code for the thermo-mechanical analysis, a stand-alone analysis for a unit cell problem was performed. The calculation results showed the temperature, thermal stress, and the thermal expansion expressed with the displacement vector can be analyzed using the customized code. In the future, it is required to couple the OpenFOAM-ANLHTP with a reactor physics code for the multi-physics simulation of a heat pipe cooled reactor core.

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REFERENCES

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

[2] M.A. Gibson et al., NASA's Kilopower Reactor Development and the Path to Higher Power Missions, NASA, 2017.
[3] Westinghouse Global Technology Office, Westinghouse eVinci Micro Reactor, 2019.
[4] D. Palac et al., Kilopower KRUSTY Fission Power Demonstration Update, LA-UR-19-23220, 2019.
[5] P. Cardiff et al., An Open-source Finite Volume Toolbox for Solid Mechanics and Fluid-solid Interaction Simulations, arXiv preprint arXiv:1808.10736, 2018.
[6] S.W. Chi, Heat pipe theory and practice, 1976.
[7] P.D. Dunn, D.A. Reay, The heat pipe, Physics in Technology, Vol. 4, pp. 187, 1973.
[8] G.A. McLennan, ANL/HTP: A-Computer Code for The Simulation of Heat Pipe Operation, ANL-83-108, 1983.