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Research Article

NUMERICAL SIMULATION AND PARAMETRIC STUDY OF VERY HIGH-TEMPERATURE GAS-COOLED REACTOR (VHTR) FUEL ASSEMBLY

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ABSTRACT:
The very high-temperature gas-cooled reactor (VHTR) is a Gen IV nuclear reactor that has been developed from the high-temperature gas-cooled reactor (HTGR) with the aim for higher thermal efficiency and high-temperature process heat applications. There are two types of VHTR fuel assembly: prismatic block and pebble bed types. The prismatic VHTR have two designs consisting of multi-hole and pin-in-hole configuration. This paper focuses on the heat transfer enhancement and flow characteristics of fuel assemblies of the multi-hole prismatic block type that uses helium as a coolant. The pitch's size and the inlet velocity of coolant are the parameters of interest in this study. A detailed thermo-fluid analysis using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) are performed by using COMSOL Multiphysics software. Various physical modules in COMSOL e.g. Heat Transfer in Solids and Fluids and Turbulent Flow (k-ε) are used together to analyze the heat transfer and fluid flow in a multiphysics approach where several important parameters of each module are linked and evaluated simultaneously through the multiphysics function. The thermo-fluid performance of a multi-hole fuel assembly shows that the variation of assembly pitch results in an increase in the average temperature of the graphite moderator and the fuel rod; however, it has minor effect on the temperature and the velocity of the helium coolant. Finally, increasing the pitch's size could reduce the pressure drop by up to 1.5 kPa. In addition, the inlet velocity has a strong impact to the temperature profiles. When the velocity increases; the temperatures of the coolant, the moderator, and the fuel rod decrease accordingly. However, it has a negative impact on the pressure drop as the pressure drop could go up to 40 kPa at the inlet velocity of 40 m/s.

Keywords: *Nuclear reactor, Very high temperature gas-cooled reactor, Numerical simulation*

1. INTRODUCTION

The Generation IV nuclear systems designs are expected to be deployed in the next decade and are identified as being economical, safe, efficient, and proliferation-resistant [1]. The Very-High-Temperature Reactor (VHTR) is one of the Generation IV nuclear systems and the next step in the evolutionary development of a high-temperature gas-

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cooled reactor (HTGR). The VHTR is a high-temperature gas-cooled reactor with a graphite-moderated, helium-cooled reactor with a thermal neutron spectrum. Figure 1 shows an overview of VHTR system for hydrogen production. Helium as a working fluid will transfer heat from the reactor core to a heat exchanger supplying process heat for hydrogen production plant. The range of core outlet temperatures is between 700 and 950 °C, or more than 1000°C in certain designs [1]. This range of temperature is suitable for both electricity generation and the production of hydrogen fuel with co-generation efficiency up to 50% [2]. The reactor can fall into two general categories: prismatic block reactors, and pebble bed reactors. Prismatic block reactors involve a fuel core surrounded by a hexagonal graphite moderator, while pebble bed reactor cores use mobile fuel spheres that cycle throughout the core. Although the shape of the fuel element is different (hexagonal block vs. spherical balls), the technical basis for both configurations is the same. For example, the fuel consists of TRISO coated particle fuel in the graphite matrix, full ceramic (graphite) core structure, helium coolant.

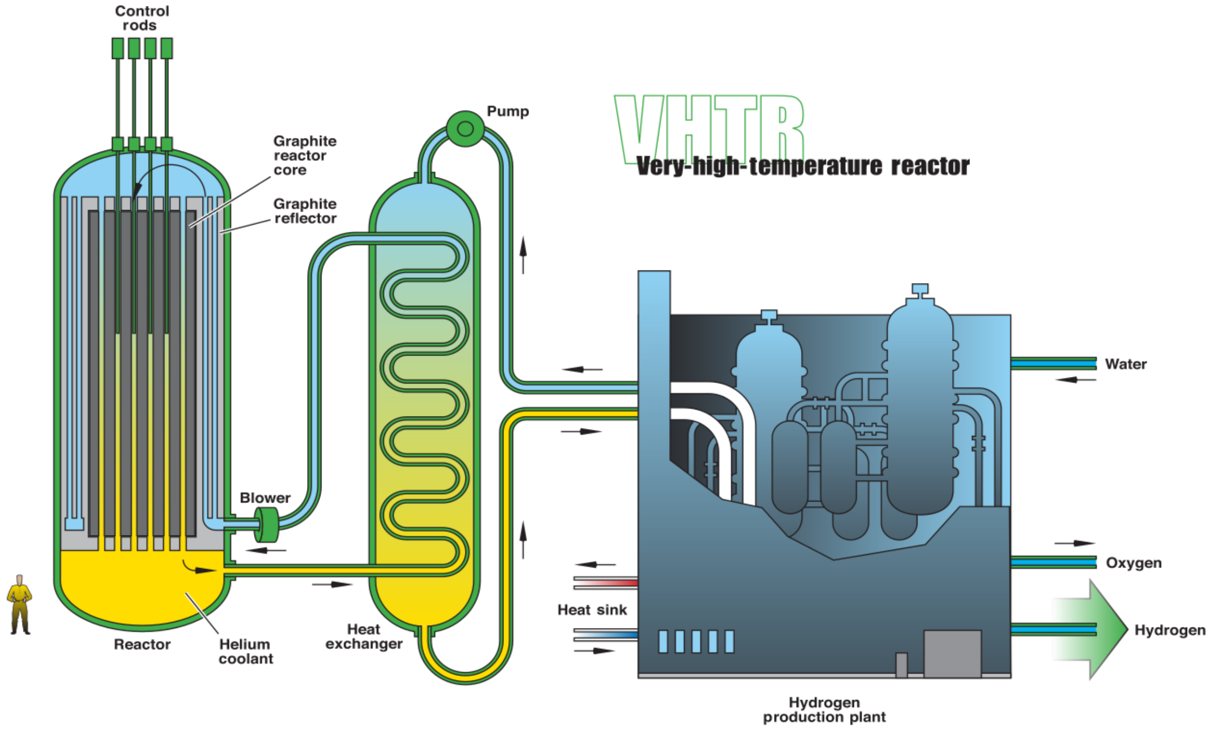

Fig. 1. A schematic of VHTR for hydrogen production [1].

Tak et al. [2] evaluated thermo-mechanical performance of the fuel assemblies of VHTR designs with prismatic cores. A double-side-cooled annular fuel concept for a prismatic type reactor has been proposed with the aim to reduce the maximum fuel temperature. Two types of VHTR fuel assemblies: pin-in-hole and multi-hole, as shown in Fig. 2 were analyzed by using Computational Fluid Dynamics (CFD). The results showed that the maximum temperature of the proposed design is lower than that of the existing prismatic designs. The maximum fuel temperature of the proposed design under normal operating conditions is found to be sufficiently below the design limit, which is a rigorous constraint in the VHTR core design due to a high coolant outlet temperature. Moreover, the pressure drop is lower than those of the existing prismatic designs.

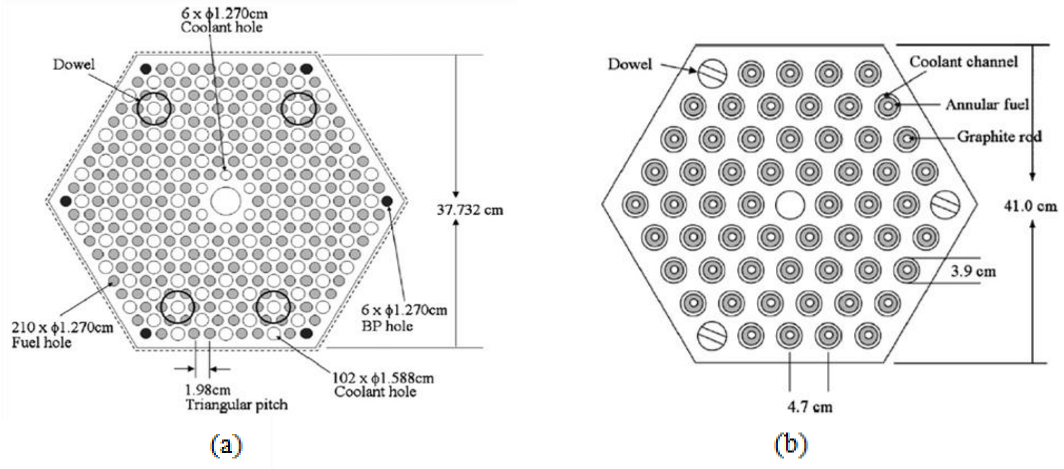

Fig. 2. Typical (a) multi-hole and (b) pin-in-hole type fuel assembly [2].

Lee et al. [3] studied the effect of variable bypass gap sizes on the temperature of the prismatic VHTR reactor core. In this study, three-dimensional computational grids were used for the calculation of the temperature distributions in the fuel assemblies. As fuel thermal expansion reduces the gap size between the assemblies, the coolant will redistribute along the axial plane between the assemblies. With the strong heat source as function of variable bypass gap size in the fuel assemblies, the differences between the maximum temperatures were not large. The initial bypass gap and burn-up cycle across the outer reflector's temperature difference can be affected by the change of the gap sizes [4]. Wang et al. [5] also supported this phenomenon by using CFD codes with 3D full size model of fuel column. In their study, the hot spot temperature increases when bypass gap size expands. In addition, increasing the bypass gap width results in an increase in the bypass flow fraction. However, the downstream conditions of the flow do not greatly influence the pressure drops in the bypass gaps, as the pressure drop is more dependent on the bypass gap width [4]. Thus, reliable estimation of bypass flow is significantly essential for the design and safety analysis of the VHTR core [6]. The main reason is that the challenging of prediction the flow distribution in the core from the complexity of the core geometry and gap arrangement [7].

To achieve high outlet temperature and the retention of fission production inside the graphite matrix under reasonable operation conditions and accident conditions, it is important to ensure proper cooling of the flow channel. The cross flow can be divided into 2 types which consist of the cross flow from the bypass gap to the coolant channels and the cross flow from the high-pressure coolant channels to low-pressure coolant channels, which has an opposing effect on the temperature gradient [5]. This paper discusses the heat transfer enhancement and flow characteristics of fuel assemblies of the prismatic block type that use helium as a coolant. The pitch size and the inlet velocity of coolant are the parameters of interest are the parameters of interest in this study. Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) with multiphysics coupling are used for analysis.

2. NUMERICAL SIMULATION OF THERMO-FLUID PERFORMANCE ANALYSIS

2.1. Test piece parameters and simulation environment

Table 1 shows the thermal-hydraulic assessment for the multi-hole type which are used for the condition of simulation.

Table 1: A table of thermal-hydraulic assessment for the condition of simulation

	Multi-hole type
Assembly power (MW)	5.882
Compact power density (W/cm^3)	28.78
Assembly flow area (cm^2)	208
Coolant inlet velocity (m/s)	23.9
Coolant inlet temperature (◦C)	491
Coolant outlet temperature (◦C)	1000

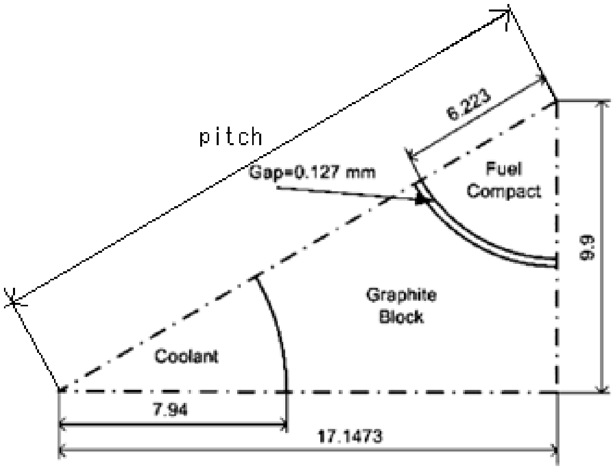

Fig. 3. Unit cell of the multi-hole type for the CFD analysis (unit: mm).

Figure 3 shows the unit cell of the multi-hole fuel assembly investigated in this study. Figure 4 shows the fuel geometry, computational domain, and specific boundary conditions used in this study. It can be seen that the model assumes 1/8th rotational symmetry. For the parametric study, this work studies the effect of pitch size and inlet velocity on the temperature profiles and pressure drop. The pitch size is varied from 20 mm to 100 mm while the inlet velocity ranges from 3 to 40 m/s.

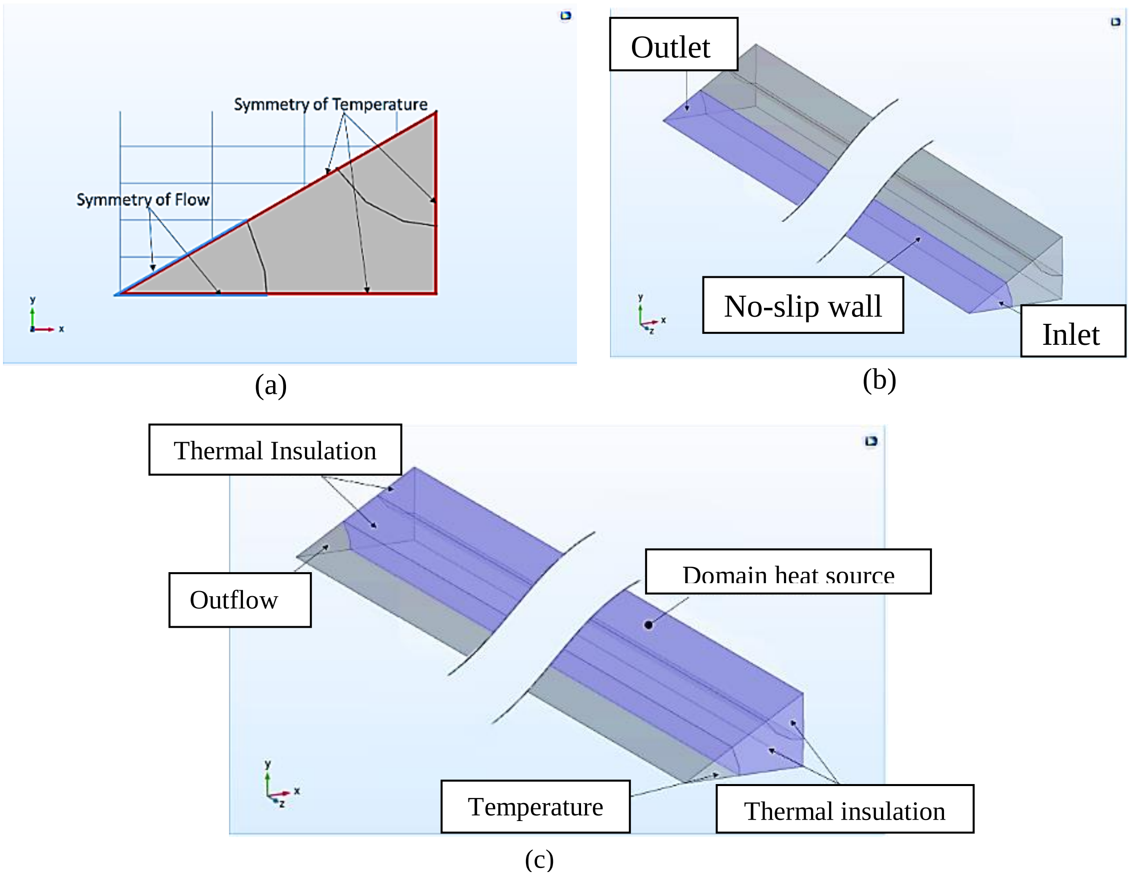

Fig. 4. Model for simulation (a) the symmetry of temperature and flow boundary condition (b) the turbulence k-ε boundary condition (c) the heat transfer in solid and fluid boundary condition.

2.2. Equation for simulation

The physical phenomena involving the working can be described by 3 main equations including turbulent flow k-ε, heat transfer, and equation for Multiphysics (non-isothermal flow).

2.2.1Turbulent flow, k-ε

The turbulent flow, k-ε model is used for simulating single-phase flows at high Reynolds numbers. The physics model is suitable for incompressible flows, weakly compressible flows, and compressible flows at low Mach numbers (typically less than 0.3). The equations are solved by the turbulent flow when a k-ε interface is the Reynolds-averaged Navier-Stokes (RANS) equations for conservation of momentum, and the continuity equation for conservation of mass. This module includes the standard k-ε model. Turbulence effects are modeled by using the standard two-equation k-ε model with realizability constraints, which introduces two additional transport equations, and two dependent variables: the turbulent kinetic energy, k, and the turbulent dissipation rate, ε. The turbulent viscosity is modeled by model constant C_μ, while the flow near walls is modeled by using wall functions. The boundary and symmetry conditions are applied at each surface of the control volume.

2.2.1.1 Governing equation

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot[-p\mathbf{I}+\mathbf{K}]+\mathbf{F} \tag{1}$$

$$\nabla\cdot(\rho\mathbf{u}) = 0 \tag{2}$$

$$\mathbf{K} = (\mu+\mu_\mathrm{T})\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^\mathrm{T}\right) - \frac{2}{3}(\mu+\mu_\mathrm{T})(\nabla\cdot\mathbf{u})\mathbf{I} - \frac{2}{3}\rho k\mathbf{I} \tag{3}$$

$$\rho(\mathbf{u}\cdot\nabla)k = \nabla\cdot\left[\left(\mu+\frac{\mu_\mathrm{T}}{\sigma_\mathrm{k}}\right)\nabla k\right] + P_\mathrm{k} - \rho\epsilon \tag{4}$$

$$\rho(\mathbf{u}\cdot\nabla)\epsilon = \nabla\cdot\left[\left(\mu+\frac{\mu_\mathrm{T}}{\sigma_\epsilon}\right)\nabla\epsilon\right] + C_{\epsilon 1}\frac{\epsilon}{k}P_\mathrm{k} - C_{\epsilon 2}\rho\frac{\epsilon^2}{k}, \quad \epsilon = \mathrm{ep} \tag{5}$$

$$\mu_\mathrm{T} = \rho C_\mu\frac{k^2}{\epsilon} \tag{6}$$

$$P_\mathrm{k} = \mu_\mathrm{T}\left[\nabla\mathbf{u}:\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right) - \frac{2}{3}(\nabla\cdot\mathbf{u})^2\right] - \frac{2}{3}\rho k\nabla\cdot\mathbf{u} \tag{7}$$

2.2.2 Heat transfer

The heat transfer in solids and fluids is used for modeling heat transport phenomena by conduction, convection, and radiation. A solid model is active by default on all domains, and a fluid model is also added but not active. The temperature equation defined in solid domains corresponds to the differential form of the Fourier's law, and the temperature equation defined in fluid domains corresponds to the convection-diffusion equation that may contain additional contributions like heat sources. The boundary condition, source term, and symmetry conditions are applied. The multiphysics coupling between heat transfer and fluid flow are corresponding to the temperature of element and material properties.

2.2.2.1 Governing equation

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \tag{8}$$

$$\mathbf{q} = -k\nabla T \tag{9}$$

2.2.2.2 Equation for Multiphysics (Non-Isothermal flow)

$$-\mathbf{n} \cdot \mathbf{q} = \rho C_p u_\tau \frac{T_w - T}{T^+} \tag{10}$$

2.2.3 Properties of materials

The properties of the fluid helium gas (Thermal conductivity, Density, Specific heat capacity Pressure constant, Specific heat capacity Volume constant, and Viscosity are based on the NIST database [8] and the solid UO_2 and graphite (Thermal conductivity, Density, and Specific heat capacity Pressure constant) is from McEligot's technical report [9].

2.3. Thermo-fluid performance analysis

2.3.1 The effect of pitch's size

A thermo-fluid performance of the unit cell including temperature, velocity and pressure of the helium coolant, the graphite moderator, and the fuel rod at a reference pitch size of 20 mm have been evaluated. In this case, the fuel length is set to 8 m for the active core and the helium coolant enters the flow channel from the right of model. The temperature of the coolant, the moderator, and the fuel increase significantly along the axial length as the coolant absorbs heat from the surface of graphite block. The axial velocity profile of the helium coolant, which has an initial velocity of 24 m/s and increases by 33 m/s at the outlet. Finally, the axial pressure profile along the helium coolant, which drops to 7 MPa at the outlet side. In this case, the pressure drop is approximately 17.5 kPa.

For the parametric study on the effect of pitch size on the temperature, velocity, and pressure profiles, the simulations results when the pitch size is varied into 6 difference sizes: 20 mm (reference), 30 mm (case 1), 40 mm (case 2), 50 mm (case 3), 80 mm (case 4) and 100 mm (case 5) have been studied in this work. The active core length is fixed at 8 m. When the pitch size increases, the temperature of the graphite moderator and the fuel rod increases. However, it does not affect the helium coolant as it shows negligible impact on the temperature profile. Similarly, for the axial velocity and pressure profile of the helium coolant, the change in pitch size results in small variation. The axially averaged temperature of the helium coolant, graphite moderator, and fuel rod as a function of pitch sizes is shown in Fig. 5a, 5b, and 5c, respectively. Strong influence of pitch size to the average temperature of the graphite moderator and the fuel rod can be observed while it virtually has no impact on the helium coolant. In Fig. 5d, increasing the fuel pitch from 20 mm to 40 mm shows small impact on the outlet pressure as it changes from 7.0175 MPa and 7.0167 MPa. The difference between the inlet and outlet pressure becomes smaller as the pitch size increases from 20 mm to 40 mm and it stays constant if the pitch size is greater than 40 mm. After this point, the outlet pressure is constant at 7.0167 MPa.

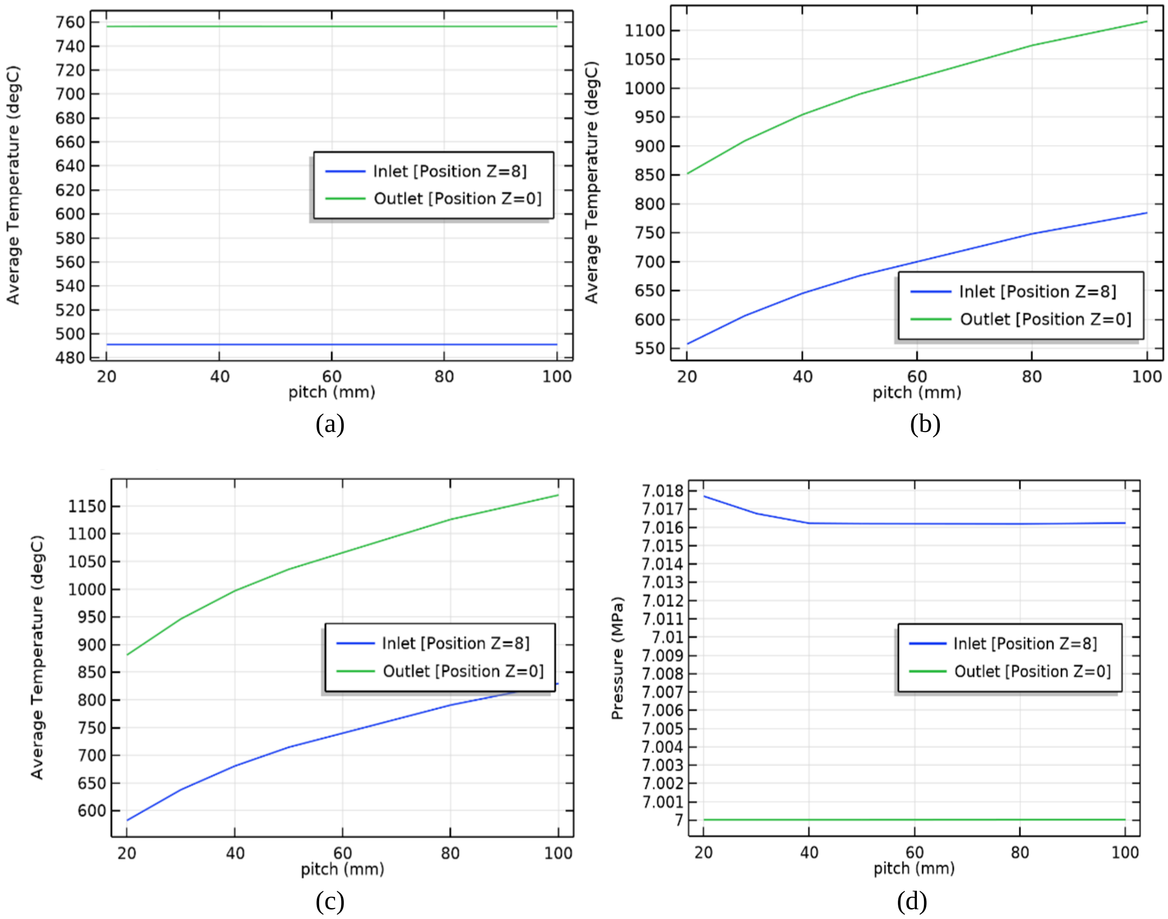

Fig. 5. Average temperatures at the inlet and outlet of (a) helium coolant (b) graphite moderator (c) fuel rod and (d) average pressure at inlet and outlet of the helium channel as a function of pitch size.

2.3.2 The effect of inlet coolant velocity

Another parameter of interest is the inlet coolant velocity. In this study, the inlet velocity has been studied for 9 values including 3, 5, 10, 15, 20, 23.9, 30 35, and 40 m/s. Note the reference values is 23.9 m/s. The axial temperature profiles of the helium coolant, the graphite moderator, and the fuel rod as a function of axial length at various inlet velocities have been evaluated from the simulation. As expected, increasing the coolant velocity results in a reduction in the temperature while decreasing it causes a significant increase in the temperature profiles. Unlike the pitch size, the inlet coolant velocity has a noticeable impact on the axial velocity and pressure profiles of the helium coolant. The higher the inlet velocity, the higher the pressure drop at the outlet of the flow channel. Figures 6a, 6b, and 6c show the axially averaged temperature of the helium coolant, graphite moderator, and the fuel rod as a function of inlet coolant velocity. An inversely proportional relationship between the temperature profile and the inlet coolant velocity are noted in this plot. Figure 6d shows a slightly negative impact between the inlet velocity and the outlet pressure as the increase in velocity results in a larger pressure drop across the flow channel.

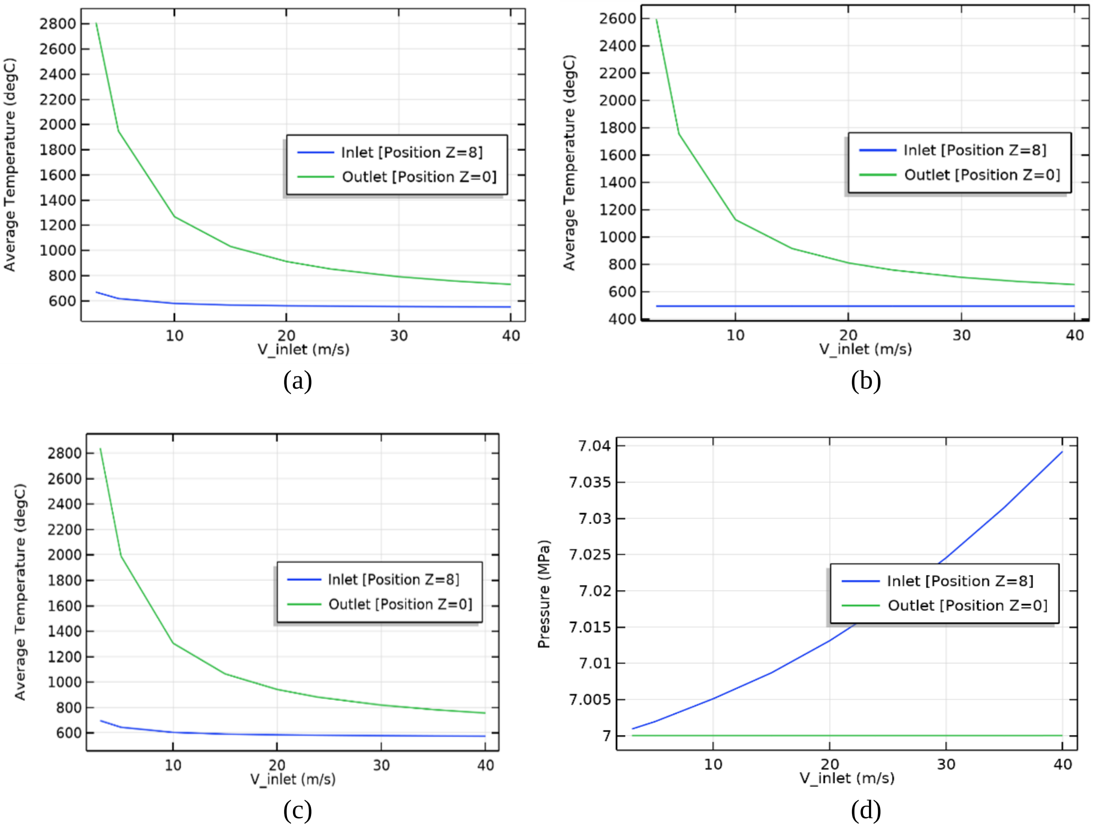

Fig. 6. Average temperature at inlet and outlet of (a) helium coolant, (b) graphite moderator, and (c) fuel rod and (d) average pressure at inlet and outlet of the helium channel as a function of inlet coolant velocity.

3. CONCLUSION

In conclusion, the effects of the pitch size and the inlet velocity of coolant to the thermo-fluid behaviors are simulated by using the COMSOL Multiphysics with a constant volumetric heat generation rate. The temperature of helium as the coolant is independent of the pitch size. The main reason is that as the helium continuously flows into the channel and receives thermal energy from heated surfaces, the convection heat transfer coefficient does not significantly change in this flow geometry and heat transfer regime resulting in nearly constant temperature profiles regardless of the pitch size. On the other hand, the pitch size strongly affects the graphite moderator and the fuel rod by increasing their average temperature because the increase in material thickness increases the thermal resistance for heat transport by conduction. If the heat generation rate is kept constant, the additional thermal resistance will increase the temperature gradient. Moreover, the velocity inside the coolant channel slightly changed with pitch size. The pressure drop also slightly decreases with increasing pitch size. At a reference pitch size, the pressure drop is 17.7 kPa whereas, at 100 mm, it reduces to 16.2 kPa. The change in inlet coolant velocity strongly affects the temperature profiles of the helium coolant, the graphite moderator, and the fuel rod, as the convection heat transfer and the amount of thermal energy, that uses the coolant as a transporter, per unit time heavily depends on how fast the coolant can move pass through the channel. When the coolant velocity increases, it decreases the temperature of all components. However, increasing the coolant velocity will increase the pressure drop. From the study, at the inlet coolant velocity of 40 m/s, the pressure can go up to 40 kPa.

NOMENCLATURE

C_p	specific heat of fluid, J/kg-K
C_μ	model constant = 0.09
$C\varepsilon 1$	model constant = 1.44
$C\varepsilon 2$	model constant = 1.92
F	the volume force vector (SI unit: N/m3)
I	Identity matrix
K	the deviatoric stress tensor
k	-the turbulent kinetic energy (for turbulent k-ε) -thermal conductivity (for heat transfer)
P_k	the generation of turbulence kinetic energy due to the mean velocity gradients
ΔP	pressure drop, Pa
q	the conductive heat flux vector
T	temperature, K
T_w	wall temperature
T^+	dimensionless temperature
u	the velocity vector (SI unit: m/s)
u_τ	friction velocity
ν	kinematic viscosity, m^2/s

Greek symbols

ρ	fluid density, kg/m^3
σ_k	model constant = 1.0
σ_ε	model constant = 1.3
μ_T	The turbulent viscosity
ε	the turbulent dissipation rate

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