NUMERICAL SOLUTION OF HEAT TRANSFER PROCESS IN A PRISMATIC VHTR CONSIDERING CORE BYPASS AND CROSS FLOW

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ABSTRACT

The existence of interstitial gaps between fuel blocks in a VHTR are inevitable due to tolerances in manufacturing and installation, thermal expansion and irradiation shrinkage. Both bypass flow and cross flow gaps exist in the core. The coolant mass flow rate distribution, temperature distribution and hot spot are significantly affected by bypass and cross flow. In the present study, three-dimensional CFD analysis is conducted for the thermal analysis in the reactor core. Validation study for the turbulence model are performed by comparing the friction coefficient with published correlations. A sensitive study for near wall mesh is conducted to ensure the mesh quality. Parametric study by changing the size of bypass gap and cross gap are performed with a one-twelfth sector of fuel block. Simulation results show the influence of bypass gap size on temperature distribution and coolant mass flow rate distribution in the prismatic core. It is shown that the maximum fuel and coolant channel outlet temperature increases with the increase of gap size which may lead to a risk on the structure of fuel block. The cross flow is divided to two kinds. One is the cross flow from bypass gap to coolant channels and another is the flow from high pressure coolant channels to low pressure coolant channels. These two kinds of flow have opposite influence on temperature gradient. It is found that the presence of the cross flow gaps may have a significant effect on the distribution of the coolant in the core due to flow mixing in the cross gaps.

KEYWORDS
VHTR, Core bypass flow, Cross flow, CFD, Turbulence model

1. INTRODUCTION

The very high temperature reactor (VHTR) is developed aiming not only for electricity generation but also for process heat utilization e.g. hydrogen production, coal gasification, etc. due to the high reactor outlet temperature to be achieved at about 1000℃. In the present stage, two types of reactor concepts, i.e., a prismatic graphite block type and a pebble bed type, are under development in the national research program such as the next generation nuclear plant project (NGNP) of the US. The prismatic VHTR is a helium-cooled block type reactor. Hexagonal graphite blocks with fuel embedded are stacked as concentric rings in the core. A cutaway view of the 600MWth General Atomics Gas-Turbine Modular Helium Reactor [1, 2] is shown in Fig.1. A total of 10 layers of fuel blocks are stacked in the vertical direction, each block is 360 mm in width and 793 mm in height. A cross section view of the core is shown in Fig.2. Small gaps among the neighboring blocks exist due to tolerances in manufacturing and installation. Also, the gap size will change during the operation because of thermal expansion and fast-neutron induced shrinkage [3]. The flow paths in the prismatic core are shown in Fig.2. Most of the coolant flows through the coolant holes as designed, while a little portion of coolant will flow through the gaps between hexagonal graphite blocks, which is defined as bypass flow. Besides, coolant flows in perpendicular direction to the coolant holes through the interfacial gaps between two block prisms is defined as crossflow. The existence of bypass and cross flow decreases the coolant flows through coolant channel and thus leads to an increase in maximum fuel temperature, which raises potential structural problems. In addition, some research indicate that bypass and cross flow will cause a large variation in temperature for the coolant jets exiting the core into the lower plenum, which may cause "hot streaking" issue near the entrance of the hot outlet duct [4]. In this regard, evaluation of the core flow distribution and thermal hydraulic analysis are important for the reactor design and safety assessment.

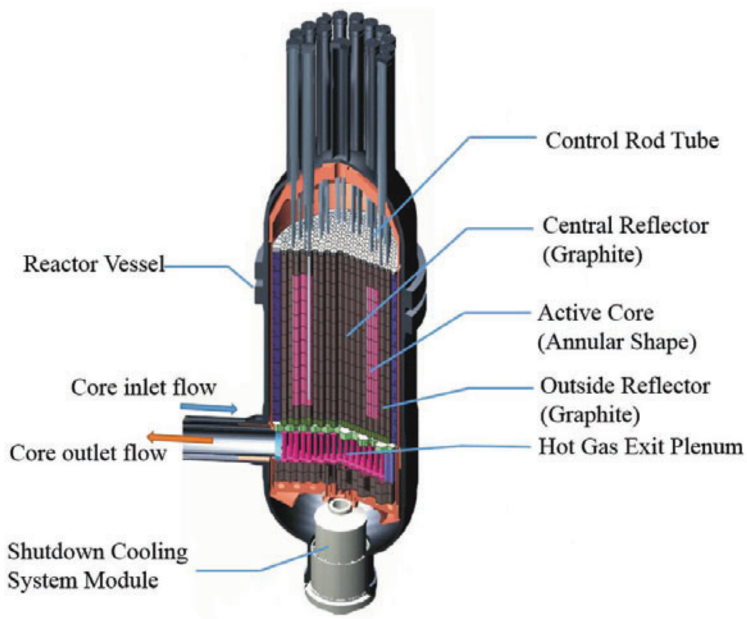


Figure 1. Cutaway View of the GT-MHR [1, 2].

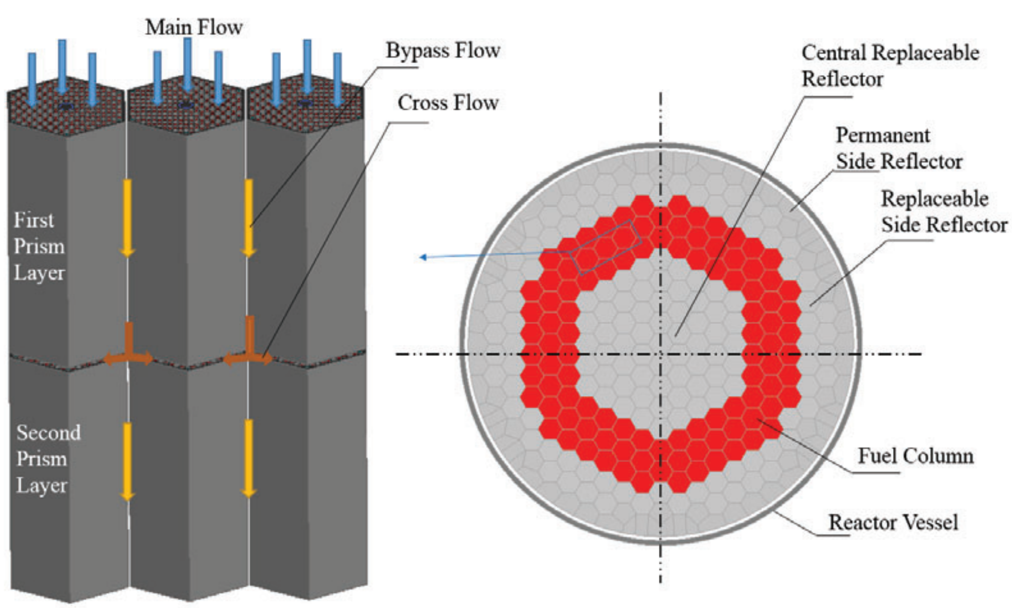


Figure 2. Bypass Flow and Cross Flow Gaps in the Core.

Simplified models such as the equivalent cylinder model and the unit cell model have been widely used for the analyses and designs for prismatic reactors [5]. Although a basic evaluation of heat transfer in the core can be acquired with economically reduced computational efforts, these simplified models are hard to take the interior heat transfer within a single fuel assembly and the gap flow between fuel assemblies into consideration. Thus, several experimental researches and computational fluid dynamic (CFD) analysis have been carried out to investigate the bypass and cross flow phenomena. For the complexity of core, experimental studies are based on simplified structures. These results show the effect of bypass and cross flow on flow distribution, and it is considered that pressure difference is the main influencing factor [6]. A Three dimensional simulation by using a one-twelfth sector of fuel block in full length of core has been conducted by Tak et al. [7]. The temperature distribution of the fuel block was clearly shown and a better understanding of the bypass flow influence was acquired. However the coolant mass flow rate distribution was not clarified through the calculation model. Sato et al. [8, 9] also conducted a research on the core by a one-twelfth sector. The influence of bypass flow on maximum fuel temperature and mass flow distribution were investigated.

For the study of cross flow in full length of core, CFD approach is even more complex due to the block structure. Thus, very few reports can be found. Wang et al. [10] studied the cross flow phenomenon based on a two-layer block model. According to the simulation result, a significant flow occurs in the crossflow gap by removing coolant from bypass flow gap toward coolant holes with a reduction up to 28% of the mass flow rate in the bypass flow gap. However this study is based on normal atmospheric temperature without heating and the inlet boundary condition adopted is uniform mass flow rate condition.

In the present study, heat transfer process within a referenced GT-MHR is investigated by using the commercial code ANSYS FLUENT (ANSYS 14.0). Effect of core bypass gap on flow distribution and fuel maximum temperature are studied with a full length model. Hot spot temperature of the block, coolant outlet temperature difference and bypass flow fraction are compared for bypass gap sizes of 0, 3 and 5 mm. The detailed temperature distribution within the fuel block is clarified. Moreover, the influence of core cross flow on mass flow rate of coolant outlet channels and heat transfer in the core is also investigated.

2. SIMULATION MODEL

A one-twelfth sector of the fuel block is cut out due to the symmetry structure, shown in Fig.3. A full length model of 10.704 m is built including an upper reflector section of 1.189 m, 10 fueled blocks and a lower reflector section of 1.585 m. A cross section of the three-dimensional mesh is shown in Fig.4.

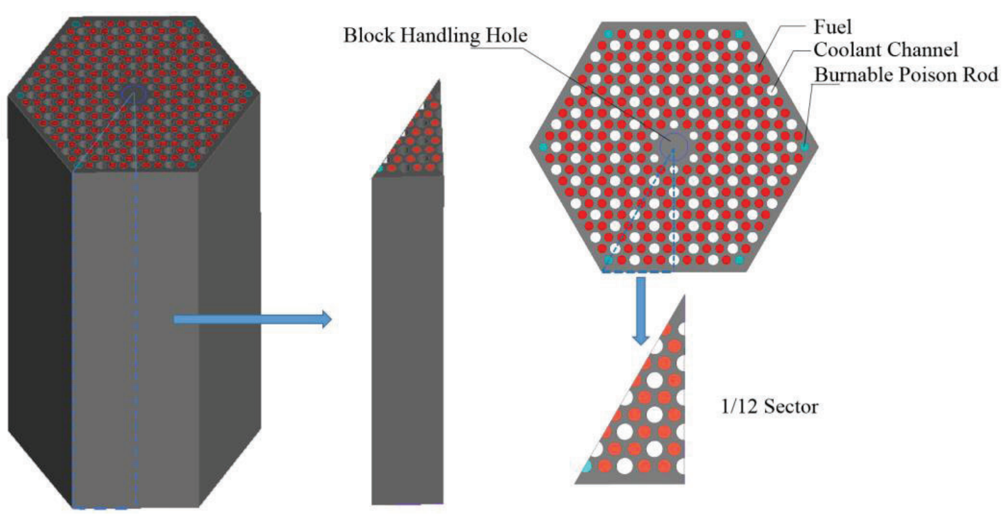


Figure 3. A 1/12 Sector of Single Fuel Block.

There are two different size for the coolant channel, 12.70 mm for a half diameter coolant near the center of a fuel block and other 5 full and 7 half diameter coolant channels of 15.88 mm. The 1/12 sector also covers 17.5 fuel holes and 0.5 burnable poison rod hole. Helium gas flows from inlet downwards into the lower plenum with an inlet temperature of 490 ℃ at about 7 MPa and a pressure drop of about 5.0 psi (34474 Pa) is used in this study. A uniform heat generation rate of 27.88 MW/m^3 is set for the fuel channels. Symmetry boundary conditions are set for all the other sides of the model.

In this study, a fine boundary mesh is used in the coolant channel with an overall Y^+ of less than 6. SIMPLE algorithm is chosen for the pressure velocity coupling method. Iteration convergence of 10^{-5} was set for all variables, and it was considered to be sufficient [8].The changes in material properties of helium gas, graphite and fuel compacts with temperature are accounted in this work, shown in Table I. Helium properties are assumed to be isobaric at 7 MPa.

Table I. Material Properties for the 3-D Numerical Analysis of the Prismatic Core.

Material	Property	Temperature range	Value or correlation	Ref.
Graphite (H-451 graphite)	Density, ρ (kg/m^3)	[255.6K-2200K]	1740	[12]
	Specific heat, c_p (J/kg·K)	[255.6K-2200K]	$-393 + 4.91T - 4.16\times10^{-3}T^2 + 1.66\times10^{-6}T^3 - 2.54\times10^{-10}T^4$	[12]
	Thermal conductivity, k (W/m·K)	[255.6K-1644.4K]	$124 - 0.332T + 4.09\times10^{-4}T^2 - 2.11\times10^{-7}T^3 + 4.02\times10^{-11}T^4$	[12]
Fuel compacts (TRISO)	Density, ρ (kg/m^3)	[255.6K-2200K]	2390	[12]
	Specific heat, c_p (J/kg·K)	[255.6K-533.3K]	581	[12]
		[533.3K-1088.9K]	$-2960 + 15T - 2.33\times10^{-2}T^2 + 1.64\times10^{-5}T^3 - 4.4\times10^{-9}T^4$	
		[1088.9K-2200K]	$414 + 8.63\times10^{-1}T - 6.14\times10^{-4}T^2 + 2.09\times10^{-7}T^3 - 2.7\times10^{-11}T^4$	
	Thermal conductivity, k (W/m·K)	[255.6K-2200K]	$3.94 + 3.59\times10^{-3}T - 1.98\times10^{-9}T^2 + 3.19\times10^{-12}T^3 - 9.77\times10^{-16}T^4$	[12]
Helium gas	Density, ρ (kg/m^3)	[300K-1500K]	P/RgT	[13]
	Specific heat, c_p (J/kg·K)	[300K-1500K]	5197	[13]
	Thermal conductivity, k (W/m·K)	[300K-1500K]	$1.034\times10^{-4} + 2.58\times10^{-7}T$	[13]
	Dynamic viscosity, μ (Pa·s)	[300K-1500K]	$1.307\times10^{-5} + 3.319\times10^{-8}T$	[13]

The standard k-ε (SKE) turbulence model with enhanced wall treatment is employed for coolant channels and gaps in this simulation [11]. Enhanced wall treatment is a near-wall modeling method that combines a two-layer model with enhanced wall functions. As we all know, the presence of walls will have a significantly influence on turbulence modeling, since the mean velocity field and the turbulence are changed near wall where large gradients occur. Usually there is three layers considered to be in the near wall region. In the innermost layer, the flow and heat transfer are dominated by viscosity. While in the outer layer turbulence plays the main role. And an intermediate region between the two layers exists where the effects of viscosity and turbulence are both not negligible. In the near wall treatment, the viscosity-affected region and a fully turbulent region is divided by a wall-distance-based, turbulent Reynolds number, Re_y, which is defined as:

$$Re_y = \frac{\rho y \sqrt{k}}{\mu} \tag{1}$$

Where, y is the wall-normal distance calculated at the cell centers, which is interpreted as the distance to the nearest wall. In the viscosity-affected region ($Re_y < Re^*$; $Re^* = 200$), the one-equation model of Wolfstein [14] is employed and in the fully turbulent region ($Re_y > Re^*$) the k-ε model is employed. The enhanced wall functions were developed by smoothly blending the laminar and turbulent wall laws by using a function suggested by Kader [15]. An influence factor of Y^+ ($= \rho u_\tau y/\mu$) is defined to judge whether the first near wall mesh is put in proper region. For very fine near wall mesh with small Y^+ value, the enhanced wall treatment is identical to two layer model, while for coarser mesh enhanced wall functions will take place.

2.1. Mesh Validation

The mesh used in this study is hexahedral dominate and is created by using ANSYS ICEM14.0. Figure 4 shows a cross section view of the mesh generated for the one-twelfth sector. Blue parts show the coolant channel, red mesh represent for fuel rods and the black mesh refers to the graphite block. Mesh independence study is conducted by comparing the previous mesh (no gap) with a finer mesh, for which smaller mesh size has been used in the fuel compact and graphite region. Total cell numbers of the two meshes are about 7.2 and 11 million, respectively. Simulation results of total mass flow rate and maximum fuel temperature are compared between the two mesh cases. The differences for the total mass flow rate and maximum fuel temperature are 0.015% and 0.01%, respectively. It indicates that the mesh size is adequate for the solid area.

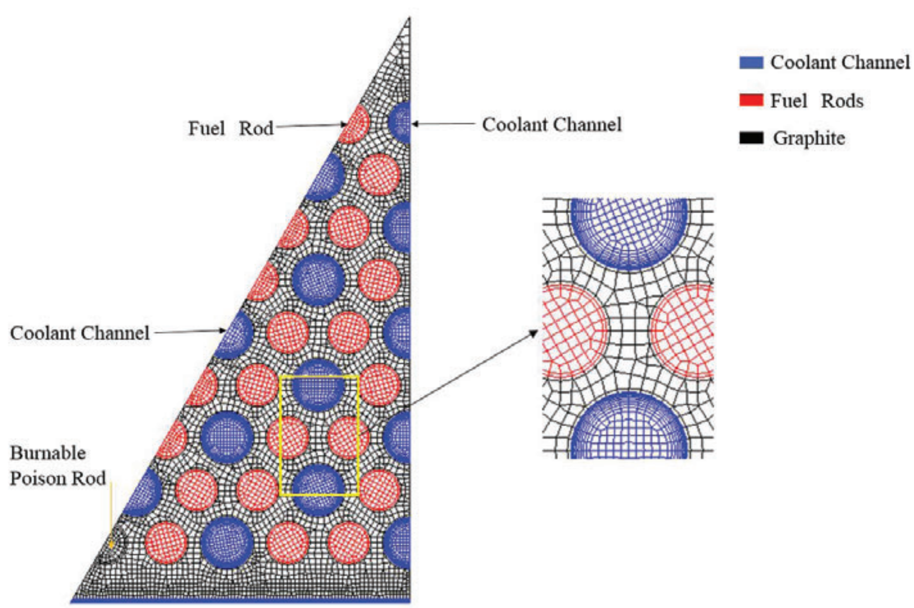


Figure 4. Cross Section View of the Mesh

Very fine meshes were set for the bypass gaps and cross flow gaps with Y^+ value of less than 3. In the very small bypass flow gaps of 3 mm (1.5 mm in the model according to symmetry structure) and 5 mm (2.5 mm in the model according to symmetry structure), 30 and 50 mesh layers were put in the gaps, respectively. By doubling the mesh layers of the 3 mm bypass gap case, less than 0.2% difference were found for the bypass gap outlet temperature and mass flow rate. In the very small cross flow gaps of 1 mm and 3 mm, 20 and 60 layers were put in the gaps, respectively. By doubling the mesh layers of 1 mm cross gap case, less than 0.05% difference were found for the total mass flow rate and coolant channel outlet temperature. Thus, it indicated that the meshes used in the bypass flow and cross flow gaps were well enough.

As mentioned before, the enhanced wall treatment used in this study is somewhat relying on the value of Y^+. Therefore, a sensitive study for Y^+ is conducted here by verifying the first layer offset distance from the wall in the coolant channel. The comparison results are shown in Table II. Y^+ is set from about 3 to 30. The minimum Y^+ is compared with as a baseline. The maximum difference occurs at Y^+ of about 12, of which the difference for total mass flow rate is as high as 4.58%. The average coolant outlet temperature of the case is also about 22℃. Therefore, although by using the enhanced wall treatment, a wall-function mesh can also be used to achieve the result without significantly reducing the accuracy, a proper Y^+ is still important.

Table II. Result of Y^+ Sensitive Study

Y^+	Coolant channel outlet Temp. (average), ℃	Total mass flow rate, kg/s	Maximum Difference with the Y+ ~3 case
~3	949.8	0.2030	-
~6	954.2	0.2011	0.94%
~12	927.4	0.2123	4.58%
~30	952.5	0.2021	0.44%

2.2. Model Validation

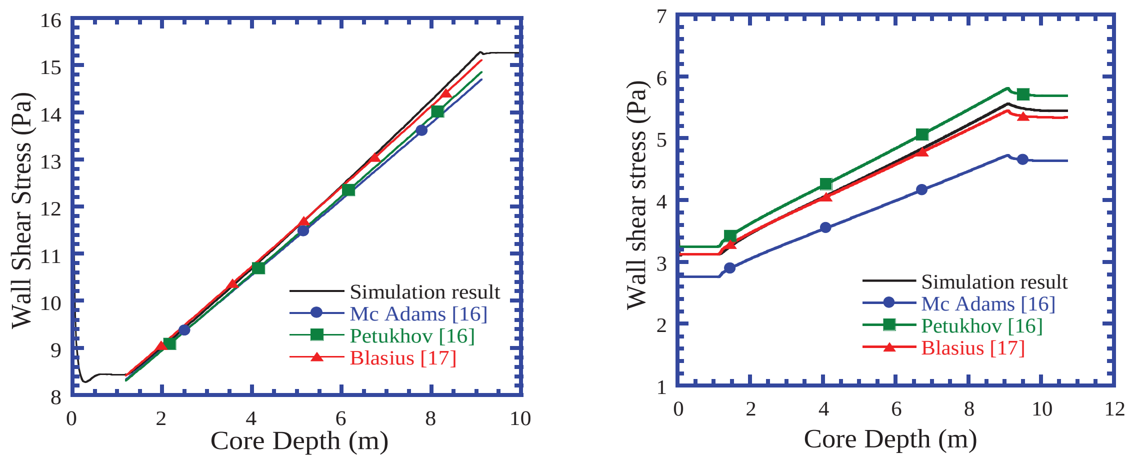
The Reynolds number in the coolant channel for the present study is from 30,000 to 45,000. So this is a fully developed turbulent flow in a circular channel. Since there are a lot of studies and correlations for flow and heat transfer in this region, several typical published empirical correlations are chosen to be compared with the simulation result. The wall shear stress for the diameter of 15.88 mm coolant channel and the bypass gap are compared with the Mc Adams correlation [16], the Petukhov correlation [16] and the Blasius correlation [17], as shown in Fig.5 (a) and (b). These correlations are list as follows:

$$f = 0.184 {Re_D}^{-0.2} \quad \text{Mc Adams} \tag{2}$$
$$f = (0.79 \ln Re_D - 1.64)^{-2} \quad \text{Petukhov} \tag{3}$$
$$f = 0.3164 / {Re_D}^{0.25} \quad \text{Blasius} \tag{4}$$

Here f is friction factor, and wall shear stress τ_w is defined as:

$$\tau_w = f \rho V^2 / 8 \tag{5}$$
$$V = \frac{\dot{m}}{\rho A_c} \tag{6}$$

Where, ρ is density, kg/m^3; V is bulk velocity, m/s; $\dot{m}$ is mass flow rate, kg/s and A_c is the section area of the circular channel, m^2.



(a) Coolant channel (b) Bypass gap

Figure 5. Comparison of Wall Shear Stress with Empirical Correlations

It can be found from Fig.5 (a) that the numerical simulation results for wall shear stress in the coolant channel matches well with the empirical correlations, especially for the Blasius correlation. And the differences between simulation results with Mc Adams and Petukhov correlations are 3.7% and 2.8%, respectively. The numerical simulation results for wall shear stress in bypass gap also matches best with the Blasius correlation, as shown in Fig.5 (b). While it is a little lower compared to the Petukhov correlation and a little higher than the Mc Adams correlation.

The Reynolds number in the bypass gap is based on the gap width, calculated by equation (7). For the 3 mm bypass gap, the *Re* ranged from about 3000 to 4200 in this study. While for the 5 mm bypass gap, the *Re* ranged from about 7000 to 10000. Thus, the flow in the bypass gap is considered as turbulent flow.

$$Re(\delta) = \frac{\rho V \delta}{\mu} = \frac{\dot{m}}{\mu L} \tag{7}$$

Where, δ is the gap width, m; μ is dynamic viscosity, kg/(m· s); $\dot{m}$ is the mass flow rate, kg/s; L is the gap length, 0.104 mm.

3. RESULTS FOR NO GAP CASE

The location of maximum temperature of the single fuel assembly is called hot spot. Due to the temperature limitation of the fuel assembly, the hot spot temperature should not get over a criterial value of about 1600 ℃ [18]. Figure 6 shows a cross section view of temperature and velocity distribution in hot spot plane, which is about 60 mm above the last prism of fuel block. The triangle AOB is the simulated 1/12 sector of a fuel block, and the figure is obtained according to the symmetry structure in order to show an entire fuel block.

As can be seen, the temperatures of the fuel rods and coolant channels in the inner side are higher than those in the outer side. The hot spot occurs at innermost fuel rods. The temperature of the innermost six coolant channels which have smaller diameters of 12.7 mm are significantly higher than other coolant channels, meaning insufficient cooling in these channels. The lowest-temperature coolant channel occurs near the block side between point A and B. The temperature distribution along OA and OB line are shown in Fig.7 (a) and Fig.7 (b). In line OA, the valleys refers to the coolant channels. In line OB, peaks are in the location where fuel rods are, and valleys are for coolant channels. It can be found that both peak and valley values decrease along the OA direction. The temperature differences between point O and A is about 34 ℃. For point O and B, the temperature difference is about 26 ℃.

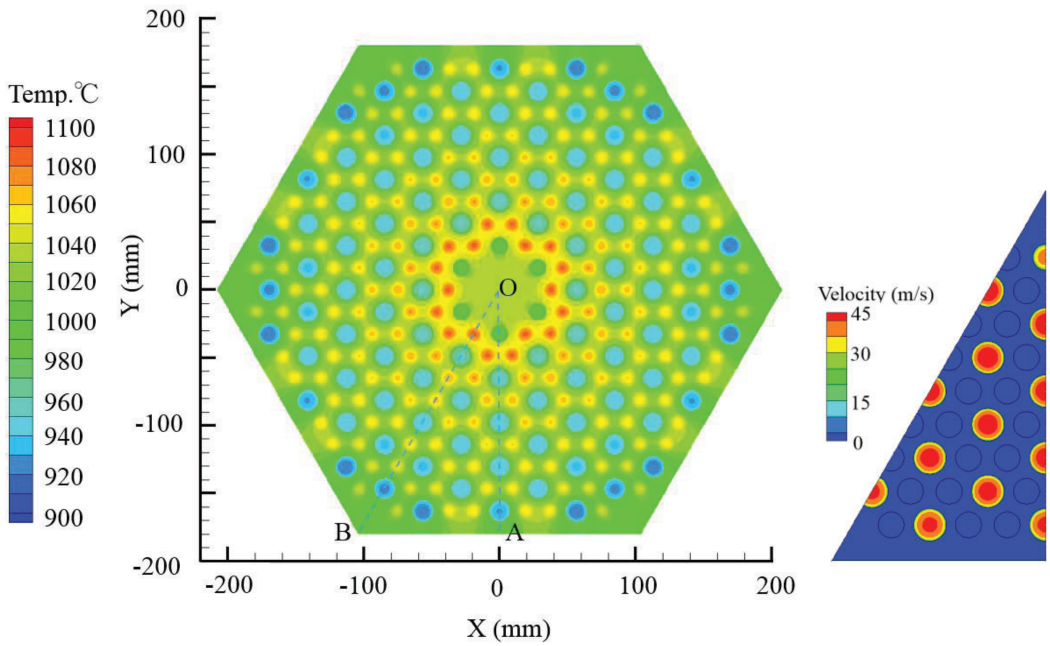
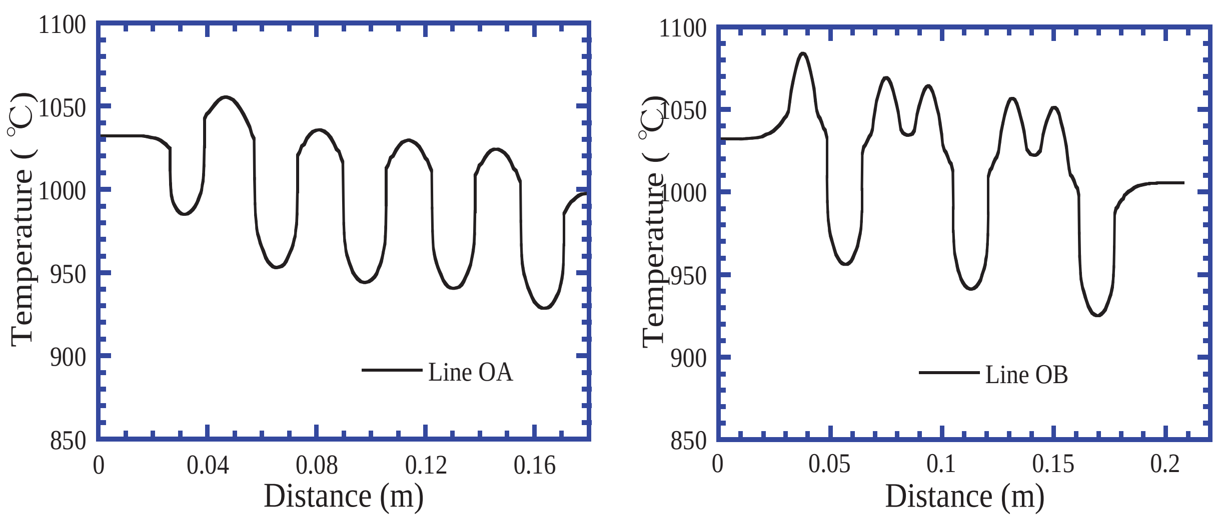


Figure 6. Cross Section View of Temperature and Velocity Distribution at the Fuel Hot Spot Plane.



(a) Line OA (b) Line OB

Figure 7. Temperature Distribution along Line OA and OB

One important reason of the temperature gradient from center to outside is due to the smaller diameter of the innermost coolant channel. As can be seen in the velocity distribution graph, the velocity for the innermost coolant channel is also small than that for other coolant channel. A smaller diameter and a smaller velocity will both lead to insufficient cooling.

4. EFFECT OF BYPASS GAP SIZE

Since the bypass gap size changes over the lifetime during operation due to thermal expansion and irradiation. Different bypass gap sizes should be studied to understand the effect of gap size on flow distribution and heat transfer. In this study, bypass gaps of 0, 3 and 5 mm are numerically simulated. Here, the bypass gaps mean the spaces between two fuel blocks in the same prism layer. Half size of the gap is included in the one-twelfth section due to symmetry. Pressure boundary conditions are adopted here to calculate the mass flow rate distribution for each coolant channel. However, the total mass flow rate will increase with the increase of bypass gap size if the pressure difference is kept constant. In order to investigate the effect of bypass flow gap size on bypass flow fraction, an approximately constant inlet total mass flow rate of 0.2 kg/s is kept for all bypass gap size cases by changing the pressure difference in this numerical simulation.

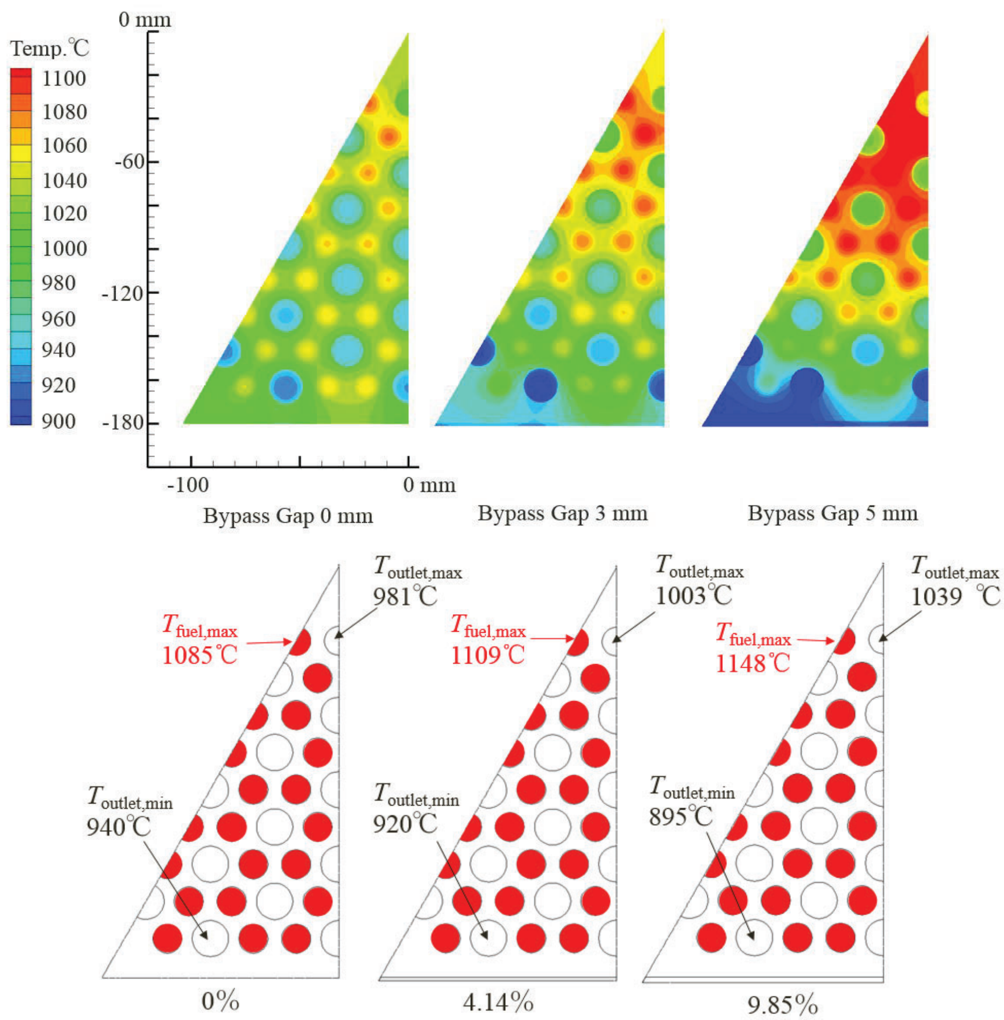


Figure 8. Temperature Distribution and Bypass Flow Fraction for Different Gap Sizes

Figure 8 shows the temperature distribution of the cross section with different bypass gap sizes in the upper half. In addition, the maximum and minimum coolant outlet temperature, the maximum fuel rod temperature and the bypass flow fraction for different gap sizes are shown in the lower half. Red circulars in the lower half represent for fuel rods and white circles are coolant channels. These are cross sections at the hot spot plane, about 60 mm above the last prism of fuel block. It can be found that the maximum fuel temperature (hot spot) increases as the gap sizes increases. With a 3 and 5 mm bypass gap, the hot spot temperature increases from 1085 ℃ to 1109 ℃ and 1148 ℃, respectively. It indicated that, the existence of the bypass gap will significantly contribute to the hot spot temperature. With the increase of gap size, the risk of losing integrity for the coated fuel rods will become higher. The coolant maximum outlet temperature also increases with the increase of gap sizes and a larger temperature difference within coolant channel outlet will occur with larger gap sizes. The maximum temperature difference of about 141 ℃ exists at the bypass gap 5 mm case.

It can be seen from the temperature distribution figure of bypass gap 5 mm case that the temperature gradients from the near center to the outside part of the fuel block for fuel rod, coolant channel and the graphite are much larger than other two cases. Therefore, the existence of the bypass gap will significantly contribute to the non-uniformity of outlet temperature of coolant channels. Which may further lead to some undesired problems like "hot streaking" issue in the insulation layer of lower plenum or insufficient mixing before flowing into the metallic outlet duct.

The mass flow fraction for a 3 mm bypass gap is about 4.14% of total mass flow rate, and increases to 9.85% for a 5 mm bypass gap. As can be found that the bypass flow fraction increasing ratio is not proportional to the gap size increasing ratio. While bypass gap size increases from 3 mm to 5 mm with a ratio of less than 2, the flow fraction increases more than twice as much. As the gap size increases, the flow velocity through the gap also increases. The increasing of bypass flow fraction will decrease the amount of coolant flowing through designed coolant channels, and lead to insufficient cooling.

5. EFFECT OF CROSS FLOW

As introduced in Fig.2, except for the designed main coolant channel flow, both bypass and cross flow will exist in the reactor core. Coolant flows in perpendicular direction to the coolant holes through the interfacial gaps between two block prisms is defined as crossflow. Different cross gap sizes of 0, 1 and 3 mm are studied. Since the cross gap size is very small and the velocity perpendicular to the main flow is also very small, the Reynolds number in the cross gap is about less than 2300. Therefore, the flow regions in the cross gaps are considered as laminar zones. As we know, the cross flow is driven by the pressure difference between the coolant channels and the bypass gap. The bypass gap size of 5 mm is used in this study. Pressure boundary conditions are adopted for inlet and outlet coolant channels. Inlet static pressure is maintained at about 7 MPa. To keep the total mass flow rate constant of about 0.2 kg/s, a pressure difference of about 4.2 psi (28958 Pa) is set for the calculation. Totally, nine layers of cross gaps between ten fuel block prisms are considered.

The cross section view of pressure and temperature distribution between the last two prisms is shown in Fig.9. This is the case for cross gap 0 mm. From the pressure distribution, it can be found that the pressure for bypass gap is higher than the coolant channels nearby, and for the coolant channels, which are located near the center of the fuel block have higher pressures than the outside. The pressure distribution for the coolant channels is alike the temperature distribution.

According to the pressure distribution, a cross flow will flow from bypass gap to the coolant channels nearby driven by the pressure difference. It will decrease the amount of coolant in the bypass gap and increase the coolant in the coolant channels. As mentioned before, the decreasing of bypass flow fraction will lead to a decrease in the fuel hot spot temperature. In addition, a crossflow between coolant channels will also occur by flowing from inside coolant channels to the outside coolant channels due to the pressure difference. This kind of cross flow will contribute to the flow mixing in the cross gaps. However, the coolant flowing from inside coolant channels to outside channels will enlarge the temperature difference since the temperatures are higher in the inside part and needs more coolant. Therefore, the cross flow between coolant channels will have negative effect on heat transfer in the fuel block and lead to an increase in hot spot temperature.

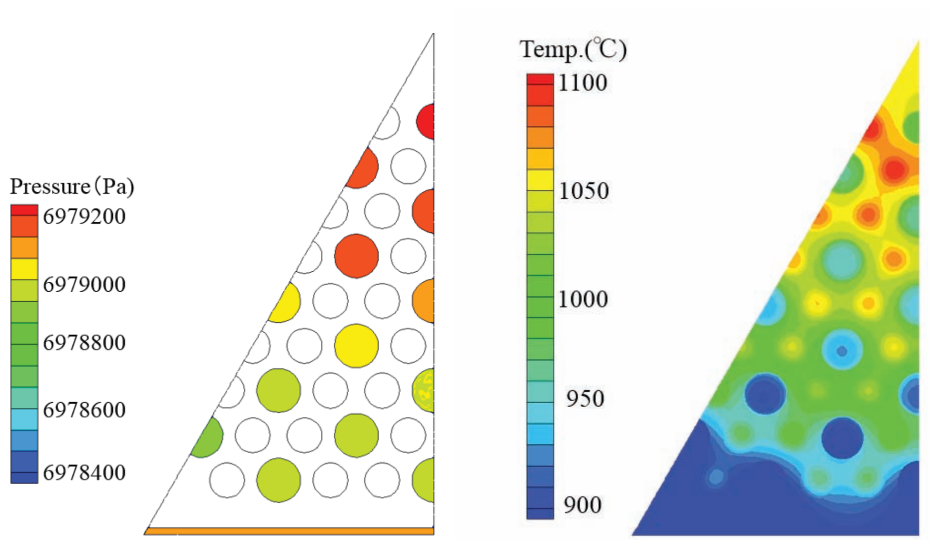


Figure 9. Pressure and Temperature Distribution for No Cross Gap Case at Cross Section Between 9th and 10th Fuel Block

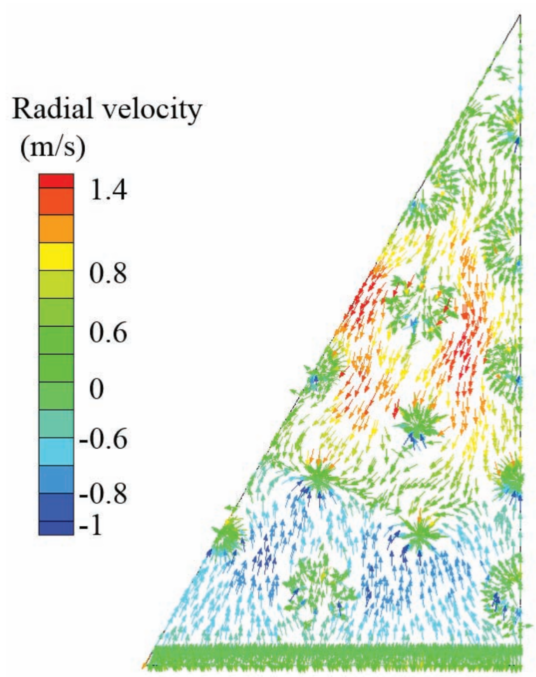


Figure 10. The Velocity Distribution of the Cross Flow Between 9th and 10th Fuel Block

A typical cross section view of the velocity distribution for the cross gap 1mm case is shown in Fig.10. The location of the figure is in the middle of the cross gap. Blue arrows show the crossflow from bypass gap to the nearby coolant channels, red arrows show the cross flow from higher pressure coolant channels to lower pressure channels and this two kinds of cross flow will mix in the middle part. The two kinds of flow have contrary influence on hot spot temperature.

The effect of cross gap size on bypass flow fraction, cross flow fraction, hot spot temperature and coolant channel outlet temperature difference is shown in Table III. The bypass flow fraction decreases with the increase of cross gap size slightly due to cross flow. The hot spot temperature decreases only one centigrade degree and the influence of gap size is not obvious. With the existence of cross gap, the coolant channel outlet temperature difference decrease from 143.5 ℃ to 136.3 ℃. However, the cross gap size of 1 mm and 3 mm do not show large difference. The improvement in uniformity of coolant channel outlet temperature is believed to be a result of the cross flow between the ten prism layers.

Table III. Effect of Cross Gap Size on Flow and Temperature Distribution.

	Cross gap 0 mm	**Cross gap 1 mm**	**Cross gap 3 mm**
Total mass flow rate (kg/s)	0.20	0.20	0.20
Bypass flow fraction (%)	9.85	9.58	9.55
Cross flow fraction (%)	0	0.27	0.30
Hot spot temperature (℃)	1148.6	1146.8	1147.0
Coolant channel outlet ΔT_{max} (℃)	143.5	136.3	136.3

6. CONCLUSIONS

Three dimensional full length model of a fuel column in a reference prismatic VHTR is conducted for heat transfer and flow distribution simulation applying commercial CFD codes. Both core bypass and cross flow are investigated for various sizes. Mesh validation is performed by adapting a finer mesh in the solid area. Besides, a sensitive study for the value of Y^+ is done for a range of 3 to 30. The calculation result of friction coefficient for a coolant channel from inlet to outlet is compared to published empirical correlations. The results show quite agreement, and then proved the validation of SKE turbulence model used in this calculation. The effects of bypass flow and cross flow on hot spot temperature, coolant outlet temperature difference and mass flow rate are clarified as follows:

(1) Bypass flow has significant influence on heat transfer in the fuel column. With a larger bypass gap size, a larger temperature gradient will occur in the block.
(2) Hot spot temperature increases as bypass gap size increases.
(3) Coolant channel outlet temperature difference increases with the increase of bypass gap size, which will increase the risk of “hot streaking” or insufficient mixing in the lower plenum.
(4) Cross flow is driven by the pressure difference between the bypass gap and the coolant channels.
(5) The cross flow from bypass gap to coolant channels will contribute to heat transfer and decrease temperature gradient, while the cross flow from inside high pressure channels to outside low pressure channels will decrease the coolant in the hot area and increase temperature gradient.
(6) The existence of cross flow will decrease the maximum coolant channel outlet temperature difference, while the gap size shows little influence on the result.

NOMENCLATURE

Ac : Circular area of the coolant channel [m^2]

c_p : Specific heat of helium gas [J/(kg·K)]
D : Diameter of the coolant channel [m]
f : Friction Coefficient
k :Thermal conductivity [W/(m·K)]
$\dot{m}$: Mass flow rate [kg/s]
p :Static pressure [Pa]
Pr : Prantl number
q :Heat flux [W/m^2]
T : Temperature [℃]
u :X component velocity [m/s]
u_τ : Friction velocity, defined as $\sqrt{\tau_w/\rho}$ [m/s]
v :Y component velocity [m/s]
V : Bulk velocity of fluid [m/s]
$\vec{V}$: Velocity vector of fluid
w :Z component velocity [m/s]
y : wall-normal distance calculated at the cell centers [m]
$Y+$: dimensionless near wall distance, defined as $\rho u_\tau y/\mu$
X : Coordinate along the shortest edge [m]
Y : Coordinate along OA direction [m]
Z : Coordinate along the height direction [m]
μ : Molecular viscosity [kg/(m·s)]
ρ : Density of helium gas [kg/m^3]
τ_w : Wall shear stress [Pa]

ACKNOWLEDGMENTS

This work was supported by the Japan Society for the promotion of Science (JSPS) (Grant-in Aid for Scientific Research (C), KAKENHI, No. 24560231).

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