INL/CON-09-15885
PREPRINT

Preliminary Studies of Coolant By-Pass Flows in a Prismatic Very High Temperature Reactor Using Computational Fluid Dynamics

NURETH-13

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September 2009

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ABSTRACT

Three dimensional computational fluid dynamic (CFD) calculations for a 1/12 sector of a prismatic block through the core of a prismatic very high temperature gas-cooled reactor (VHTR) were conducted to investigate the influence of gap geometry on flow and temperature distributions in the reactor core using commercial CFD code FLUENT. Parametric calculations changing the gap width in a whole core length model of fuel and reflector columns were performed. The simulations show the effects of core by-pass flows in the heated core region by comparing results for several gap widths including zero gap width. The calculation results underline the importance of considering inter-column gap width for the evaluation of maximum fuel temperatures and temperature gradients in fuel blocks. It is shown that temperatures of core outlet flow from gaps and channels are strongly affected by the gap width of by-pass flow in the reactor core.

KEYWORDS

CFD, prismatic, VHTR, FLUENT, core by-pass flow, maximum fuel temperature

1. INTRODUCTION

The Energy Policy of Act (EPAct) of 2005 [1] designates that the Next Generation Nuclear Plant (NGNP) will be based on a Very High Temperature Gas-cooled Reactor (VHTR) aiming not only for electricity generation but also for process heat utilization e.g. hydrogen production, coal gasification, etc. The U.S. Department of Energy is exploring the potential for the VHTR which will be either of a prismatic or a pebble-bed type. One important design consideration for the reactor core of a prismatic VHTR is coolant by-pass flow which occurs in the interstitial regions between fuel blocks. Such gaps are an inherent presence in the reactor core because of tolerances in manufacturing the blocks and the inexact nature of their installation. Furthermore, the geometry of the graphite blocks changes over the lifetime of the reactor because of thermal expansions and irradiation damages.

Several studies have been made in the past of by-pass flows by applying simplified methods such as flow network calculations and the application of correlations obtained from experiments [2, 3]. However, the distribution of temperature in the fuel pins and graphite blocks as well as coolant outlet temperatures are strongly coupled with the local heat generation rate within fuel blocks which is not uniformly distributed in the core. Hence, it is crucial to establish mechanistic based methods which can be applied to the reactor core thermal hydraulic design and safety analysis. A mechanistic study similar to the present one was performed by Tak et al. [4] wherein a 1/12 sector of the core was simulated. However, different inlet conditions were used from the present study.

The present study intends to establish a baseline of an evaluation method related to the coolant by-pass phenomena. Three dimensional computational fluid dynamic (CFD) calculations for a 1/12 sector of a prismatic block through the core of a prismatic VHTR were conducted to investigate the influence of a gap geometry on flow and temperature distributions in the reactor core by using commercial CFD code FLUENT [5]. Parametric calculations changing the gap width in a full core length model of fuel assembly and reflector were performed.

2. REFERENCE PRISMATIC VHTR

In the present study, GT-MHR [6] is selected as a reference reactor for the calculations. It is a helium-cooled, graphite-moderated, thermal neutron spectrum reactor with 850°C core outlet temperature and 600MW thermal power. Major specifications are shown in **Table I**. **Figure 1** shows the cutaway view of the reactor and cross section of the reactor core, respectively.

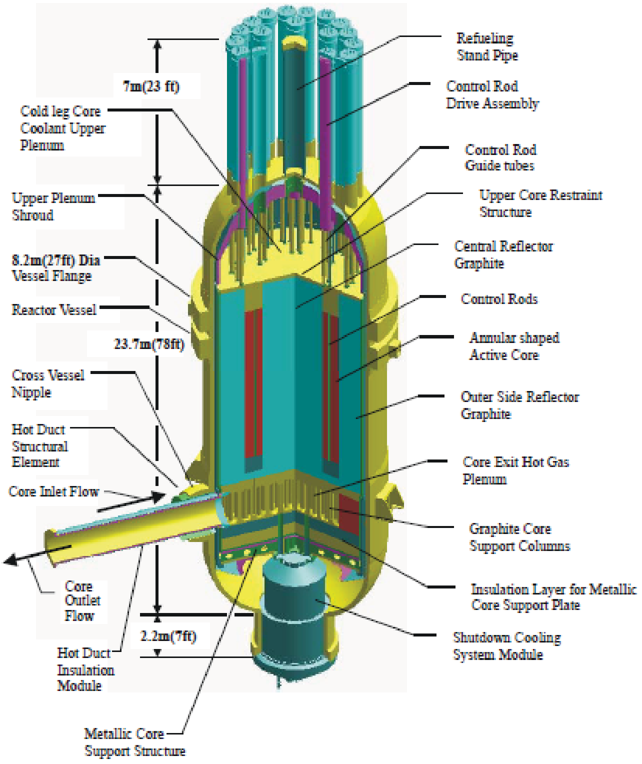


Fig.1 Cutaway view of the GT-MHR

Table I Major specifications of GT-MHR

Specifications	Values
Reactor power (MWt)	600
Reactor inlet /outlet temperature (°C)	490 / 850
Reactor pressure (bars)	70
Power density (W/cc)	5
Reactor mass flow rate (kg/s)	320
Effective core height (m)	7.93
Number of fuel blocks	1020

The GT-MHR core consists of graphite hexagonal blocks one-third of which are fuel blocks arranged annularly and, and the other two-thirds of the blocks are neutron reflector blocks arranged inside and outside of fuel blocks. Fuel columns consist of 10 layers of fuel blocks installed between the upper and lower removable reflector columns. In the outer and inner circumferential region of fuel columns, control rods and reserve shut down system channel are arranged. **Figure 2** shows the cross section of a core and cutaway of fuel and fuel blocks. The average width and height of a block are 360 and 793 mm, respectively. Each fuel block has 102 and 6 flow channels with diameters of 15.88 and 12.70 mm, respectively, and 210 fuel channels. The blocks are vertically connected with dowel pins.

Helium coolant enters the reactor pressure vessel through the outer side of an annular pipe, flows upward between the reactor pressure vessel and core barrel, and reverses the direction at upper plenum. The coolant temperature increases as it flows downward through the flow channels in the graphite columns, joins at the lower plenum, and exits the vessel through the inner side of the annular pipe.

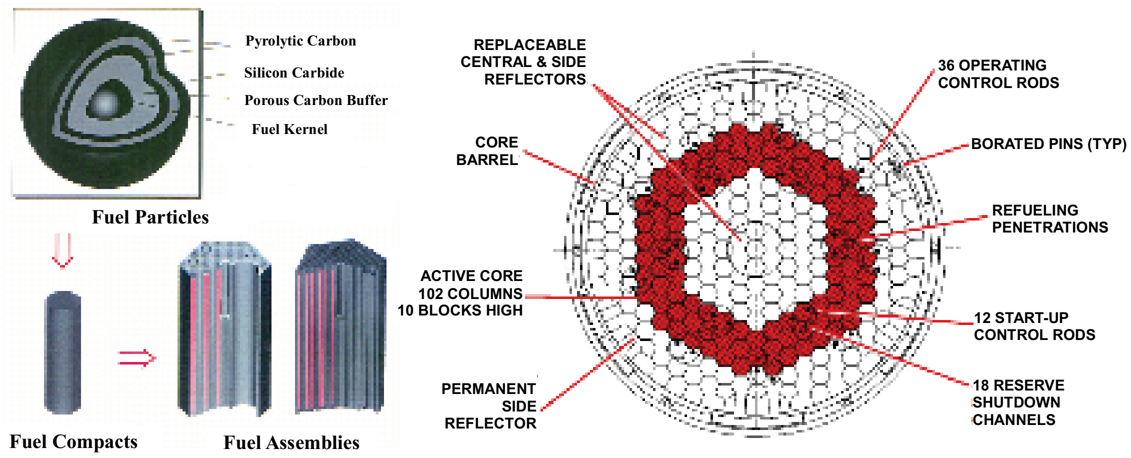


Fig.2 Cross section of a core and cutaway view of fuel and fuel blocks

There are also potential by-pass flows through gaps between the graphite columns. The flow through these interstitial gaps varies because of gap width variation which occurs because of tolerances in manufacturing and inexact installation. In addition, the non-uniform neutron fluences and temperature distributions in actual core cause non-uniform deformations in the graphite block over its lifetime, complicating the flow characteristics.

3. CALCULATION MODEL

A 1/12 sector of the hexagonal block for the whole core length of 10.704 m is modeled with 8.5 coolant channels of 15.88 mm diameter, 0.5 coolant channels of 12.70 mm diameter, 17.5 fuel channels and 0.5 burnable poison hole to obtain a mesh of sufficient quality for the computations. **Figure 3** shows the top view of the 1/12 sector. Finer meshing is applied in the boundary layers of the coolant channels and the gap. The computational domain is divided vertically with an upper reflector (1.189 m), a fuel section (7.93 m) and a lower reflector (1.585 m). Heat generation is prescribed in the fuel region only. The total number of mesh cells is approximately 7.6 million. In order to confirm the basic characteristics of by-pass flow, interstitial gap widths of 0, 1, 2 and 3 mm are modeled. Cross flows between the tops and bottoms of adjacent blocks are assumed zero. Each side of the 1/12 sector is set as a symmetry boundary.

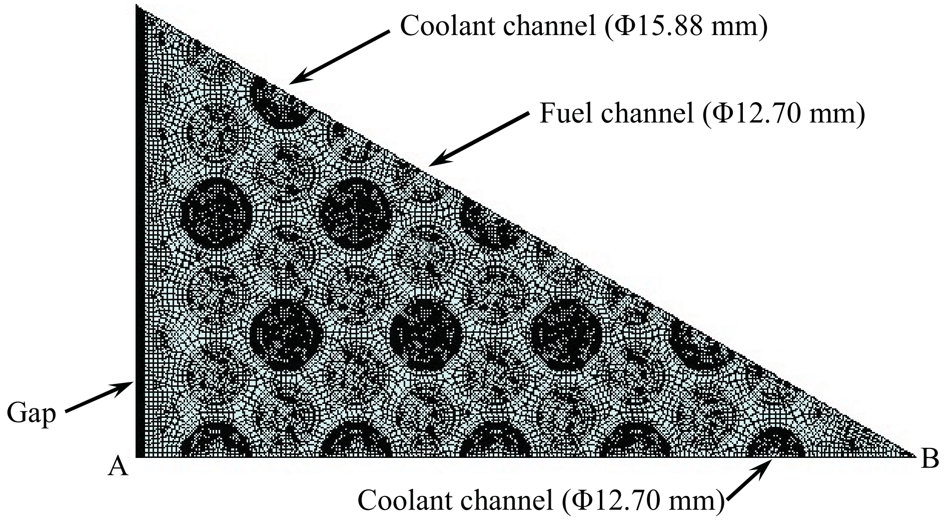
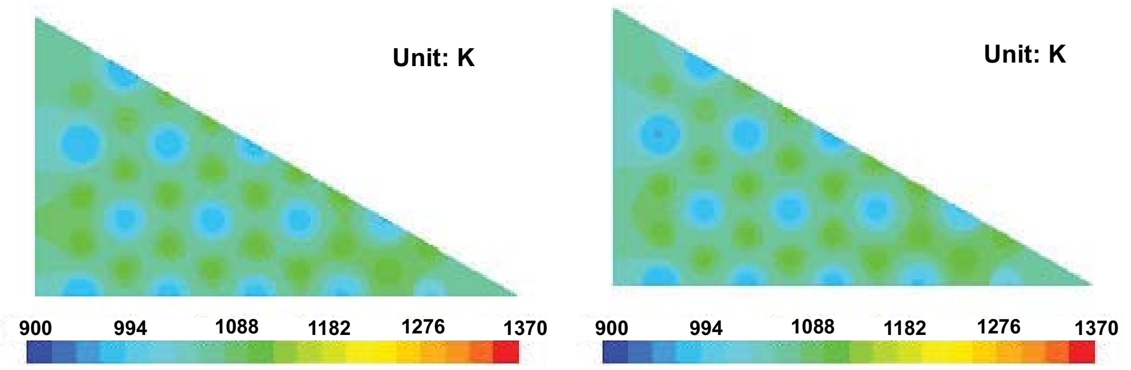


Fig.3 Top view of 1/12 hexagonal block grids

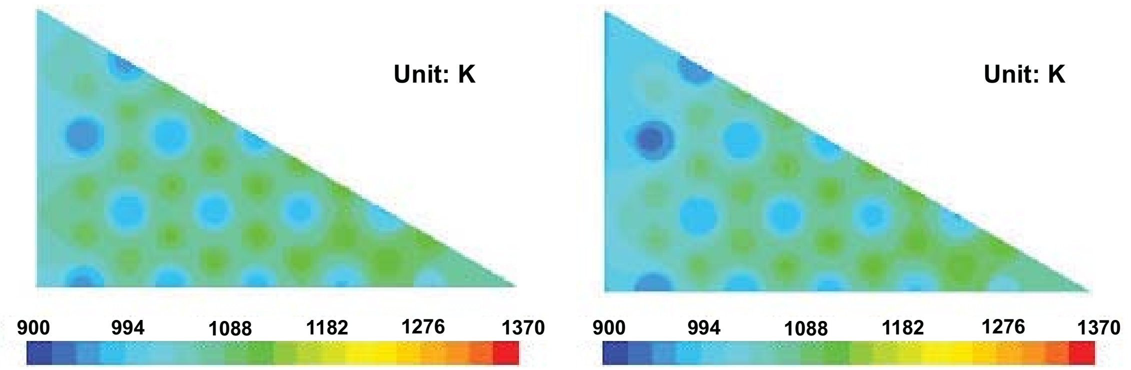
Steady state calculations are conducted using FLUENT 6.3.26 [5] with a finite volume method running on an SGI Altix ICE 8200. Helium properties, assumed to be isobaric at 70 bars, are obtained from the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce data [7]. The graphite properties are based on the data used in Fort St. Vrain safety analysis report [8]. The fuel compact properties are taken from previous thermal hydraulic studies conducted by the INL [9]. In the present study, the flow is determined by setting a differential pressure of 5.0 psi across the computational domain, which is representative of the actual operating condition. This boundary specification is realistic because it allows the physics of the flow and heat transfer to determine actual flow rates. In contrast, Tak et al. [4] set mass flow rates for each coolant channel and gap as determined by separate one-dimensional code calculations. However, the flow rates in the channels and gaps are a function of the friction, which is dependent on viscosity which is highly temperature dependent; therefore the mass flow rates are a function of the thermal characteristics of the problem. The core inlet temperatures of helium coolant are set to 490 ^{o}C. In order to investigate the effects of gap width, an average heat generation rate of 27.88 MW/m^3 based on a previous study [9] is assumed for the all fuel column regions. As for the all gap and coolant channel flow, the standard k-ε model with enhanced wall treatment is applied for the turbulence model which has a reasonable accuracy for a wide range of turbulence flow since there are no sufficient experimental data for validating the CFD for core by-pass phenomena. For the inlet turbulent conditions, 0.01 J/kg and 0.1 J/kg s are used for turbulent kinetic energy and dissipation rate. Calculations are conducted until the tolerance of iteration convergence reaches 1×10^{-5}. Momentum, energy and viscous terms are discretized by 2nd order upwind scheme. Pressure-velocity coupling is solved by the SIMPLE algorithm [10]. Default under-relaxation factors are utilized.

4. RESULTS AND DISCUSSION

Figure 4 shows temperature contours of the middle plane of the fuel column (5.154 m core



(a) 0 mm **(b) 1 mm**



(c) 2 mm **(d) 3 mm**

Fig.4 Temperature contours at the middle plane of the fuel column for different gap widths

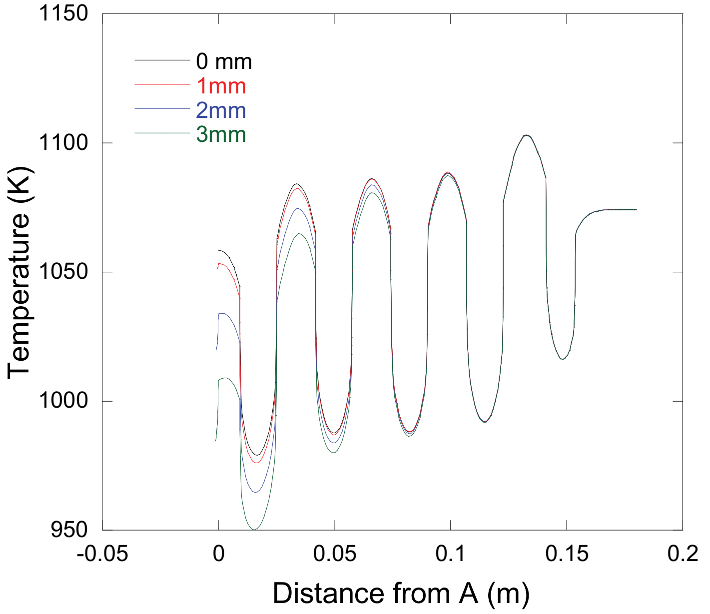
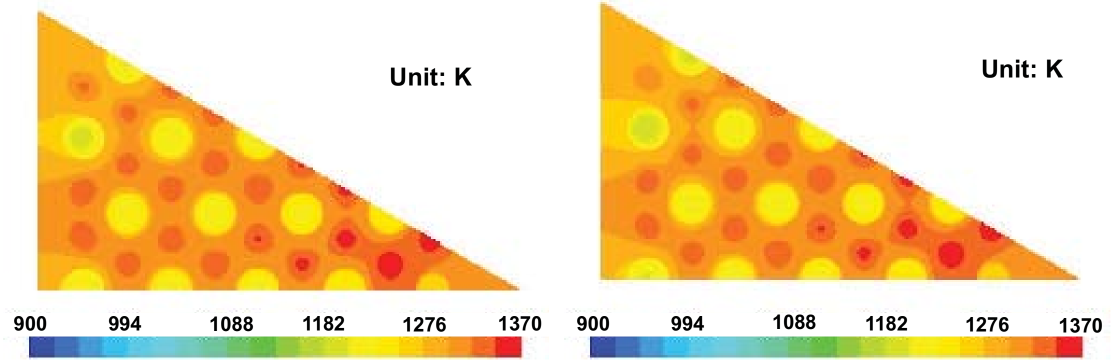


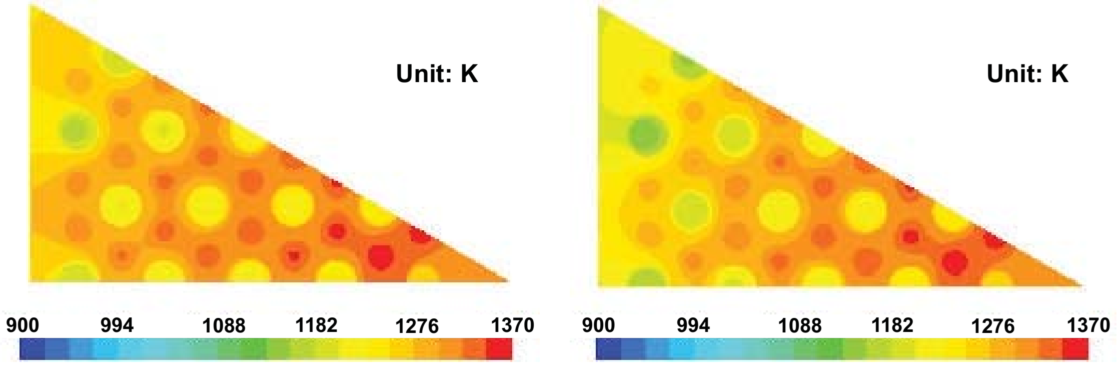
Fig.5 Temperature along line AB (c.f. Fig. 3) of the middle plane of the fuel column for different gap widths

depth). The contour temperature scale is the same for all temperature contours plotted including the fuel hot spot planes shown later in order to compare the temperatures differences between the two planes. **Figure 5** shows the temperature distribution along line A-B (c.f. Fig. 3) for all four gap-width cases. As can be seen, temperature within the block decreases from the center to the gap. Fuel temperature close to the block center (point A) shows almost the same temperature in all the gap-width cases. The largest gap width case shows the largest temperature difference from the center outward, while 0 mm and 1 mm gap-width cases show little temperature difference. In the case of the 3 mm gap width, the maximum temperature difference within the middle plane of block is approximately 100 ^{o}C.

Figure 6 shows the temperature contours of the plane involving the fuel hot spot, which is about 0.06 m above the bottom of the fuel section for all gap-width cases. **Figure 7** shows the temperature distribution along line A-B (c.f. Fig.3). As can be seen, the hottest region is at the fuel channel closest to the center of hexagonal block. Similar to the middle plane temperature gradients, temperature within the block decreases from the center to the gap region, which means that gap flow has a significant effect on the graphite block cooling. The gradient is much steeper than for the middle plane; the maximum temperature difference within the hot spot plane of the graphite block is approximately 120 ^{o}C (for the 3 mm gap-width case). Temperatures in the gap region decrease from the no-gap levels as the gap-width increases. Comparing the 3 mm and 0 mm gap-width cases, the temperature decrease in the block adjacent to the gap within the hot spot plane is about 65 ^{o}C. However, fuel temperature close to the center shows almost the same temperature in all the gap-width cases.



(a) 0 mm **(b) 1 mm**



(c) 2 mm **(d) 3 mm**

Fig.6 Temperature contours at the fuel hot spot plane for different gap widths

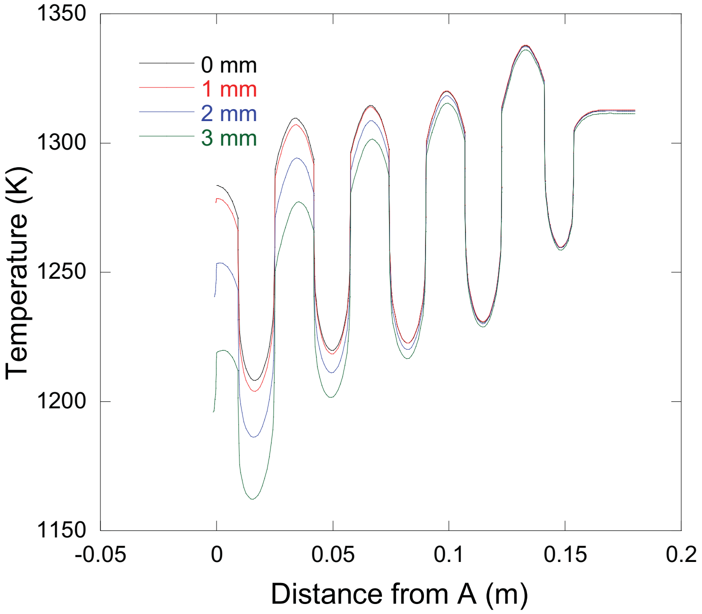
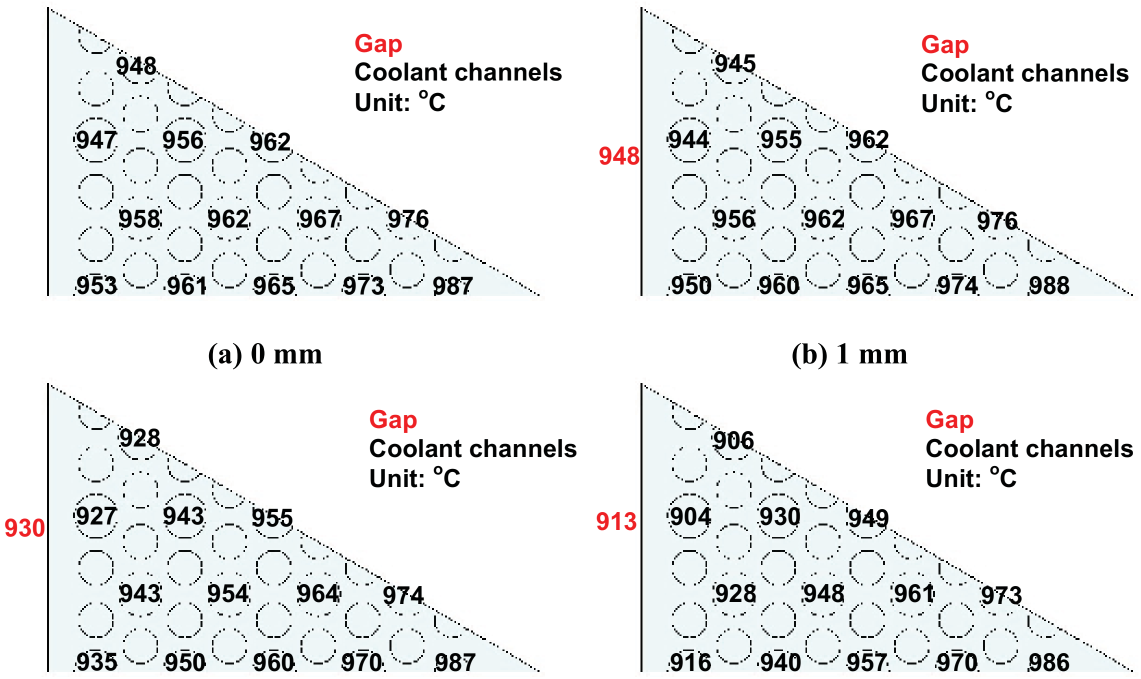


Fig.7 Temperature gradient along line AB of the fuel hot spot plane for different gap widths

Figure 8 shows the average helium gas temperatures at the coolant channels and gap outlets. The hottest temperature appears at the 12.70 mm diameter coolant channel outlet located at the center region of the block. The outlet temperature differences of corresponding coolant channels for the zero and 1 mm gap-width cases are within 1.0 %. However, the difference increases as the gap width increases, reaching a value of almost 5.0 %. On the other hand, differences of outlet temperatures at coolant channels located in the center region among different gap-width cases are within 1.0 %. This causes an increase of temperature gradient within the graphite block as the gap width increases, and the highest temperature difference among coolant outlets is 82 ^{o}C in the case of the 3 mm gap width.

The fact that the exit temperatures of some gas flow channels are relatively high could lead to hot spots occurring in the lower plenum; this phenomenon is called hot streaking. The calculation results indicate that the design consideration for the gap width is important not only for the hot spots in the fuel channels, but also for the hot streaking and hot spot issues in the lower plenum structure. The strong variation of temperature in the graphite when there are significant gaps present could also affect the structural integrity of the graphite and the fuel neutronics.



(a) 0 mm (b) 1 mm

(c) 2 mm (d) 3 mm

Fig.8 Average helium gas outlet temperatures at coolant channels and gaps for different gap widths

Table II shows the calculation results of total mass flows, gap flow fractions and maximum fuel temperatures. As expected, the flow fraction increases as the gap width increases. In addition, total mass flow rate also increases. On the other hand, calculation results of maximum fuel temperature among all the gap-width cases show small differences. This is because of the small temperature differences in the center region of a hexagonal block among all the gap width cases.

Table II Calculation results of total mass flows, gap flow fractions and maximum fuel temperatures for different gap widths

Gap width (m)	0	1	2	3
Total mass flow rate (kg/s)	0.200	0.200	0.204	0.210
Gap flow fraction (%)	-	0.425	1.98	4.18
Maximum fuel temperature (°C)	1093	1093	1092	1091

Figure 9 shows the wall shear stress at the center of the gap wall in the axial direction. As can been seen, shear stress increases in the flow direction since the viscosity increases because of the temperature increase. The gradient of wall shear stress is different among the gap-width cases. One of the reasons is a difference of temperature distribution between each gap-width case as shown in previous results. The gap mass flow rate and gap flow fraction is a function of the wall shear stress. Wall shear stresses are functions of flow velocity parallel to the wall and the velocity is affected by the temperature dependent thermal properties of helium coolant. The differences in the axial distribution of the wall shear stress for the different gap-width cases show that the temperature and flow distributions are strongly

coupled. Hence, it is important to consider local heat generation rate within fuel blocks which is not uniformly distributed in the core.

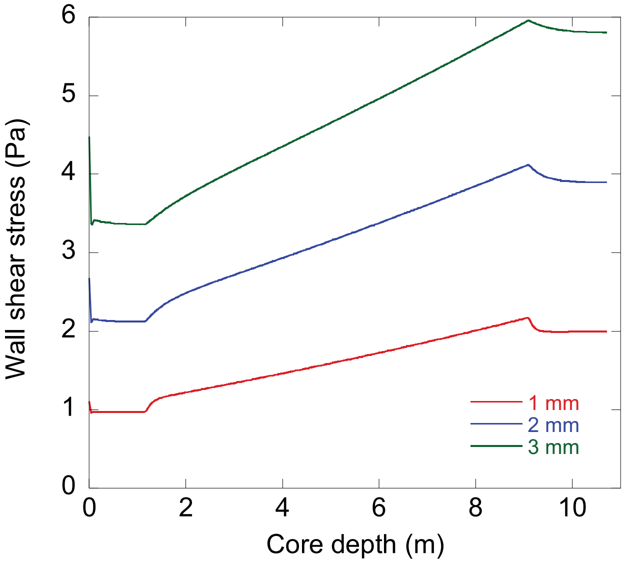


Fig.9 Wall shear stress at center of the gap for different gap widths

5. CONCLUSIONS

Three dimensional calculations of a typical prismatic VHTR were conducted by using the commercial CFD code FLUENT in order to investigate the influence of gap geometry on flow and temperature distributions in the reactor core. A 1/12 sector of the block for the whole core length is generated and parametric studies performed changing the gap width. The results are summarized as follows:

- Increasing the gap width decreases the outlet helium gas temperatures at coolant channels and gaps.
- Increasing the gap width increases the temperature gradient within the graphite block.
- Temperature and flow distributions in coolant channels and gaps are strongly coupled.
- The radial temperature gradient in a hexagonal block is considerably impacted by the gap geometry.

Preliminary calculation results showed that detailed three dimensional thermal hydraulic analysis using CFD is an effective method for reactor core designs considering the coolant by-pass phenomena. A further direction of the study will be consideration of a thermal property change of graphite because of the neutron fluences from the beginning to the end of the fuel cycle. Also, transition of the flow regime could be taken into account in case of small gap width cases. In addition, validation efforts will be conducted to ensure the quantitative results.

ACKNOWLEDGMENTS

This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy. The authors also wish to thank to Prof. Yoichi Fujii-e, former chairman of Atomic Energy Commission of Japan, for assistance under the Fujii-e Research Initiative by the U.S. Department of Energy.

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