Thermal-Fluid Analysis of the Local Hot Core Region in a Pebble-Bed Reactor

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1. Introduction

The core outlet temperature required for the hydrogen production by the Very High Temperature Reactor (VHTR) is above 950^{o}C, higher than that of the conventional High Temperature Gas-cooled Reactor (HTGR). An increase of the outlet temperature accompanies a rise of the core temperature. Therefore, maintaining the maximum fuel temperature below 1250^{o}C, its steady state operating limit, is one of important issues in the VHTR design.

In general, the steady-state core temperature in the HTGR has been evaluated by system thermal fluid analysis codes using the porous media approach that are not appropriate for the VHTR core having a less temperature margin, which needs a detailed analysis. Applications of three dimensional computational fluid dynamic codes to the thermal-fluid analysis of a core have been increasing. There were CFD analyses for prismatic core reactors that employed a unit-cell approach for the entire core height [1][2]. Although the unit-cell approach is employed, however, the CFD analysis of a pebble core for a full height cannot be performed because of a large number of pebbles, the irregularity of pebble arrangement, and high Reynolds number flows,. Therefore, a local CFD analysis for a selected hot core region is recommended. The selection of a hot core region can be obtained from the result of a system analysis code.

In this study, CFD analyses are carried out to assess the local hot core temperature of a 400MWt pebble bed reactor during a steady state operation by using the CFX-10 commercial code. Three pebble arrangements are selected. The results are compared not only between them but also with an experimental correlation.

2. Computational Method

For the CFD analysis of a local core region, some boundary conditions are needed such as the local power of a pebble, the inlet temperature and so on. To obtain these conditions, the GAMMA system code [3] was employed for a full core analysis of the pebble bed reactor of which the parameters are shown in Table 1.

Table 1. Main Parameters of pebble core

Reactor Power (MWt)	400
System Pressure (bar)	70
Core Inlet/Outlet Temperature (oC)	490/950
Total Mass Flow (kg/s)	166
Core Mass Flow(kg/s)	131

The GAMMA core divides the core into 55 meshes consisting of 11 rows and 5 columns in a cylindrical coordinate system as shown in Figure 1. According to the GAMMA analysis, the local hot region of the core occurred at the fifth raw from the bottom and the near to inner reflector. The results of GAMMA analysis at the local hot region are presented in Table 2.

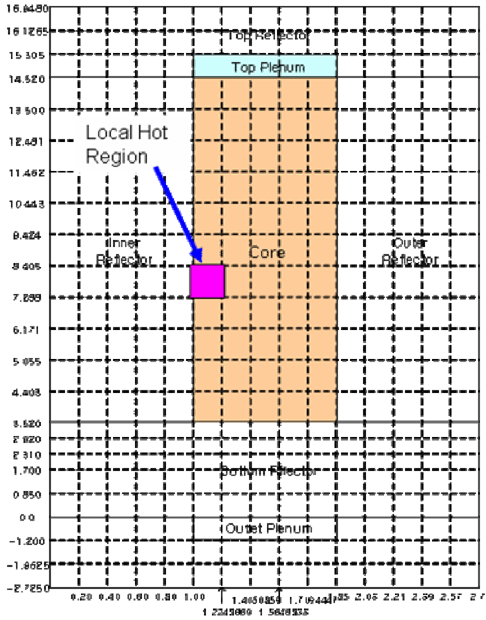


Figure 1. Pebble core model used in the GAMMA analysis

Table 2. GAMMA results for the local hot region

Radial Position (m, Ring 1)	1.112
Vertical Position (m, axial zone 5)	7.846
Local Core Power Density (MWt/m3)	9.6
He Temperature (^{o}C)	1087
He superficial velocity (m/s)	6.7
Core porosity(ε)	0.39

Pebble arrangements considered in the CFD analysis are simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC). Because the porosity varies with the arrangement, it is not appropriate to apply an actual helium velocity to all the pebble arrangements. In this study, the mass flow is determined in order to keep the superficial velocity constant regardless of the pebble arrangement.

Figure 2 shows the grid systems used for each pebble arrangement. The numbers of nodes are 361,427 for the SC, 872,293 for the BCC, and 1,232,831 for the FCC, respectively. The grid system includes not only the fluid region but also the pebble solid region which contains the fuel with a diameter of 50cm and the graphite with a thickness of 5cm. A gap size of 0.5mm between the pebble spheres is assumed to avoid the difficulty of a grid generation at a contact surface.

The mass flow is fixed at the inlet boundary. At the outlet boundary, the relative static pressure is set as zero. Periodic condition is imposed on the transverse direction. The Reynolds number based on the inlet superficial velocity and the pebble diameter is 1.84×10^4, which means the flow is turbulent. Standard k-ε model with a wall function method is selected for the turbulence closure.

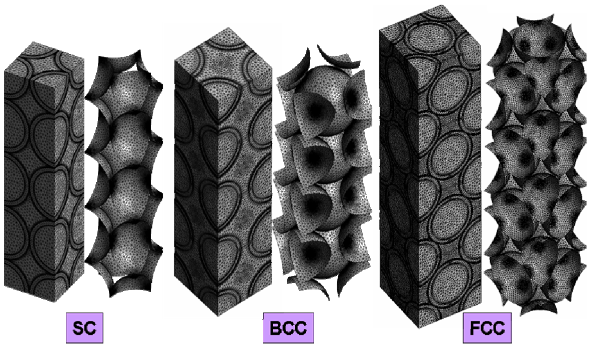
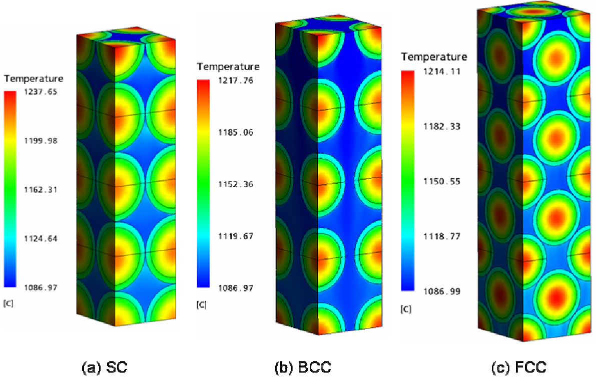


Figure 2. Computational grid systems

3. Results and Discussions

Temperature distributions for each pebble arrangement are shown in Figure 3. The maximum fuel temperature of the SC is 1237°C that is about 20°C higher than the others but still below the normal operation limit of 1250°C. Temperature profiles along the pebble centerline are compared in Figure 4. The BCC and the FCC represent a similar profile to each other and their temperatures are lower than that of the SC about 15 °C to 20 °C. The temperature profile is asymmetric. That is, the location of maximum temperature is below the pebble center, which is more evident in the SC arrangement.



(a) SC (b) BCC (c) FCC

Figure 3. Temperature distributions

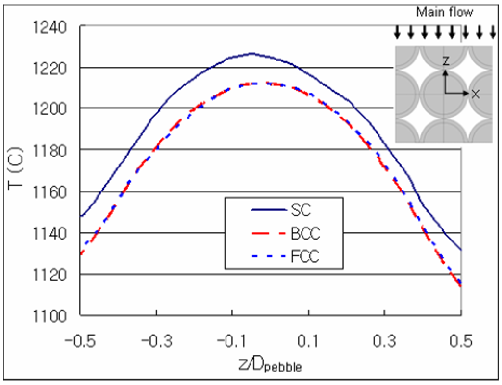


Figure 4. Comparison of temperature profiles along the pebble centerline

Pressure drop across the pebbles and average Nusselt number at the pebble surface are calculated from the CFD results. The results are shown in Table 3, compared with the predictions of the correlations [4][5]. Both the CFD and the correlation results show that the pressure drop increases as the porosity decreases. There are big differences between their absolute values because no pebble arrangement is in the applicable porosity range of the correlation which is from 0.36 to 0.42. This also implies that the pressure drop correlation for the full core is not applicable for the local pebble analysis. The CFD results show that the heat transfer in the BCC is better than the SC but similar to the FCC while the correlation indicates a continued heat transfer enhancement with a decrease of the porosity.

Table 3. Comparison of pressure drop and Nusselt number

Variable		SC	BCC	FCC
Porosity		0.489	0.336	0.277
ΔP/H (kPa/m)	CFD	3.56	14.2	19.9
	Correlation	9.09	37.3	72.9
Nu	CFD	224	386	352
	Correlation	367	553	683

4. Conclusion

CFD analyses on a local hot core region in a pebble type VHTR were performed to investigate the local fuel temperature by using the input and boundary data obtained from the GAMMA system code. Three pebble arrangements were selected. Among them, the SC arrangement showed the maximum fuel temperature of 1237°C, which is still below the normal operation limit of 1250 °C. It was also found that the correlation for the full core used in the system code is not necessarily valid for the prediction of the local thermal fluid behavior.

Acknowledgement

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