Three-Dimensional Analysis of the Hot-Spot Fuel Temperature in Pebble Bed and Prismatic Modular Reactors

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1. Introduction

High temperature gas-cooled reactors(HTGR) have been reviewed as potential sources for future energy needs, particularly for a hydrogen production. Among the HTGRs, the pebble bed reactor(PBR) and a prismatic modular reactor(PMR) are considered as the nuclear heat source in Korea's nuclear hydrogen development and demonstration project. PBR uses coated fuel particles embedded in spherical graphite fuel pebbles. The fuel pebbles flow down through the core during an operation. PMR uses graphite fuel blocks which contain cylindrical fuel compacts consisting of the fuel particles. The fuel blocks also contain coolant passages and locations for absorber and control material. The maximum fuel temperature in the core hot spot is one of the important design parameters for both a PBR and a PMR.

The objective of this study is to predict the hot-spot fuel temperature distributions in a PBR and a PMR at a steady state. The computational fluid dynamics(CFD) code, CFX-10 is used to perform the three-dimensional analysis. The latest design data was used here based on the reference reactor designs, PBMR400 [1] and GT-MHR600 [2].

2. Numerical Methods

2.1 CFD Model

The PBMR core consists of approximately 450,000 fuel pebbles that are stacked in a graphite reflector structure. A typical fuel pebble consists of a fueled region surrounded by a thin unfueled region at the surface. The fueled region consists of a graphite matrix surrounding several tens of thousands of fuel particles. The pebble diameter is 60mm with a 5mm unfueled layer. Unstaggered and 2-D staggered arrays of 3x3 pebbles as shown in Fig. 1 are simulated to predict the temperature distribution in a hot-spot pebble core. Total number of nodes is 1,220,000 and 1,060,000 for the unstaggered and staggered models, respectively.

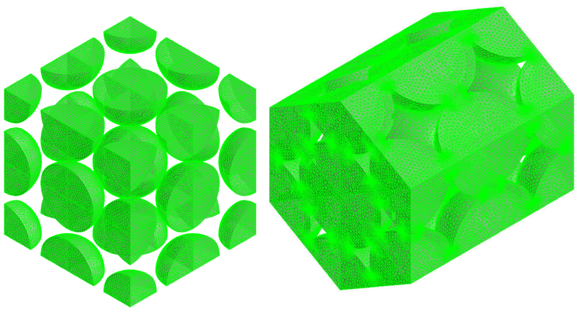

Figure 1. Unstaggered and staggered 3x3 pebble arrays for CFD.

The GT-MHR(PMR) reactor core is loaded with an annular stack of hexahedral prismatic fuel assemblies, which form 102 columns consisting of 10 fuel blocks stacked axially in each column. Each fuel block is a triangular array of a fuel compact channel, a coolant channel and a channel for a control rod. Diameters of the fuel channel and the coolant channel are 12.7mm and 15.9mm, respectively. It is noted that there is a 0.125mm gap between the fuel compact and the fuel channel. The central distance between the fuel channels and the coolant channel is 18.85mm. The height of each block is 793mm.

Only 1/6 of the two fuel channels and a single coolant channel are modeled by using the symmetry of the fuel block. The 10-block PMR model uses 347,900 nodes with the grid sizes of 0.06mm to 0.8mm in the lateral direction and 16mm in the axial direction, respectively.

2.2 Boundary Conditions

For the PBR core models, a uniform flow condition and constant pressure are applied respectively at the inlet and outlet boundaries in a streamwise direction. A periodic condition is used at the lateral boundaries where an inflow as well as an outflow are allowed. Constant heat generation rates in the fueled region of the pebbles are given.

The uniform cooling flow and constant pressure are assumed respectively at the inlet and the exit of the coolant channel in the PMR fuel block. Symmetric conditions are used at the side boundaries of the PMR model. Constant heat generation rates in the fuel channels of each block are given.

2.3 Design Operating Conditions

Helium at the inlet pressure of 70 bar is used as coolant for both the PMR and the PBR. For the PBR case, the bulk velocity and temperature of the helium in the hot

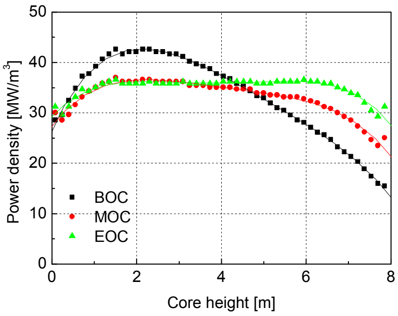

Figure 2. Axial power density distribution in the PMR core.

core region are known to be approximately 15.0 m/s and 1130°C, respectively. The heat generation rate in the hot pebbles is 9.1 MW/m^3. The helium mass flowrate per the PMR coolant channel is 0.0176 kg/s and the core average inlet/outlet helium temperatures are 399 °C and 950 °C. Figure 2 shows the axial distribution of the power density with the average values of 33.3(BOC), 33.1(MOC) and 35.0(EOC) MW/m^3.

The physical properties of the helium are given as a function of the temperature at the operating pressure of 70 bar. The thermal conductivities of the fuel compact, fuel gap, pebble and graphite also vary with the temperature.

3. Results and Discussions

Figure 3 shows a plane view of the pebble temperature distribution in the pebble core. The pebble center temperatures are 1296 °C and 1313 °C for the unstaggered and staggered array pebbles, respectively, which are higher than the design limit(1250 °C). The average temperature drops in the pebbles are estimated as 65 °C and 108 °C, respectively. It can also be seen that the pebble temperature at the downstream side is predicted to be 10 °C higher than the one at the upstream side.

Figure 4 shows the calculated temperature distribution at the exit of the PMR core(EOC). The maximum fuel temperature is 1295 °C which is also higher than the fuel temperature limit. The axial variation of the temperature in the fuel, graphite and coolant is shown in Fig. 5. The bulk exit temperature of the coolant(helium) is 1144 °C. The temperature difference between the coolant and the

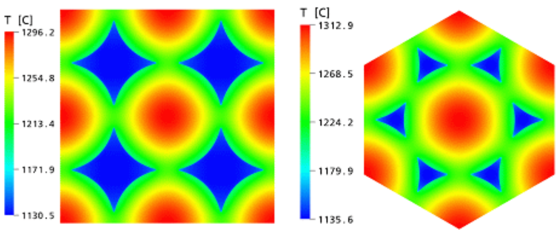

Figure 3. Pebble temperature distributions for the unstaggered and staggered arrays.

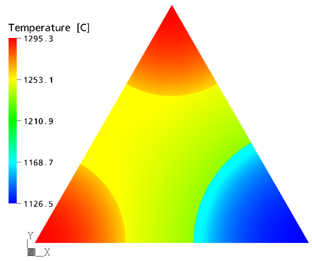

Figure 4. Temperature distribution at the exit of the PMR core(EOC).

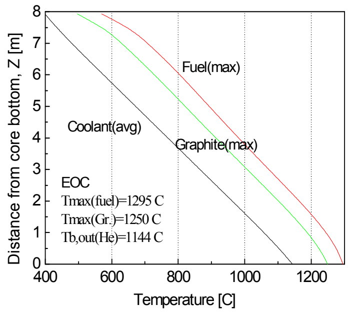

Figure 5. Axial temperature distribution in the PMR core(EOC).

fuel is approximately 150 °C. Additional calculations showed that the fuel temperature limit can be met if the power density at EOC is decreased by more than 5% or the axial power peak by more than at least 10%.

4. Conclusion

The fuel temperature distributions for both a PBR and a PMR were calculated by using the recent core design data. The maximum fuel temperatures in the hot region were predicted to be 1296 °C and 1295 °C for the PBR and the PMR, respectively which are higher than their limits(1250 °C) during a normal operation. It was also found that either the power density or the axial power peak should be decreased by more than 5% and 10%, respectively, for the PMR core in order to meet the fuel temperature limit.

Acknowledgement

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