Coupling of FLUENT and ANLHTP for Steady-State Thermal Analysis of a Heat Pipe Cooled Reactor Core

San Lee [a*], Hyoung Kyu Cho [a], Changho Lee [b], Taek K. Kim [b]
[a] *Department of Nuclear Engineering, Seoul National Univ., 1 Gwanak-ro, Gwanak-gu, Seoul 08826*
[b] *Argonne National Laboratory, Nuclear Science & Engineering Dept., 9700 Cass Avenue, Lemont, IL 60439*
[*] *Corresponding author: dgfhio2844@snu.ac.kr*

1. Introduction

Recently, heat pipe cooled reactors, which use heat pipes to transfer heat from the core to the power conversion system, are under development. Since the heat pipe operates with driving forces from phase change and capillary action, it is not required to incorporate devices such as a pump and pressurizer and the reactor system can be simpler, smaller, and more reliable than conventional reactors that use pumped coolant for core cooling [1]. This characteristic is suited for mobile and portable applications, and various designs of heat pipe cooled reactors were proposed, MegaPower [1], Kilopower [2], eVinci [3], etc. Fig. 1. shows an example configuration of the reactor system and core geometry of a heat pipe cooled reactor.

In the case of the heat pipe cooled reactor, heat conduction analysis through the monolith to the heat pipe plays an important role in design and safety analysis. The thermal analysis needs to provide the heat transfer performance of the heat pipes, boundary condition for stress analysis, satisfaction of design criteria and properties of core materials for neutronics analysis.

For this purpose, a methodology for thermal analysis of a heat pipe cooled reactor core was established in this study through the coupled calculation of a heat pipe analysis code and a commercial CFD code. This paper presents a brief introduction of the heat pipe code, coupling method, and demonstration of the coupled simulation for a unit cell of a heat pipe cooled reactor core.

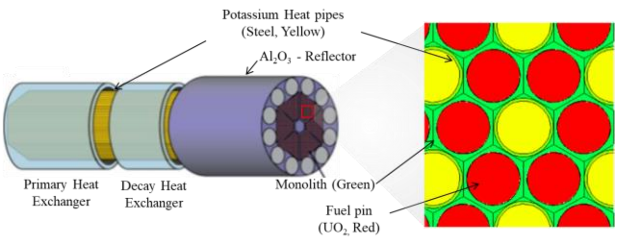


Fig. 1. Example of a heat pipe cooled reactor and its core [1]

2. Code coupling method and Results

2.1 Heat pipe thermal analysis code: 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 [4], which is a one-dimensional heat pipe analysis code developed at Argonne National Laboratory (ANL) in the 1980s. The code was developed to simulate a sodium heat pipe based on theory, analyses, and experimental data presented by Chi [5] and Dunn and Reay [6]. For the simplification, it was assumed that the evaporator and condenser are nearly isothermal (at uniform temperature) 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.

At first, ANLHTP makes an initial guess for the heat transfer rate to solve the non-linear equation. Then, the flow rates in each part of the heat pipe and required thermal resistances are evaluated. With these, the heat transfer rate is updated. Iterations are made until the convergence on the heat transfer is achieved. Then, the code compares the estimated value with five operational limits of a heat pipe including the viscous limit, sonic limit, entrainment limit, boiling limit and capillary limit. The simplified calculation procedure of the code is plotted in Fig. 2.

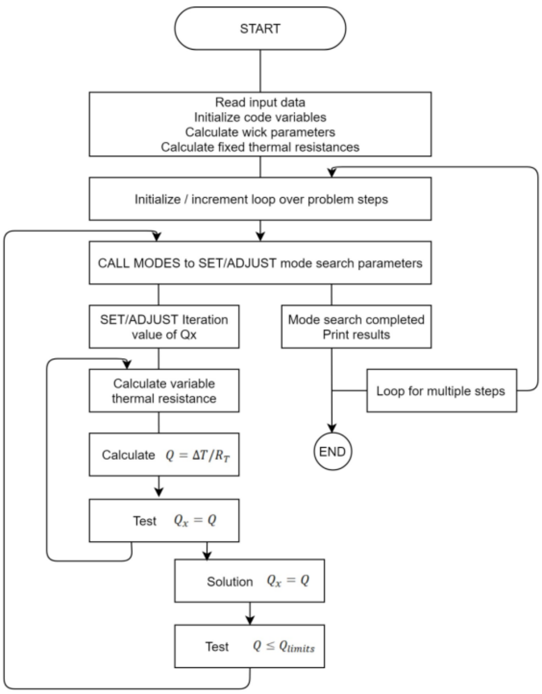
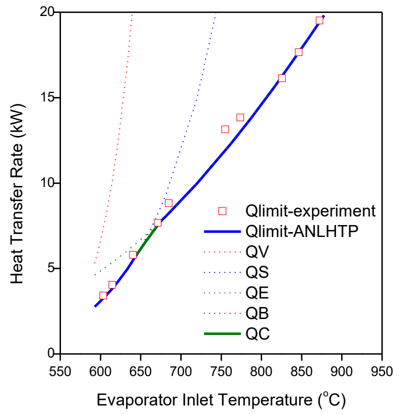
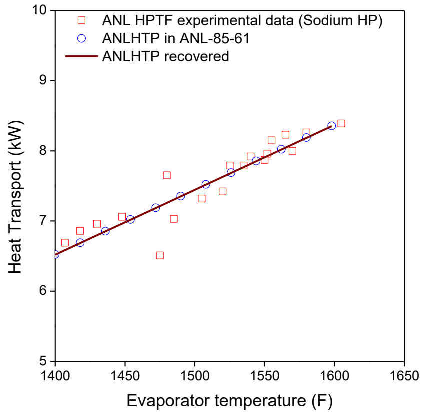


Fig. 2. ANLHTP code structure



a) LASL sodium heat pipe test simulation



(b) ANL HPTF test simulation

Fig. 3. ANLHTP validation result

ANLHTP has been validated against two existing experimental results on sodium heat pipes: one was the operation limit test result conducted at Los Alamos Scientific Laboratory [7] and the other ANL's Heat Pipe Test Facility (HPTF) [8]. For both cases, ANLHTP showed reasonable prediction capability as shown in Fig. 3.

Afterward, the improvement of ANLHTP was proceeded in order to couple it with a commercial code. At first, its robustness was enhanced by removing the discontinuity in physical models when a flow regime inside of a heat pipe undergoes a laminar-turbulent or incompressible-compressible flow transition. Secondly, solid properties for new materials were added for various wick structure modeling. Finally, input and output processes were modified in order to handle the code using script languages such as MATLAB or PYTHON and a script code was written to control the boundary conditions of ANLHTP. This improved ANLHTP and the correspondent scripts were used for the coupled simulation with a commercial code.

2.2 Coupling strategy

For the coupling, we refer to the paper in [9] and write an external script that can control both ANLHTP and a commercial code. ANSYS Fluent was used for the monolith and fuel thermal conduction analysis in the

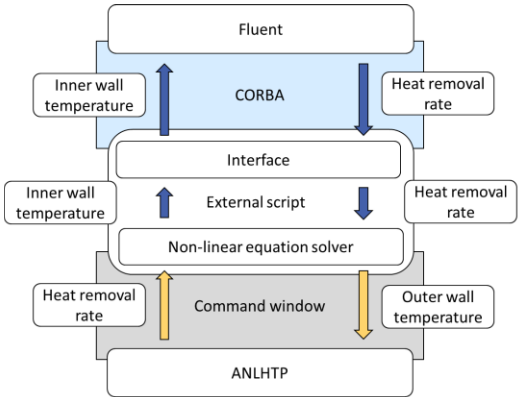


Fig. 4. Fluent/ANLHTP coupling scheme

present study. The coupling scheme is shown in Fig. 4. In the process of the coupling, Fluent and ANLHTP exchange the information of the inner wall temperature and heat removal rate by the heat pipe to determine the temperature distribution of the core.

For the first step calculation, initial guesses are made for the heat pipe inner wall temperatures. The guessed value is transferred to Fluent as a boundary condition by the external script code. With the boundary condition, Fluent produces the temperature distribution in the fuel and monolith and the heat removal rate by the heat pipe can be estimated. The script code receives the heat removal rate and executes ANLHTP. As it requires the outer wall temperature and returns the heat transfer rate as a calculation result, an iterative procedure was implemented in order to find a wall temperature which satisfies the target heat removal rate. If the iteration converges, the heat pipe inner wall temperature is determined and then transferred to Fluent to repeat the calculation with updated boundary condition. This procedure is repeated until the temperature and heat removal rate are converged for both codes.

2.3 Single heat pipe problem

As the first verification of the coupling, a single heat pipe conceptual problem was defined, which is surrounded by monolith and six fuel rods. In this single heat pipe problem, only one iteration step is necessary between the two codes, as all of the heat from the fuel rods is supposed to be removed thoroughly by the heat pipe. Therefore, the objective of this conceptual problem was to confirm the agreement in the heat pipe outer wall temperatures between the two codes and the robustness of the coupling.

The geometry and mesh scheme for this conceptual problem are shown in Fig. 5. The detail dimensions were obtained from the core configuration of MegaPower. 88,260 cells were used with 30 extrusion layers in the axial direction. A cosine shape power distribution was applied for the core region, which was obtained from a neutron transport code, PROTEUS [10]. The total power was 4680 W. The material properties of

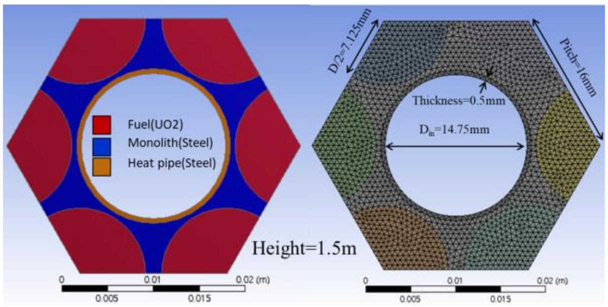


Fig. 5. Geometry and mesh scheme of single heat pipe problem.

uranium dioxide and stainless steel are evaluated using consistent models with PROTEUS and ANLHTP, respectively.

The calculated temperature distribution are shown in Fig. 6. The result shows that temperature distribution was calculated according to the cosine shaped power distribution. The calculated outer wall temperature from ANLHTP was compared with the area averaged temperature along the heat pipe outer wall in Fluent. The resulting ANLHTP and Fluent temperatures are 906.55 K and 906.56 K, respectively, and satisfactory energy conservation between the two codes was verified.

2.4 Multi-heat pipe problem

Applying the same method, a multiple heat pipe problem was simulated. In this conceptual problem, total seven heat pipes surrounds six fuel rods, of which powers are different from each other. In this situation, the heat removal rates by each heat pipe cannot be pre-determined and should be determined during the iterative procedure coupled with ANLHTP and Fluent. Thus, the objective of this problem was to confirm the convergence of the iteration.

The mesh and geometry used in the calculation for seven heat pipes are shown in Fig. 7. 111,180 cells were used with 30 axial layers for the monolith and fuel rods. The total power was 14,215 W and ~1.4% lower power was applied to the fuel rods 2 and 5 in order to generate asymmetric temperature distributions. The power ratio of the rods given in Fig. 6.

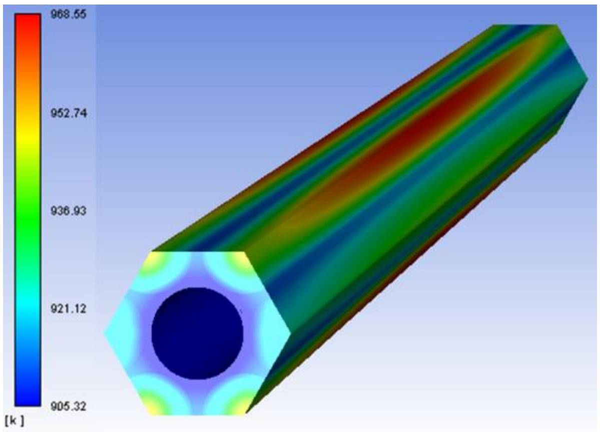


Fig. 6. Temperature distribution for single heat pipe problem

The calculated temperature distribution after convergence and the converging trend of the heat pipe inner wall temperature are shown in Fig. 8 and Fig. 9, respectively. As shown in Fig. 8, it was confirmed that the wall temperature of each heat pipe converged successfully. Moreover, the results clearly indicated that the closer the heat pipes are to the higher power fuel rods, the higher heat pipe wall temperatures they have. From these analysis results, it was verified that ANLHTP and Fluent were coupled successfully and can be used for the thermal analysis of the heat pipe cooled reactor core.

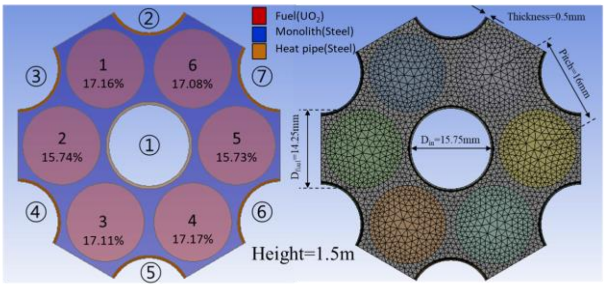


Fig. 7. Geometry and mesh scheme of multi-heat pipe problem.

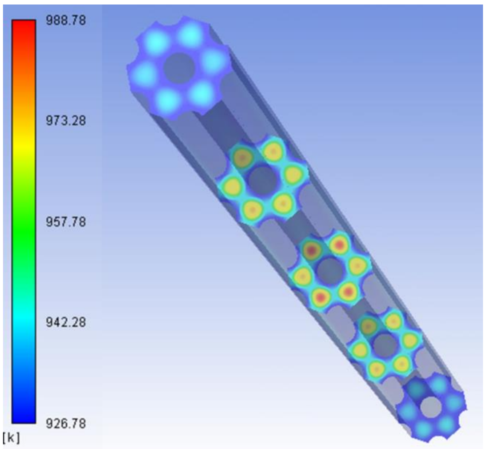


Fig. 8. The temperature distribution of multi-heat pipe problem

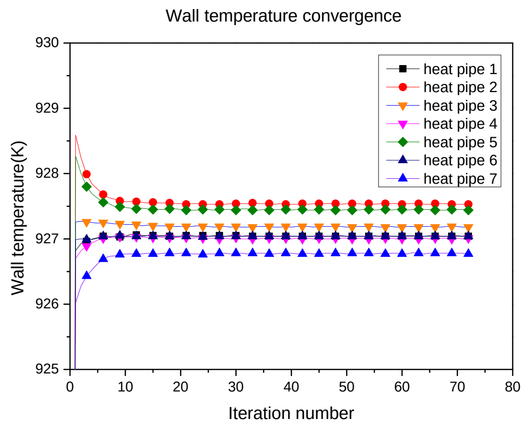


Fig. 9. Heat pipe wall temperature convergence result of multi-heat pipe problem

3. Conclusions

In this study, the coupling between ANLHTP for calculating the heat pipe thermal performance and Fluent for calculating the total core temperature distribution is performed for the thermal analysis of the heat pipe reactor core. The coupled calculation results converged successfully.

For more realistic thermal analysis of the core, coupling with the neutronics code PROTEUS will be carried out in the further study. If the coupling with the three codes is completed, the code package can be a useful tool for design and safety analysis of a heat pipe cooled reactor.

ACKNOWLEDGMENTS

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