CFD Analysis for Hot Spot Fuel Temperature of Deep-Burn Modular Helium Reactor

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1. Introduction

As an alternative concept of a conventional transmutation using fast reactors, a deep-burn modular helium reactor (DB-MHR) concept has been proposed by General Atomics (GA)[1]. Kim and Venneri [2] published an optimization study on the DB-MHR core in terms of nuclear design. The authors concluded that more concrete evaluations are necessary including thermo-fluid and safety analysis. The present paper describes the evaluation of the hot spot fuel temperature of the fuel assembly in the 600MWth DB-MHR core under full operating power conditions. Two types of fuel shuffling scheme (radial and axial hybrid shuffling and axial-only shuffling) are investigated. For accurate thermo-fluid analysis, the computational fluid dynamics (CFD) analysis has been performed on a 1/12 fuel assembly using the CFX[3] code.

2. Analysis

2.1 Reference Design

The reference DB-MHR core consists of 144 fuel columns in five annular rings with 9 fuel blocks per fuel column in the active core. The height of the active core is 7.93 m. The thermal power of the core is designed to be 600 MWth. The coolant inlet/outlet temperatures are 490 and 850 ^{o}C, respectively. Figure 1 shows the geometry of the standard fuel blocks of DB-MHR. A tiny gap (~0.1 mm) exists between the fuel compact and the graphite block.

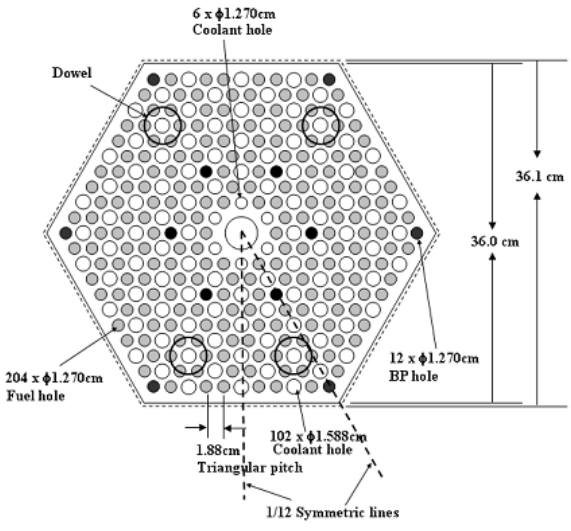


Fig. 1. The geometry of standard fuel block.

2.2 Computational Model

By assuming that the effects of the four dowels are negligible, the entire fuel assembly shown in Fig. 1 can be simulated by its 1/12 section due to its symmetry [4]. Figure 2 shows the computational domain of the 1/12 fuel assembly model for the CFD analysis. The size of the inter-assembly gap is assumed to be 2 mm.

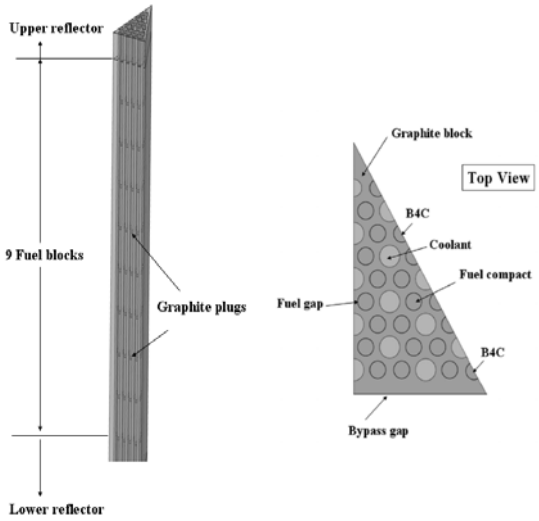


Fig. 2. Computational domain for the CFD analysis.

The total number of nodes for the reference meshes is ~2 millions. The standard k-ε turbulence model with the scalable wall function is applied to the coolant channels, while the bypass flow through the gap is assumed to be laminar. Three dimensional power profiles are provided by the MASTER-GCR calculations [4]. In addition, the results of GAMMA+ [5] provide the inlet temperature and the flow rate of the coolant flowing through the fuel assembly. Two types of the candidate designs (i.e., hybrid shuffling core and axial shuffling core) are analyzed at the BOC, MOC, and EOC conditions.

3. Results & Discussions

Figure 3 shows the temperature contour calculated by CFX at BOC of the hybrid shuffling core. The predicted maximum fuel temperature is 1135 ℃. The figure shows that the fuel compacts near the bypass gap are relatively colder. The calculated temperature contours for the other conditions are similar to that of Fig. 3 except the highest value, i.e., the hot spot fuel temperature. Table I summarizes the predicted hot spot

fuel temperatures of the considered designs throughout the burnup. It can be seen that the predicted hot spot fuel temperatures for the considered designs are sufficiently below the generic design limit (i.e., 1250 ℃) under normal operating conditions.

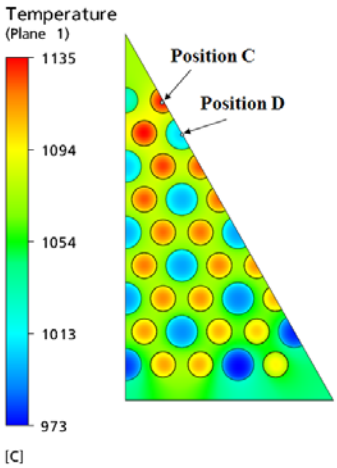


Fig. 3. Temperature contour at BOC of the hybrid shuffling core (top view at the maximum temperature plane).

Table I: The Predicted Hot Spot Fuel Temperature

	Hybrid shuffling core	Axial shuffling core
BOC	1135 ℃	1093 ℃
MOC	1077 ℃	1019 ℃
EOC	1070 ℃	1029 ℃

Figure 4 shows the axial temperature profile along Position C and Position D (designated in Fig. 3). The sharp temperature drops between the fuel blocks are shown in the figures. These are due to the fuel-free top and bottom graphite regions of the fuel block.

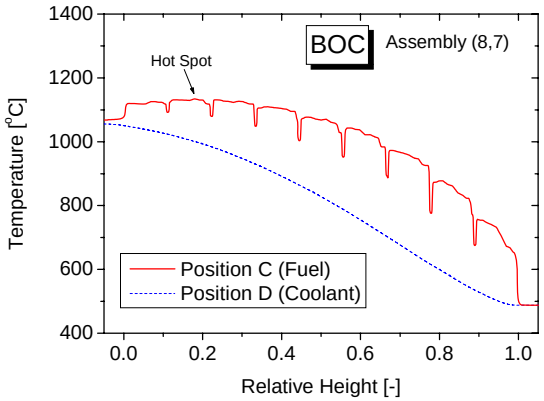
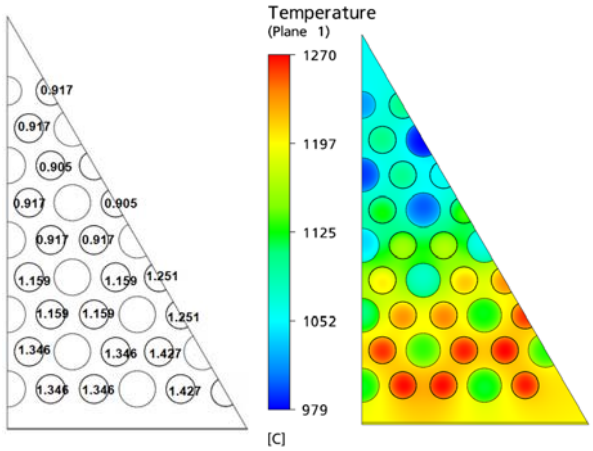


Fig. 4. Axial temperature profile of the hybrid shuffling core.

The above results were obtained by assuming a uniform radial power profile within the assembly. However, higher local power densities are expected at the fuel rods adjacent to reflector assemblies. Figure 5(a) shows a normalized radial power profile within the assembly. Additional CFX calculation was performed with the non-uniform power profile and the result is provided in Fig. 5(b). Figure 5(b) shows that the peak fuel temperature is 1270 ℃, slightly higher than the limit. However, the local power distribution in Fig. 5(a) was obtained without the control rod insertion. In the actual core, control rods are inserted into the reflector blocks neighboring the hottest fuel column, thereby reducing the power peaking factor. Also, the power peaking can be further lowered through a core design optimization.



(a) Relative power within assembly (b) CFX result

Fig. 5. Effect of the local power profile within the assembly.

4. Conclusions

The predicted hot spot fuel temperatures for the hybrid shuffling core and the axial shuffling core are sufficiently below the design limit of 1250 ℃ with uniform radial power distribution within the assembly. With a detailed local power profile within the assembly, the peak fuel temperature exceeds slightly the generic limit. However, it is expected that the peak fuel temperature can be easily reduced through a core design optimization.

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