

## Preliminary Development of a Multidimensional Thermal Network Analysis Code for the rHPMR Core under Steady-State Conditions

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### 1. Introduction

Heat-pipe-cooled microreactors use embedded heat pipes to transport fission heat from a solid reactor core to an external heat-rejection system. Their compact scale, passive heat-transport capability, and potential suitability for remote or constrained applications have motivated broad development and analysis efforts [1-4]. In a heat-pipe microreactor core, fuel compacts and heat pipes are distributed within a heterogeneous solid structure, so generated heat can spread through several lateral paths within a layer and redistribute axially before reaching a heat pipe. The core thermal response therefore depends on local generation, the connectivity and directional resistance of the solid-conduction network, transfer across the solid-to-heat-pipe interfaces, and heat removal by the heat pipes.

Detailed multiphysics and computational fluid dynamics models can resolve local temperature fields and provide high-fidelity reference information for design assessment [2,3]. However, their large spatial systems and coupled physics make repeated whole-core calculations burdensome during design iterations, sensitivity studies, or the evaluation of many operating conditions. One-dimensional or spatially uniform representations may reduce this burden but do not retain all lateral and axial pathways created by the heterogeneous core arrangement. A reduced model that preserves the dominant multidimensional solid-conduction mechanisms at lower spatial resolution is therefore useful as a complement to detailed analysis.

Three-dimensional thermal-network methods have previously been applied to prismatic reactor cores [5]. Related reduced thermal modules have been developed for other reactor systems [6]. These approaches replace the detailed field within a coarse cell by network temperature variables and directional conductances. Material heterogeneity within a computational cell can be represented by an effective thermal conductivity (ETC), and direction-dependent ETC models are particularly relevant when the unresolved constituent arrangement has different transverse and axial heat-transfer characteristics [7].

The thermal-network concept and ETC methodology are not introduced anew in this study. Instead, the present work focuses on preliminary development and

application of an established multidimensional thermal-network framework to a realistic heat-pipe-cooled microreactor (rHPMR) core. The implementation combines automatic cell connectivity, directional ETCs for heterogeneous thermal-network cells, and a simplified lumped-parameter heat-pipe model. It is examined with an independently discretized three-dimensional solidFoam benchmark, applied to a 5-MW rHPMR core model, and quantitatively compared with detailed OpenFOAM temperatures volume-averaged for corresponding thermal-network cells. This sequence assesses whether the reduced formulation retains benchmark conduction behavior and the principal whole-core temperature trends.

### 2. Thermal Network Analysis Method

#### 2.1 Thermal Network Formulation

Fig. 1 illustrates the thermal-network representation of lateral heat transfer between adjacent cells and axial heat transfer between axially aligned cells. The conductive heat rate  $q_{ij}$  and equivalent intercell thermal conductance  $G_{ij}$  between cells  $i$  and  $j$  are

$$q_{ij} = G_{ij}(T_i - T_j) \quad (1)$$

$$G_{ij} = \left[ \frac{d_i}{k_i A_{ij}} + \frac{d_j}{k_j A_{ij}} \right]^{-1} \quad (2)$$

where  $A_{ij}$  is the common-face area,  $d_i$  and  $d_j$  are the normal distances from the cell centroids to that face, and  $k_i$  and  $k_j$  are the conductivities in the heat-transfer direction. The series-resistance form is used for both lateral and axial intercell thermal connections. Lateral connectivity is obtained from shared cell boundaries, whereas axially aligned cross-sectional cells define the axial thermal connections. Exterior faces without a prescribed heat flux do not contribute an external thermal connection. This formulation represents multidimensional solid heat transfer at the thermal-network cell level, while constituent effects enter through directional properties rather than additional material-temperature unknowns. Accordingly, each thermal-network cell temperature is coupled laterally and axially through these conductances. The directional ETC

treatment introduced next therefore enters through the intercell conductances rather than through additional constituent-temperature equations.

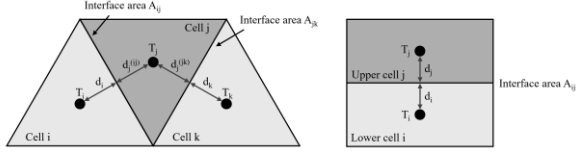


Fig. 1. Lateral and axial heat conduction between thermal-network cells.

## 2.2 Effective Thermal Conductivity

A thermal-network cell may contain multiple material constituents that are not assigned separate temperature unknowns. Their fractions and thermal conductivities are combined using a directional ETC. The axial conductivity  $k_{eff,z}$  is evaluated with a parallel rule, while the transverse conductivity  $k_{eff,r}$  is described by a graphite-matrix Maxwell-type formulation. This directional homogenization follows prior ETC treatment for heterogeneous graphite blocks [7].

$$k_{eff,z}(T) = \sum_l f_l k_l(T) \quad (3)$$

$$\Phi(T) = \sum_{l \neq g} f_l \frac{k_g(T) - k_l(T)}{k_g(T) + k_l(T)} \quad (4)$$

$$k_{eff,r}(T) = k_g(T) \frac{1 - \Phi(T)}{1 + \Phi(T)} \quad (5)$$

Here,  $f_l$  and  $k_l$  are the fraction and conductivity of constituent  $l$ ,  $g$  denotes the graphite matrix, and  $\Phi$  is the aggregate contribution of non-graphite constituents. The constituent conductivity models used in this reduced representation were adopted from the material-property models used in the detailed OpenFOAM reference analysis [8]. The temperature-dependent constituent conductivities and resulting directional ETCs are updated using the current cell temperatures during each nonlinear iteration.

## 2.3 Heat-Pipe Model

The simplified lumped-parameter heat-pipe model adopted in the thermal-network analysis is illustrated in Fig. 2. Each physical heat pipe (HP) is represented by one representative temperature variable  $T_{HP,m}$ . Heat transferred from the associated solid cells is summed and balanced by a prescribed temperature-dependent heat-pipe heat-removal relation. The detailed internal two-phase behavior is not spatially resolved in the present reduced model.

For a solid cell, the steady-state balance includes thermal connections to neighboring solid cells and to any associated heat pipe, together with the prescribed volumetric source  $Q_{gen,i}$ . The corresponding solid-cell and heat-pipe balances are

$$\sum_j G_{ij} (T_i - T_j) + \sum_m G_{i,m} (T_i - T_{HP,m}) = Q_{gen,i} \quad (6)$$

$$\sum_i G_{i,m} (T_i - T_{HP,m}) = Q_{HP,m}(T_{HP,m}) \quad (7)$$

The temperature-dependent heat-pipe heat-removal relation  $Q_{HP,m}(T_{HP,m})$  was prescribed for each heat pipe. The temperature unknowns comprise the solid-cell and heat-pipe temperatures. The resulting nonlinear algebraic system was solved iteratively until convergence. Material properties, directional ETCs, and thermal conductances were reevaluated using the current temperature field.

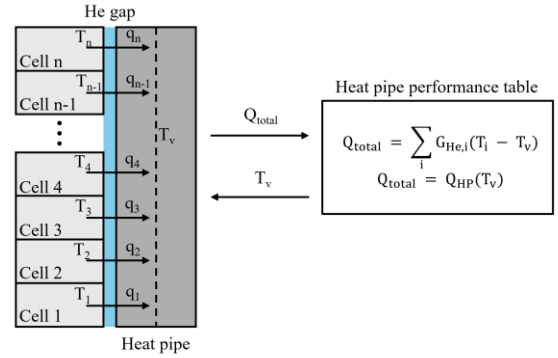


Fig. 2. Simplified lumped-parameter heat-pipe model and temperature-dependent heat-removal treatment.

## 3. Code Verification

### 3.1 Verification Problem

The multidimensional thermal-network formulation was examined using the rectangular-solid problem in Fig. 3(a). The  $10 \times 10 \times 45.0333$  mm<sup>3</sup> domain had a thermal conductivity of 1 W/m-K and an initial temperature of 1000 K. A 1 W heat input was applied over the  $2 \times 2$  mm<sup>2</sup> lower-center region and removed from the corresponding upper region; all other boundaries were adiabatic. The same physical problem was independently discretized with approximately 4.5 million solidFoam cells and 1,430 thermal-network cells.

### 3.2 Verification Results

Fig. 3(b) compares the centerline temperatures, while Table I summarizes the mean absolute error (MAE), root mean square error (RMSE), and maximum absolute error at the center, face-center, and edge locations. The network follows the solidFoam axial profile closely away from the localized source and sink, with the largest deviations where those boundary inputs produce the steepest gradients. Together, the profile and location-specific metrics test the implementation in both smooth and strongly varying regions.

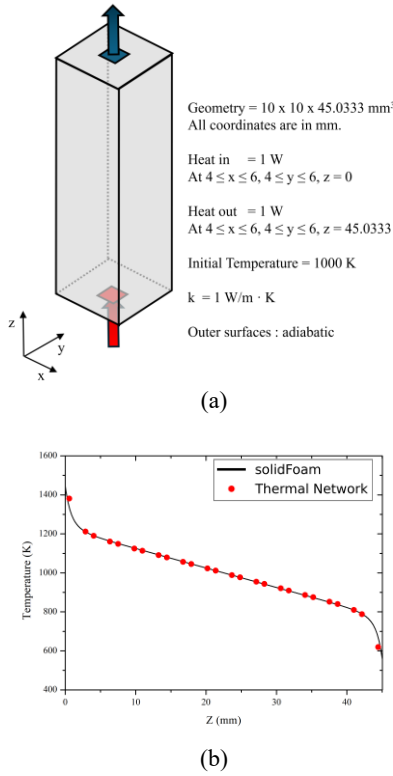


Fig. 3. Three-dimensional solid-conduction verification: (a) problem configuration and (b) comparison of centerline temperature distributions.

Table I: Three-dimensional solid-conduction verification results

| Location       | MAE (K) | RMSE (K) | Maximum absolute error (K) |
|----------------|---------|----------|----------------------------|
| Center         | 4.82    | 12.8     | 45.8                       |
| Center of Face | 1.84    | 2.10     | 3.32                       |
| Edge           | 2.27    | 2.69     | 4.79                       |

#### 4. Steady-State Analysis of the rHPMR Core

##### 4.1 rHPMR Core Model

An rHPMR-based core configuration was constructed using geometric information reported for the eVinci-like reference model [4]. The three-dimensional triangular-prism thermal network is shown in Fig. 4. The cross-sectional discretization represents the assembly region, where fuel compacts and heat pipes are embedded in the monolith, together with the surrounding reflector, and is extruded axially to form thermal-network cells. The 5 MW model contains 1,296 fuel compacts and 342 heat pipes. The algebraic system contains 4,920 solid-cell temperatures and 342 heat-pipe temperatures, for a total of 5,262 temperature unknowns. Volumetric heat generation is assigned to thermal-network cells containing fuel compacts in the 16 axial layers from L2 to L17. All exterior solid boundaries are adiabatic, and

heat is removed through the lumped-parameter heat-pipe model.

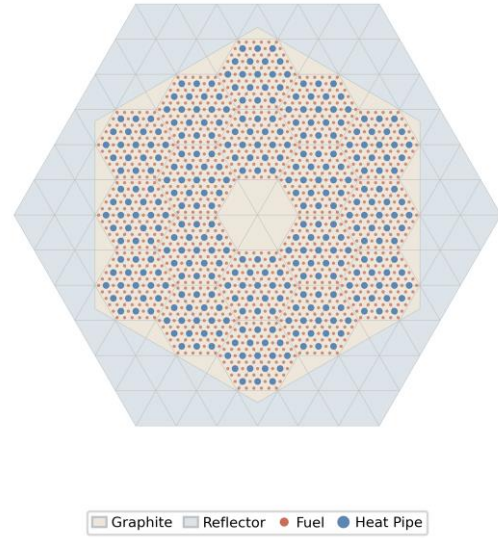


Fig. 4. Triangular-prism thermal-network representation of the rHPMR core.

##### 4.2 Steady-State Results and OpenFOAM Comparison

The steady-state calculation converged in seven iterations. Total generation and heat removal both matched the prescribed 5 MW source, leaving an energy imbalance of  $1.86 \times 10^{-9}$  W. This overall energy balance confirms consistency among the prescribed heat generation, solid-to-heat-pipe heat transfer, and heat-pipe heat removal at the converged state. The cumulative linear-solver time was 1.68 s; it does not represent the total program wall-clock time.

The thermal-network cell temperatures ranged from 1150 to 1480 K, with a volume-weighted mean of 1350 K. Fig. 5 presents the temperature distributions for the 16 axial layers from L2 to L17. The maps show the axial evolution and lateral variation of the temperature field: the temperature rises from the lower part of this range toward the interior and then decreases toward the upper layers, while lateral variations follow the heterogeneous core arrangement. Within the interior axial layers, the high-temperature region changes gradually in cross-sectional extent from layer to layer, and repeated relatively cooler patterns around heat-pipe locations are superposed on the broader lateral variation. These values are representative thermal-network cell temperatures rather than resolved local constituent temperatures.

For the code-to-code comparison, the OpenFOAM solid-domain temperatures were volume-averaged over the region corresponding to each thermal-network cell [8]. The comparison included 108 thermal-network cells containing fuel compacts in each of the 16 axial layers from L2 to L17, yielding a total of 1,728 paired temperatures. Table II summarizes the quantitative

metrics, and Fig. 6 compares the axial trends and paired temperatures at corresponding cell locations.

The thermal-network model generally yielded lower temperatures than the OpenFOAM results at the comparison locations. The axial comparison in Fig. 6(a) nevertheless shows similar axial temperature trends over L2-L17. The parity plot in Fig. 6(b) shows a systematic offset while retaining a clear positive association between corresponding temperatures.

Although both calculations represent the same rHPMR-based core concept, the two models differ in spatial discretization and in their representations of the monolith, helium gaps, and reflector. The results are therefore interpreted as a code-to-code comparison at corresponding cell locations rather than an exact mesh-to-mesh verification. The remaining differences may be associated with the reduced spatial resolution, directional homogenization, and simplified heat-pipe treatment of the thermal-network model.

For this coarse thermal network, Table II quantifies agreement in representative cell temperatures, not in unresolved local constituent temperatures. Volume averaging makes the two temperature fields comparable at the cell scale without recovering their internal spatial variation. The similar MAE and RMSE, together with the systematic offset in Fig. 6(b), indicate that the discrepancy is not confined to an isolated extreme value. Retaining the overall axial trend should therefore be distinguished from matching the absolute temperature at each comparison location.

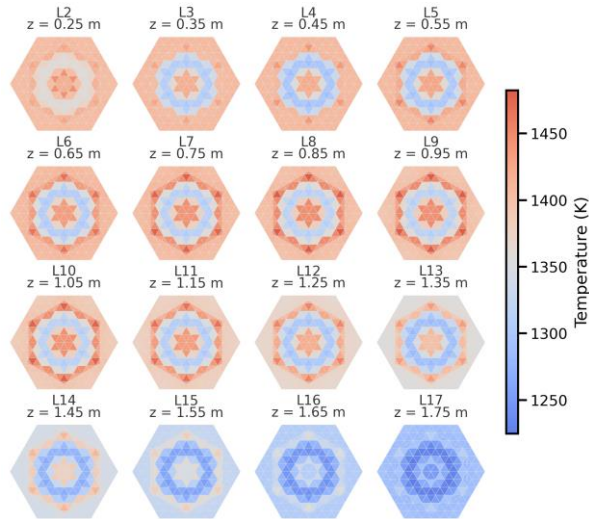


Fig. 5. Layer-wise temperature distributions obtained from the thermal-network analysis.

Table II: Quantitative comparison with the OpenFOAM reference results

| Quantity               | Value  |
|------------------------|--------|
| Comparison points      | 1,728  |
| MAE                    | 36.7 K |
| RMSE                   | 39.5 K |
| Maximum absolute error | 83.6 K |

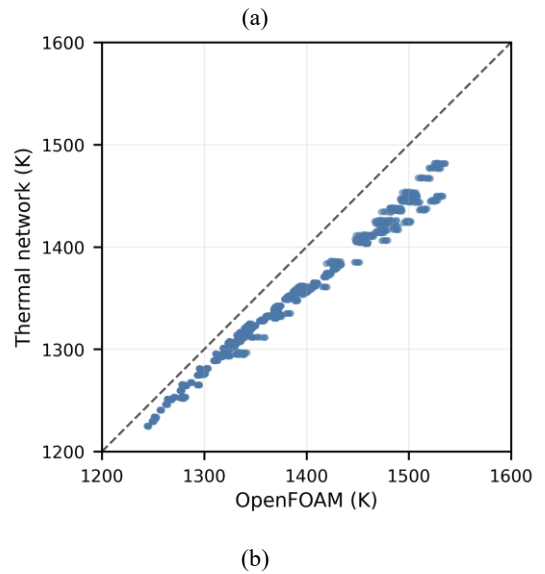
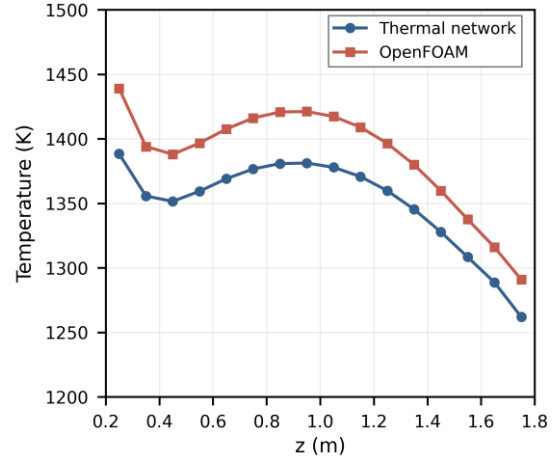


Fig. 6. Comparison of the thermal-network and OpenFOAM temperature results: (a) axial temperature distributions and (b) parity comparison at corresponding cell locations.

## 5. Conclusions

A multidimensional thermal-network code was developed for preliminary steady-state analysis of the rHPMR core using directional ETCs and a simplified lumped-parameter heat-pipe model. An independently discretized three-dimensional solid-conduction benchmark verified the implemented lateral and axial conduction treatment.

The 5 MW application satisfied the energy balance and reproduced the principal lateral and axial trends in the OpenFOAM results, while generally yielding lower temperatures. Differences in spatial discretization and model representation require treating the results as a code-to-code comparison at corresponding locations rather than an exact mesh-to-mesh verification.

Future work will focus on improving the directional ETC and lumped-parameter heat-pipe model while retaining the efficiency of the reduced approach.

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