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Numerical Simulation of a Coolant Flow and Heat Transfer in a Pebble Bed Reactor

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1. Introduction

Pebble Bed Reactor(PBR) is one of the very high temperature gas cooled reactors(VHTR) which have been reviewed in the Generation IV International Forum as potential sources for future energy needs, particularly for a hydrogen production. The pebble bed modular reactor(PBMR) exhibits inherent safety features due to the low power density and the large amount of graphite present in the core. PBR uses coated fuel particles(TRISO) embedded in spherical graphite fuel pebbles. The fuel pebbles flow down through the PBR core during a reactor operation and the coolant flows around randomly distributed spheres. For the reliable operation and the safety of the PBR, it is important to understand the coolant flow structure and the fuel pebble temperature in the PBR core. There have been few experimental and numerical studies[1-4] to investigate the fluid and heat transfer phenomena in the PBR core. The objective of this paper is to predict the fluid and heat transfer in the PBR core. The computational fluid dynamics (CFD) code, STAR-CCM+(V2.08) is used to perform the CFD analysis using the design data for the PBMR400.

2. Numerical Methods

The PBMR400 core consists of approximately 450,000 fuel pebbles that are randomly stacked in a graphite reflector structure. A typical fuel pebble consists of a fueled region surrounded by a thick graphite layer that is fuel free. The fueled region consists of a graphite matrix surrounding several tens of thousands of fuel particles, i.e., TRISO. The pebble diameter is 60mm with a 5mm graphite layer

2.1 CFD Model

This study simulated a staggered array of pebbles which represents one of the pebbles arrangements in the PBR core. Direct area contact among the pebbles was assumed in this model because it was judged to be reasonable based on a previous sensitivity study on a numerical treatment of a pebble contact[3].

The staggered model(Fig.1) is a 3x3 array of pebbles which is equivalent to sixteen(16) full size pebbles. The porosity for fluid flow is estimated as 0.34. This model includes the solid(pebble) region as well as the fluid region. It should be noted that the fluid region is extended to generate fully developed flow at the outlet boundary of computational domain. This is because a reversed flow is expected to occur downstream of the pebble array. The solid region is divided into a core region(mixture of UO_2 and graphite) and a graphite coating layer.

The current model uses 1.8 million cells and 0.4 million cells for a fluid region and a solid region, respectively. The minimum and target sizes of the surface mesh are 0.3 mm and 3.0 mm in the fluid region, and 1.0 mm and 5.0 mm in the solid region, respectively. It uses a combination of polyhedral and prism cells as illustrated in Fig.2. Five prism layers are used at the interface between the fluid and solid domains.

2.2 Boundary Conditions

A uniform flow condition and constant pressure were applied at the inlet and outlet boundaries of the fluid region, respectively. Symmetric conditions were used in the side fluid boundaries. A constant heat generation rate was imposed at the pebble core region. Adiabatic conditions were applied at the side boundaries of the solid region.

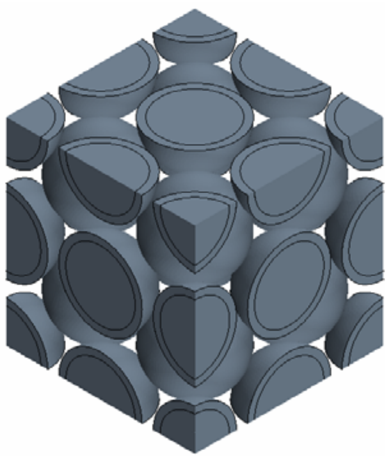

Fig. 1. Staggered pebble array model for CFD analysis.

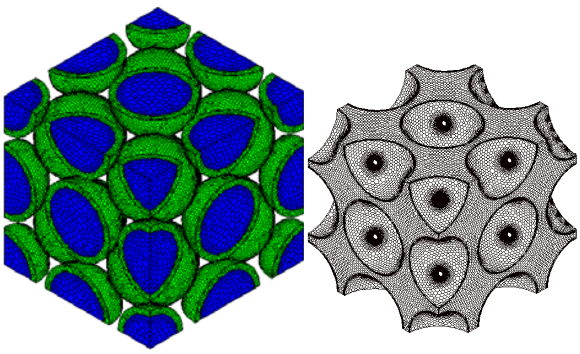

Fig. 2. Computational meshes for solid and fluid regions.

2.3 Numerical Procedure

The numerical simulation used helium at 70bar as a coolant. The bulk velocity and temperature of the helium at the inlet boundary were assumed to be 15m/sec and 1000K, respectively. The Reynolds number is estimated as 65000 based on the bulk helium velocity and pebble diameter. The heat generation rate of 9.0MW/m^3 was given in the fueled core region of the pebbles. Turbulence models used in this study were Sparat-Allmaras model, k-epsilon and SST k-w models with scalable wall treatments.

Iterative calculations were conducted to obtain converged solutions. The iterations were terminated when both residuals of all the governing equations decreased to asymptotic values and the monitored value of a variable at a specified location was constant.

3. Results

Figure 3 shows the velocity vectors around the central pebble. Multiple vortices are predicted at the bottom of the pebble as well as at the side downstream of the pebble contact. The vortices are believed to be formed by the effect of the curvature of the spherical pebbles. The gas (helium) flow would separate at certain points downstream of the pebble. The vortices appear to be symmetric because the pebbles are assumed to be symmetrically distributed in the current CFD model. It is also noted that a large fluid flow occurs in a region between the pebble contacts.

As shown in Fig. 4, the surface temperature is low in a large flow region and high in a narrow flow region. Particularly, the surface temperature in the downstream side of the pebble is higher than the average surface temperature. It also reveals a significantly high temperature near the pebble contact region. The maximum variation of the pebble surface temperature is predicted at about 30K.

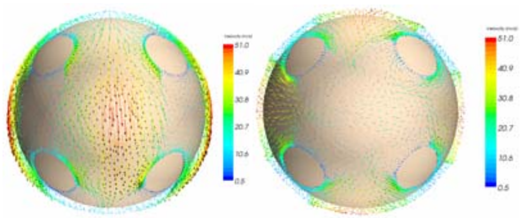

Fig. 3. Velocity vector around central pebble: (left) side view and (right) bottom view.

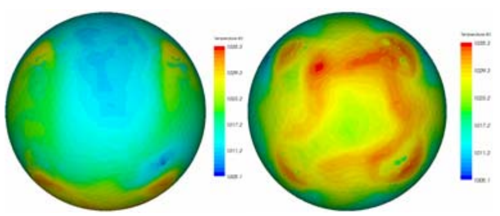

Fig. 4. Temperature contour of central pebble: (left) side view and (right) bottom view

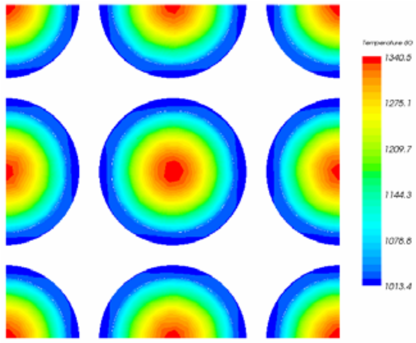

Fig. 5. Sectional view of temperature contour.

The sectional view of the pebble temperature is shown in Fig. 5. The plane section is defined as a central plane normal to the streamwise direction. The pebble temperature appears to be distributed as circumferentially symmetric showing a maximum value at the center of the pebble. This is because the coolant-flow pattern is also shown to be symmetric. The temperature drop in the central pebble is estimated at approximately 340K. The Sparat-Allmaras(SA) model predicts the largest temperature drop while the SST k-w model reveals the least.

4. Conclusions

A series of CFD calculations using a 3x3 staggered array model were performed to simulate a fluid flow and a heat transfer in a pebble bed reactor core. A large temperature variation was predicted on the pebble surface as well as in the pebble core. Multiple vortices were predicted to occur downstream of the spherical pebbles due to a flow separation. A strong vortex was predicted to occur at the bottom as well as at the side of the pebble. Since the local coolant flow structure in the PBR core largely depends on the in-core distribution of the pebbles, various CFD models should be evaluated to more adequately represent the pebbles randomly stacked in the PBR core in the future.

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