Development of a Unit-Cell Based Multi-dimensional Heat Conduction Model for a Prismatic Fuel Block

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1. Introduction

Computational fluid dynamics (CFD) analysis has been successfully applied to obtain an accurate temperature distribution of prismatic fuel blocks in a very high temperature reactor (VHTR) [1-2]. However, it requires elaborate computational efforts to analyze whole prismatic fuel blocks due to complex geometry. In particular, tremendous efforts have to be devoted to generate computational grids for the CFD analysis. Such efforts might be huge burdens for a designer who wants a large number of calculations with various design options.

In this work, a new multi-dimensional heat conduction model has been developed to overcome the demerits of the existing methods (e.g., CFD analysis and system analysis). This new model focuses on the regular arrangement of unit cells in a prismatic fuel block. The use of the unit cell concept enables an efficient generation of unstructured meshes without a mesh generator.

This paper presents a brief outline of the new heat conduction model for a prismatic fuel block and some results of the verification and validation (V & V) study of the new model. The numerical results by the CFX 11 code [3] are used for a comparison.

2. Numerical Method

In order to solve heat conduction in a prismatic fuel block, the present model adopts the finite volume method which is the most popular technique. Unstructured meshes are chosen to model the complex geometry of prismatic fuel blocks. In particular, the present model notices the regular arrangement of unit cells in a prismatic fuel block. As shown in Fig. 1, a prismatic fuel block consists of hexagonal or pentagonal unit cells.

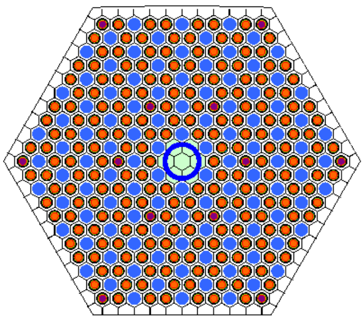

Fig. 1. A typical arrangement of unit cells in a prismatic fuel block.

In the new model, a prismatic fuel block is modeled by the basic unit cells shown in Fig. 2. Then the computational nodes are defined in the basic unit cells. An efficient generation of unstructured computational grids is possible by using the basic unit cells when the solid region of a prismatic fuel block is modeled.

Fig. 2. Basic unit cells used in the present model.

3. Verifications & Validations

3.1 Single Unit Cell

The V & V study starts from a single unit cell problem which is the one of the simplest test cases. The unit cell consists of the fuel compact, the helium gap, and the graphite region. A uniform heat generation of 28.76 MW/m^3 in the fuel compact is assumed and the temperature of the outmost boundary is fixed to1024 ^{o}C. Fig. 3 compares the predicted temperature profile by the present model with that by CFX 11. It shows that the present model accurately solves the heat conduction equation. It is obvious that the finer mesh provides the more accurate result.

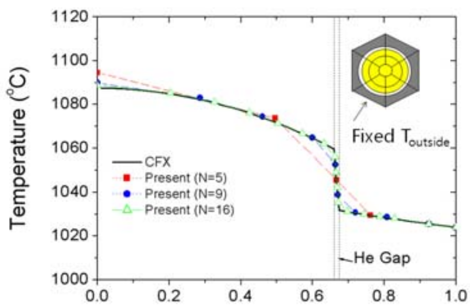

Fig. 3. Comparison of the predicted temperature profiles inside the single unit cell containing fuel compact.

3.2 Seven Unit Cells

The second case considers seven unit cells composed of one coolant cell (designated by 'C') surrounded by six fuel cells (designated by 'F') as shown in Fig. 4. A uniform heat generation of 28.76 MW/m^3 in the fuel compacts is assumed. The temperature at the coolant boundary is fixed to 1017 ^{o}C and the adiabatic boundary condition is imposed on the outmost boundary of the unit cells.

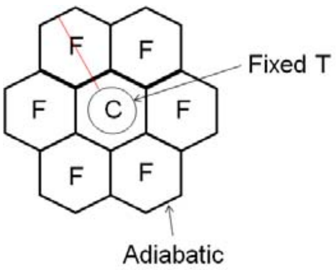

Fig. 4. A layout of seven unit cells and boundary conditions.

Fig. 5 shows the predicted temperature profiles along the specified red line in Fig. 4. It is observed that when a fine mesh is adopted, the accuracy of the present model is close to that of the CFX 11. The figure shows that the calculation by a coarse mesh could over-predict the temperature of the fuel compact in this case.

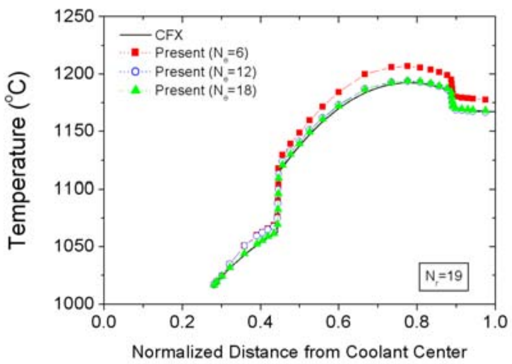

Fig. 5. Comparison of the predicted temperature profiles in the seven unit cells.

3.3 Single Column Stacked by Ten Fuel Blocks

The last test case presents a thermo-fluid calculation for single column stacked by ten fuel blocks in a VHTR under full power operating conditions. The standard fuel block shown in Fig. 1 is considered. The total height of the column is 7.93 m. A cosine shape for the axial power distribution is assumed. Table I lists the major thermo-fluid parameters for the considered problem.

Table I: Major Thermo-fluid Parameters for Single Fuel Column Analysis

Parameter	Value
Total thermal power (MW)	5.88
Axial power peaking factor (-)	1.2
Total flow rate (kg/s)	2.15
Bypass gap flow fraction (%)	1.1
Coolant inlet temperature (^{o}C)	490

This problem requires one-dimensional (1-D) fluid models for the coolant channels and the bypass gap channels. Typical Nusselt number correlations for a circular tube are used to couple the three-dimensional (3-D) solid model and the 1-D fluid model.

Fig. 6 shows the predicted axial temperature profiles along the centers of the selected fuel compact (i.e., F01 which is located at the inner most ring in Fig. 1). A good agreement is seen in Fig. 6. It clearly indicates that the present method can reasonably simulate a thermal behavior in a prismatic fuel block. The predicted maximum fuel temperature by the present model is 1122 ^{o}C whereas the temperature calculated by CFX 11 is 1118 ^{o}C. It should be noted here that several hours were spent for the CFX 11 calculation whereas several minutes are enough for the calculation by the new method.

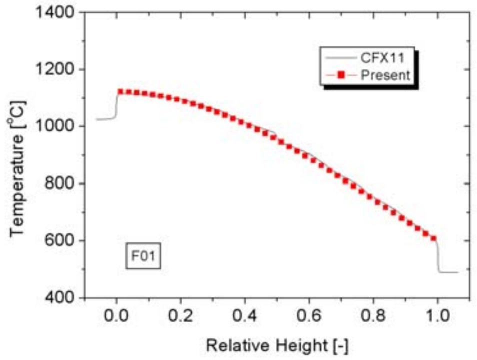

Fig. 6. Comparison of the predicted axial temperature profiles along the center of the selected fuel compact.

4. Conclusions & Outlooks

A unit-cell based multi-dimensional heat conduction model was developed for a prismatic fuel block and some results of the V & V study were presented in this paper. The results of the V & V study show that the developed model is highly reliable and reasonably accurate.

The developed model will be combined with a 1-D fluid network model for an efficient simulation of prismatic cores. It is envisaged that the combined method will significantly reduce the computational burdens for thermo-fluid analysis of prismatic core with reasonable computational accuracy.

ACKNOWLEDGMENTS

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