

Preliminary thermal analysis of a heat pipe-cooled reactor core using MARS-KS.

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1. Introduction

States around the world, faced with rapidly increasing energy demand, are developing and commercializing various Small Modular Reactors (SMRs) and Micro Modular Reactors (MMRs) [1, 2]. Among these advanced reactors, the heat pipe-cooled reactor (HPR) has attracted considerable attention, particularly following the successful experiment of the KRUSTY reactor by LANL in 2018 [3].

The HPR core consists of a solid structure called a monolith, multiple fuel rods, and heat pipes. HPR has several advantages, including enhanced safety, compactness, and transportability, achieved by passively removing heat from the reactor core using heat pipes. However, in the HPR core, high thermal stress due to the high temperature gradient in a narrow region and reactivity feedback due to the thermal expansion of the solid structure could be expected. To evaluate the safety of the HPR core, multiphysics analysis including structural mechanics, thermal, and neutronics analysis is required to account for these phenomena.

Accordingly, various research institutions are developing multiphysics analysis tools. U.S. NRC introduced the BlueCRAB framework for multiphysics analysis of non-LWR-type reactors, including HPR [4]. Korea Atomic Energy Research Institute (KAERI) developed McCARD-HEPITOS-LUHPIS-LuNAS multi physics analysis code for space HPR analysis [5]. Seoul National University (SNU) developed the OpenFOAM-PRAGMA-ANLHTP coupled code for thermal-structural analysis of HPR core [6].

However, existing high-fidelity multiphysics analysis tools for HPR require high computational costs and long computation times. As a result, it is difficult to simulate the entire HPR system or perform analysis under various conditions. As an alternative, a method using relatively simple system analysis code for modeling the HPR core and system is proposed.

In this study, the analysis capability of a system-scale code for HPR core thermal analysis and its extension to system analysis is considered.

This paper presents a methodology for the preliminary thermal analysis of an HPR using MARS-KS and performs a code-to-code comparison with a coupled OpenFOAM-ANLHTP analysis framework.

2. Analysis tool

2.1 MARS-KS

MARS-KS is a 1-D system thermal-hydraulic code developed for LWR system analysis and is based on mass, momentum, and energy conservation equations. The heat structure model of MARS-KS can simulate 2-D heat conduction within a limited predefined geometry [7].

The core of a heat pipe cooled reactor typically consists of multiple fuel rods and heat pipes arranged in a regular pattern, as shown in Fig. 1.

However, MARS-KS has limited capability for directly representing the complex geometry of the HPR core. Hence, the HPR unit cell is transformed into a volume-equivalent cylindrical geometry, as illustrated in Fig. 2. The resulting cylindrical geometry is then modeled in MARS-KS using the heat structure, as shown in Fig. 3.

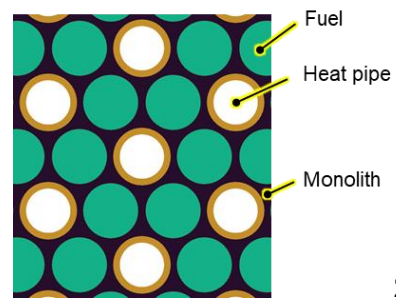


Figure 1. Schematic of a heat pipe reactor core

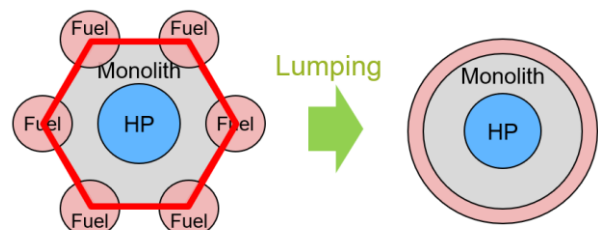


Figure 2. Volume-equivalent geometric transformation of HPR unit cell

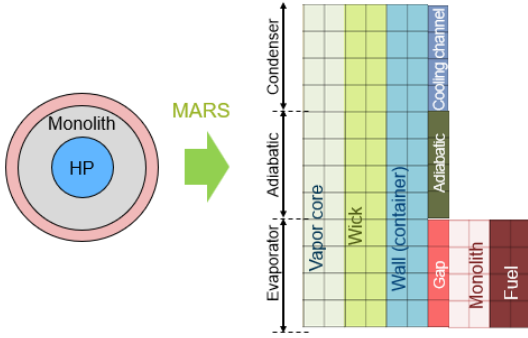


Figure 3. HPR Unit cell modeling in MARS-KS

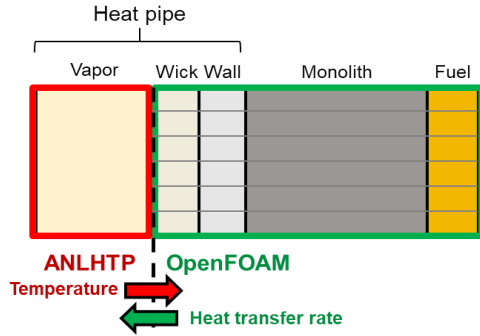


Figure 4. Coupling scheme of the OpenFOAM-ANLHTP model

In this approach, the heat pipe, monolith, and fuel regions are transformed into a cylindrical heat structure while preserving the volume of each region. To compensate for the change in conduction heat transfer characteristics caused by the geometric transformation, the equivalent thermal conductivity was defined using geometric correction factors defined in eq. (1) ~ (2) [8]. Since both the monolith and the heat pipe are modeled as heat structures, a fluid component is required between the heat structures. Hence, a virtual air gap region is introduced between them with a sufficiently high heat transfer coefficient. Heat transfer through the heat pipe vapor region is modeled using temperature-dependent effective thermal conductivity obtained from the ANLHTP. The calculated values are implemented in MARS-KS as a property table.

$$\lambda'_f = k_f \lambda_f \quad (1)$$

$$k_f = \frac{2r_{f,o}^2 \ln\left(\frac{r_{f,o}}{r_{f,i}}\right) - (r_{f,o}^2 - r_{f,i}^2)}{r_f^2} \quad (2)$$

Where λ is the thermal conductivity, λ' is the equivalent thermal conductivity and k is the geometry correction factor. The subscripts r and f denote the radius and fuel whereas, the subscripts o and i denote the outer and inner boundaries.

2.2 OpenFOAM-ANLHTP

In this study, the coupled code is used for code-to-code validation of the MARS-KS HPR core model. OpenFOAM-ANLHTP is developed at SNU for the thermal-structural analysis of the HPR core, as shown in Fig. 4. OpenFOAM [9] is an open-source CFD software package, and it includes a basic thermal-structural analysis solver.

ANLHTP is a heat pipe thermal analysis code developed by Argonne National Laboratory (ANL) to predict the heat transfer capability and operating limits of sodium heat pipes using a thermal network [10]. The source code of ANLHTP is publicly available; the code was reconstructed at SNU.

OpenFOAM conducts 3D heat conduction analysis for the original unit cell geometry, and ANLHTP provides boundary conditions to OpenFOAM. During the calculation, because ANLHTP could not consider axial heat transfer through the heat pipe outer wall, the heat transfer rate and temperature are exchanged at the wick-vapor interface of the heat pipe. The axial temperature of the vapor core is calculated at four locations: the start and end of the evaporator and the start and end of the condenser. Temperatures at the intermediate nodes are obtained by linear interpolation. These interpolated temperatures are applied as boundary conditions during the coupled OpenFOAM-ANLHTP calculations.

3. Code-to-code validation

3.1 Modeling of SNU single HP experimental facility

To conduct code-to-code validation, the SNU single heat pipe experimental facility was modeled using MARS-KS and OpenFOAM-ANLHTP. The experimental facility consists of a hexagonal SS316 heating block, an electrical heater, a sodium heat pipe, and an air-cooling system, as shown in Fig. 5. The specifications of the facility and heat pipe are listed in Table 1 [11].

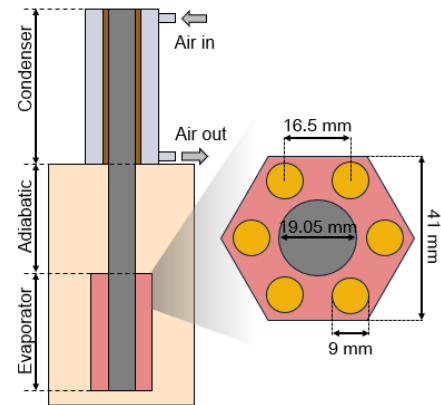


Figure 5. Schematic of SNU single heat pipe experimental facility

Table 1. Specifications of SNU single heat pipe experimental facility

Parameter	Value
Evaporator length (mm)	300
Adiabatic length (mm)	300
Condenser length (mm)	400
Vapor core radius (mm)	5.85
Wick thickness (mm)	1.575
Container thickness (mm)	2.1
Heater thermal conductivity (W/mK)	24 (Inconel 600)
Heating block/container thermal conductivity (W/mK)	22.4 (SS316)
Wick thermal conductivity (W/mK)	41.2 (SS316/Na)
Heat source (W)	600
Heat sink temperature (°C)	$T_c=45$
Heat sink heat transfer Coefficient (W/m ² K)	$h=45$

Fig. 5 shows the geometry of the single heat pipe experimental facility, and Table 1 summarizes the main geometric and operating conditions [11].

The nodalization of the experimental facility in MARS-KS is illustrated in Fig. 6. Each section of the heat pipe is modeled with 15 axial nodes. The adiabatic section was modeled by connecting the heat structure to a dummy stagnant volume using heat transfer package 101 without an external cooling condition. In the condenser section, the air-cooling channel was modeled with a convective boundary condition using the average air temperature and heat transfer coefficient from the experimental results.

In OpenFOAM-ANLHTP modeling, the original experimental facility geometry was modeled with 100 axial nodes. The total computational mesh number in OpenFOAM is about 24k, and the mesh is shown in Fig. 7. The adiabatic section and condenser section were modeled using insulated boundary conditions and a convection boundary condition, the same as in MARS-KS modeling.

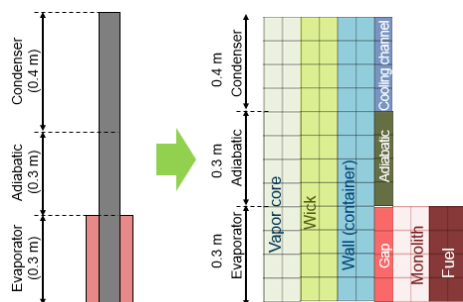


Figure 6. MARS-KS modeling of the SNU single heat pipe experimental facility

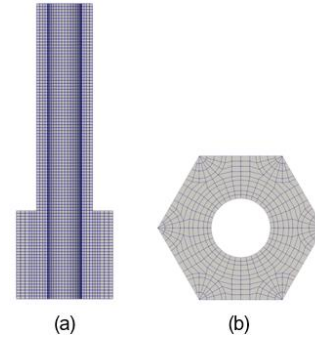


Figure 7. OpenFOAM mesh of the SNU single heat pipe model: (a) axial and (b) cross-sectional views

In both MARS-KS and OpenFOAM modeling, the heater is modeled with a uniform volumetric heat source, and a steady-state analysis was conducted.

3.2 Analysis results

Fig. 8 and Fig. 9 show the axial temperature distribution of the vapor core and the heat pipe outer wall. As shown in Fig. 8, both MARS-KS and OpenFOAM-ANLHTP models predicted similar axial temperature profiles in the vapor core. The overall temperature levels were similar, with a maximum difference of approximately 2°C in the evaporator section. In MARS-KS, the temperature-dependent effective thermal conductivity obtained from ANLHTP is implemented as a tabulated property. However, ANLHTP calculates spatially varying inertial and frictional pressure drops for each heat pipe section, whereas spatially averaged values are used in the MARS-KS model. This difference is considered to contribute to the observed differences in the axial temperature-gradient trends.

Outer wall temperatures predicted by the two codes are also in good agreement, as shown in Fig. 9. The temperature was higher in the evaporator section and gradually decreased toward the condenser section. At the boundaries between the regions, the MARS-KS temperature profile changes more gradually than the OpenFOAM-ANLHTP result.

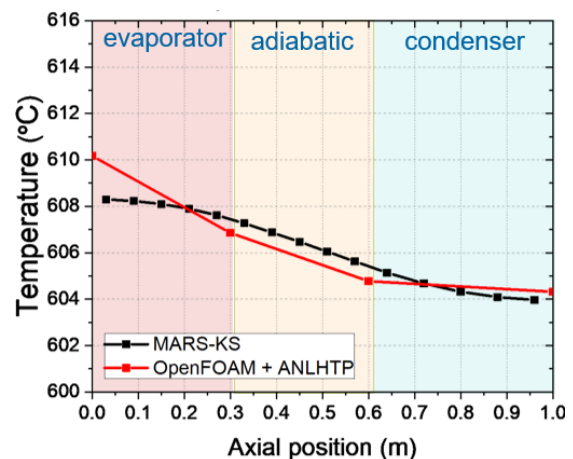


Figure 8. Axial temperature distribution (Vapor core)

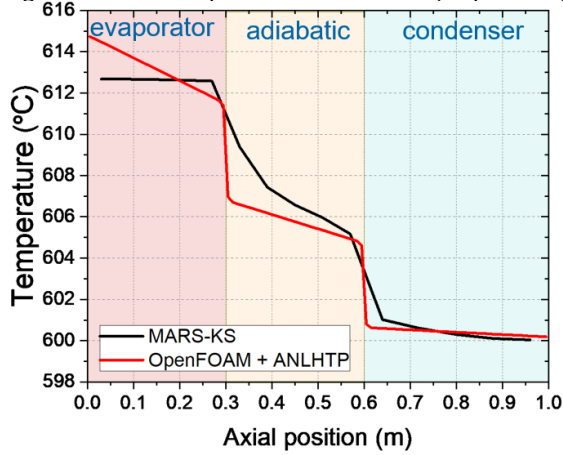


Figure 9. Axial temperature distribution (outer wall)

The local effective thermal conductivity varies with the local heat transfer conditions and is not solely a function of temperature. However, in the MARS-KS model, it is applied only as a function of temperature, resulting in discrepancies in the axial temperature distributions of the vapor core and heat pipe outer wall. The relatively coarse axial mesh also smooths the temperature changes near the section boundaries. Nevertheless, MARS-KS reasonably reproduces the overall axial temperature distribution of the heat pipe.

Fig. 10 shows the radial temperature distribution at $z=0.15$ m, which is the middle height of the evaporator section. The colored map indicates each region of the modeled geometry in MARS-KS. Both models showed a consistent radial temperature trend, as shown in Fig. 10.

The continuous temperature distribution across the heat pipe wall and monolith indicates that the virtual gap in MARS-KS can simulate heat transfer between the wall and the monolith wall. Because MARS-KS used simplified geometry, the temperature distribution of MARS-KS and OpenFOAM-ANLHTP cannot be compared directly.

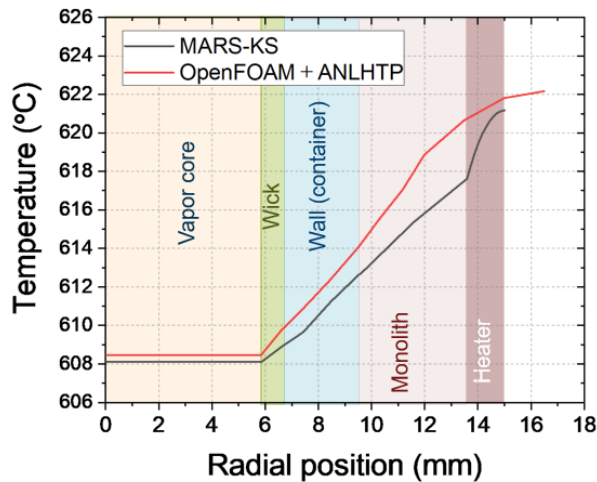


Figure 10. Radial temperature distribution ($z = 0.15$ m)

Table 2. Radial temperature rises ($z = 0.15$ m)

Region	OpenFOAM	MARS-KS	Diff.
Vapor-wall (°C)	5.64	4.55	-1.09
Wall-heater (°C)	4.78	4.97	+0.19
Across heater (°C)	3.28	3.32	+0.04
Total ΔT (°C)	13.70	12.84	-0.86

However, the two models predicted nearly identical heat pipe wall temperatures and heat removal rates at 600 W, with differences in the major temperature parameters of less than 1.09 °C. These results indicate that MARS-KS reasonably reproduced the overall heat transfer behavior between the heat pipe and monolith.

The radial temperature distributions in Fig. 10 show similar trends. Although the MARS-KS model uses a volume-equivalent geometry, the temperature rises across each region are similar to those predicted by the OpenFOAM-ANLHTP model, with differences of up to 1.09°C, as shown in Table 2. The offset between the two radial temperature profiles is mainly attributed to the difference in vapor temperature at $z = 0.15$ m, as shown in Fig. 8.

Table 3 shows a comparison of thermal analysis results of MARS-KS and OpenFOAM-ANLHTP. Differences in average temperature of the heat pipe wall and vapor regions were within 0.5°C. In comparison, the maximum heater temperature difference was 1.22°C, which mainly resulted from the vapor temperature difference at $z = 0.15$ m, with an additional contribution from the volume-equivalent geometry. Therefore, an improved effective thermal conductivity model considering the local heat transfer conditions is expected to reduce the temperature differences.

Table 3. Code-to-code validation results

Parameter	OpenFOAM	MARS-KS	Diff.
Heater max. temp. (°C)	622.16	620.94	-1.22
Wall(evap.) temp. (°C)	613.14	612.64	-0.50
Wall(cond.) temp. (°C)	600.415	600.415	0.00
Vapor(avg.) temp. (°C)	606.50	606.12	-0.38
Heat removal rate (W)	600.00	600.00	<0.01

4. Conclusions

In this study, preliminary thermal analysis was conducted for the evaluation of the analysis capability of system-scale code for the HPR core. The 1-D system thermal-hydraulic code MARS-KS was used for thermal analysis of the HPR core. For MARS-KS modeling, the HPR unit cell geometry was modeled using heat structure. In this process, the original unit cell geometry was simplified to a volume-equivalent cylindrical geometry with a geometry correction factor.

Following this, code-to-code validation with OpenFOAM-ANLHTP was performed. The SNU single heat pipe experimental facility was analyzed using both codes, and the axial and radial temperature distributions were compared. The differences in the average temperatures of the heat pipe wall and vapor regions were within 0.5°C, and the heat removal rates predicted by both models were identical at 600 W. The maximum heater temperature difference was 1.22°C; the temperature-rise differences in the wall-to-heater and across-heater regions were within 0.2°C, whereas the vapor-to-wall region showed a difference of 1.09°C.

In this study, only steady-state analysis of the HPR unit cell was conducted as a preliminary analysis. In future work, the HPR unit cell model in MARS-KS could be expanded to multi-cell or full-core analysis. Additionally, further expansion to system-level transient analysis, including the heat exchanger and power conversion unit, could be conducted for the safety analysis of the entire HPR system.

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