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Numerical investigations of thermal mixing performance of a hot gas mixing structure in high-temperature gas-cooled reactor

Yang-Ping Zhou[1] · Peng-Fei Hao[2] · Xi-Wen Zhang[2] · Feng He[2]

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Abstract A numerical simulation study was performed to clarify the thermal mixing characteristics of coolant in the core bottom structure of the high-temperature gas-cooled reactor (HTR). The flow field and temperature field in the hot gas chamber and the hot gas duct of the HTR were obtained based on the commercial computational fluid dynamics (CFD) program. The numerical simulation results showed that the helium flow with different temperatures in the hot gas mixing chamber and the hot gas duct mixed intensively, and the mixing rate of the temperature in the outlet of the hot gas duct reached 98 %. The results indicated many large-scale swirling flow structures and strong turbulence in the hot gas mixing chamber and the entrance of the hot gas duct, which were responsible for the excellent thermal mixing of the hot gas chamber and the hot gas duct. The calculated results showed that the temperature mixing rate of the hot gas chamber decreased only marginally with increasing Reynolds number.

Keywords High-temperature gas-cooled reactor · Numerical simulation · Thermal mixing · Swirling flow

✉ Peng-Fei Hao
haopf@tsinghua.edu.cn

[1] Institute of Nuclear and New Energy Technology, The Key Laboratory of Advanced Reactor Engineering and Safety, Ministry of Education, Tsinghua University, Beijing 100084, China

[2] School of Aerospace, Tsinghua University, Beijing 100084, China

1 Introduction

The modular high-temperature gas-cooled reactor (HTR), with high thermal efficiency and inherent safety, is advantageous over other new generations of reactors. China has already built the HTR-10 reactor, which is adopted by a side-by-side arrangement of reactor and a steam generator and is in successful operation. The 250 MW one-zone module is an upscaling of the HTR-10. The demonstration power plant and the pebble-bed modular HTR (HTR-PM) are graphite-moderated, helium-cooled and shall operate at a nominal thermal power of 250 MW. The helium flow at outlet of the hot gas duct is about 750 °C, pressured at about 7.0 MPa [1–3]. The power system of HTR-PM essentially consists of a reactor, a primary loop and a secondary loop. As shown in Fig. 1, the primary loop is comprised of a reactor pressure vessel, a steam generator pressure vessel and a hot gas duct vessel. The steam generator is installed aside the reactor pressure vessel, connected by a horizontal hot gas duct. The main thermal-hydraulic process in the reactor and the primary loop can be explained as follows. Before entering the reactor vessel, helium gas of around 250 °C is compressed to about 7 Mpa by a helium blower. By flowing through the hot fuel spheres in the reactor core, the helium gas reaches 750 °C. Via the hot gas duct, the hot helium gas transfers its thermal power to the water in the steam generator, where it is cooled down to 250 °C. Through the outer coaxial pipes of the hot gas duct, the cooled helium gas is blown into the reactor pressure vessel, where it is heated again. By employing this method, a closed cycle of helium gas flow takes place in the primary loop.

Due to high temperature of the reactor outlet, thermal loading on materials of the heat-exchanging components

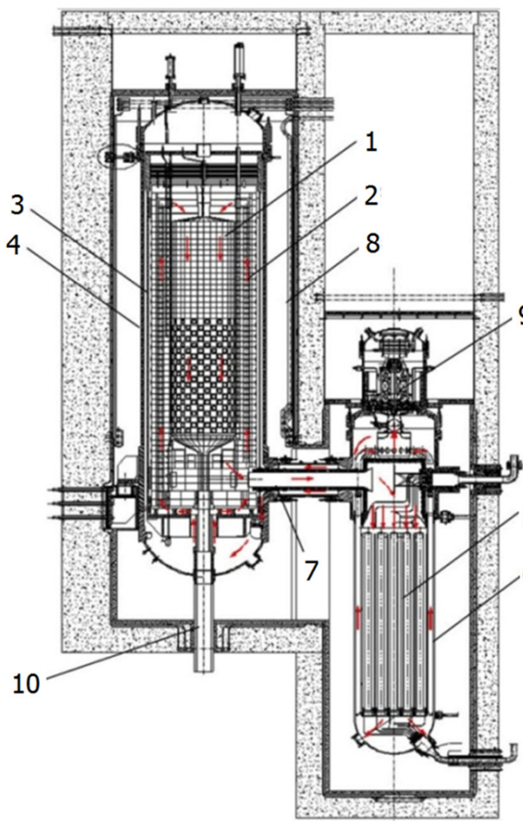

Fig. 1 (Color online) Structure of the HTR-PM reactor. *1*. Reactor core; *2*. side reflector and carbon thermal shield; *3*. core barrel; *4*. reactor pressure vessel; *5*. steam generator; *6*. steam generator vessel; *7*. coaxial gas duct; *8*. water-cooling panel; *9*. blower; *10*. fuel discharging tube

shall be as low as possible. Thermal-hydraulic calculation results showed that during nominal operation, there will be a large coolant radial temperature deviation at the exit of the HTR-PM core because of uneven distributions of neutron flux and gas flow rate. The radial temperature differences are as high as 150 °C between the hot helium in center area of the reactor core and the cooled helium in the edge area, whereas the temperature difference should be reduced to ±15 °C at the inlet of the steam generator to guarantee its service life. To minimize the radial temperature differences in the main flow below the core, the thermal mixing structure was designed to enhance the thermal mixing of coolant in the core bottom.

In developing the HTR-type nuclear reactors, researchers of different countries extensively investigated the coolant mixing phenomena. In Japan, Hishida et al. [4] carried out experiment using cool and hot air jets to obtain basic data on coolant mixing inside outlet cavity of the experimental very high-temperature gas-cooled reactor. Inagaki et al. [5, 6] reported their thermal mixing of the coolant of the high-temperature engineering test reactor. The results showed that the coolant mixed sufficiently in the hot gas chamber, and there was only a minimized hot streak in the outlet gas duct when the coolant temperature in the central region was higher than that in the circumferential regions. The mixing characteristics did not depend strongly on the Reynolds number or the temperature difference between the hot and the cool regions. In Germany, Damm and Wehrlein [7] investigated the temperature-mixing behavior of the coolant in a core bottom model of an HTR module designed by Siemens. Based on air experiments in a 1:2.9 scale model, a very good simulation of mixing phenomena was performed, and the simulated coolant matched the experiments by over 95 %. These results enabled revising the core bottom geometry for the HTR module into simple straight hot gas channels rather than complex networks of gas mixing channels used previously. Yao et al. [8] experimented with air on a 1:1.5 scale model of hot gas chamber and found that with the Reynolds numbers of 1.4×10^5–5.8×10^5, the hot gas chamber with a radial mixer reached excellent thermal mixing of the coolant of about 94 %. Recently, Travis and El-Genk [9] worked with a simplified methodology for conducting thermal-hydraulics analyses of very high-temperature reactor (VHTR) core and hexagonal fuel elements with and without helium flows through the control rod channels and in interstitial gaps. They demonstrated that the method was effective in performing thermal-hydraulic analyses for fuel elements, and for a one-fuel element (0.793 m high) VHTR 1/6 core with helium bypass flow in interstitial gaps between fuel elements and helium "bleed" flow through the control rod channels.

In this paper, we report a numerical thermal-hydraulics analysis in the hot gas mixing structure of the HTR-PM reactor. This is aimed at studying the thermal mixing performance, understanding mechanism of thermal mixing according to the flow structures and temperature distributions in the complex mixing structure of the HTR-PM and investigating influence of the Reynolds number in the hot gas duct on the flow resistance and thermal mixing.

2 Hot gas mixing structure of HTR-PM

The mixing structure in the core bottom of the HTR-PM reactor is shown in Fig. 2, and main parameters of the actual structure of the HTR-PM are listed in Table 1. It consists of three components: the bottom graphite reflectors, a hot gas chamber and a hot gas duct. The narrow radial channels are divided into three layers. There are 150, 30 and 15 radial channels in the top, middle and bottom layers, respectively. Each narrow radial channel is formed by two adjacent flake graphite components which support

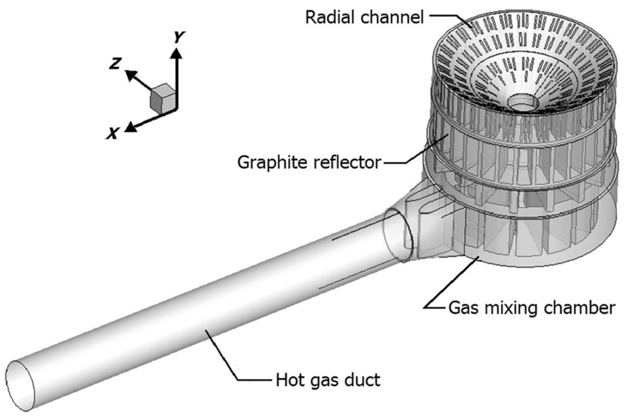

Fig. 2 Sketch map of the mixing structure in the outlet of the reactor core of the HTR-PM

Table 1 Main parameters of the mixing structure of the HTR-PM

Flow media	Helium
Height of the gas mixing chamber (mm)	800
Diameter of hot gas mixing chamber (mm)	3100
Min width of the radial channel (mm)	20
Max width of the radial channel (mm)	90
Diameter of hot gas duct (mm)	750
Length of hot gas duct (mm)	5750
Primary helium pressure (MPa)	7
Flow rate in hot gas duct (kg/s)	96
Mach number of flow in hot gas duct	0.033
Temperature in hot gas duct (°C)	750
Re number of flow in hot gas duct (10^6)	3.67
Pr number of flow in hot gas duct	0.654

the weight of the reactor core. The maximum and the minimum widths of the radial channels are 90 mm and 20 mm, respectively. The arc-shaped channels are set in the entrance of the annular mixing chamber to produce swirling flow. The coolant helium flows from the reactor core outlet, through the radial channels and into the annular gas mixing chamber. Finally, the coolant helium gas flows through the outlet of the hot gas mixing chamber to the hot gas duct and is further mixed in it.

3 Numerical analysis

Numerical investigations to study the mass and the heat mixing from the inlet of the hot gas mixing structure to the outlet of the hot gas duct were carried out using the commercial CFD software Fluent V14.0. Calculations were done for some cases with different Reynolds numbers of the gas flow in the hot gas duct. The control volume finite method was employed to solve the governing equations. The method is a semi-implicit pressure solution method, while the second-order upwind scheme was utilized to solve the momentum and the energy equations. The inlet temperature distribution is given where the maximum difference is around 140 K. The solid and fluid in the bottom graphite reflector and the gas mixing chamber are coupled at the inner solid wall. The outer wall of the whole mixing structure is set as an insulated surface. The fuel balls in the discharge tube and the upper tube are simulated using a porous media model. In our case, thermal mixing in the hot gas mixing structure is a steady-state problem, so we apply steady turbulent model to simulate the flow and temperature field. For calculating the turbulence flow of the helium flow in our simulation, we adopted the realizable k–ε model, which is a relatively recent development and contains a new formulation for turbulent viscosity and a new transport equation for the dissipation rate ε. It was derived from an exact equation for the transport of the mean-squared vorticity fluctuation. The realizable k–ε models show substantial improvements over the standard k–ε model, where the flow features include strong streamline curvatures, vortices and rotations [10–12]. In order to speed up the convergence with high accuracy, the first-order upwind format of interpolation was adopted to obtain the initial value to solve the momentum equation. Then, a second-order upwind format was used to improve accuracy of the results. The non-uniformly structured three-dimensional mesh with hexahedral volumes was constructed using the ICEM code, and the final number of cells was $\sim 9 \times 10^6$. The numerical simulations were performed on four parallel processors.

The fluid dynamic viscosity and thermal conductivity of helium depend on temperature and pressure. The fundamental equations used in the CFD code are summarized as follows:

$$\mu = 1.855 \times 10^{-5} \left(\frac{T}{T_0}\right)^{0.68}, \tag{1}$$

$$k = k_0 \left[1 + 1.665 \times 10^{-4} \frac{\left(\frac{p}{p_0}\right)^{1.17}}{\left(\frac{T}{T_0}\right)^{1.85}} \right], \tag{2}$$

$$k_0 = 0.1448 \left(\frac{T}{T_0}\right)^{0.68}, \tag{3}$$

where $T_0 = 273.15\,\mathrm{K}$ and $p_0 = 10^5$ Pa.

4 Results and discussion

To validate accuracy and reliability of the simulations, a model experiment was carried out to investigate the thermal mixing efficiency of the HTR-PM reactor outlet. The model experiment system was set at a scale of 1:2.5 to the design of the thermal mixing structure at the HTR-PM reactor outlet. Thermal mixing on the hot gas mixing structure is a steady-state problem, so similarity theory was used to design the model experiments. According to Ref. [8], the Prandtl number (*Pr*) and Reynolds number (*Re*) are important criterion parameters to determine thermal mixing degree in hot gas mixing structure. The model experiment used air as coolant, and the *Pr* number of air flow was about 0.67, while the *Pr* number of helium flow is 0.7. The Reynolds number (*Re*) is determined by the flow rate of fluid and diameter of the hot gas duct. Taking into account the cost of constructing the experiment setup, the maximum Reynolds number is about 9.6×10^5, and the corresponding flow rate of the hot and cool air flow is 2.4 kg/s. Although the Reynolds number in the model experiment is less than that in the prototype of the HTR ($Re = 3.67 \times 10^6$), previous experimental and simulation results show that the Reynolds number has little influence on the thermal mixing rate when $Re > 10^5$ [5, 8]. Two-branch gas experiments were conducted in the experimental system and values of the thermal-fluid parameters were collected and analyzed using temperature, pressure and velocity sensors. Figure 3 shows the radial profiles of temperature and axial velocities in the outlet of hot gas duct obtained from measurements and numerical simulations. The temperature difference between the hot gas branch and the cool gas branch was 100 °C, and flow rates of the hot and cool gas branches were both 2.4 kg/s. The simulation results agree well with the experimental data. The temperature difference is less than 1.5 °C at the outlet of the mixing structure, indicating that the air was mixed sufficiently in the hot gas mixing chamber and the duct.

Based on the above numerical method and turbulence model, simulations were performed to elucidate the thermal-hydraulic performance of the helium gas at different temperatures in the hot gas mixing structure of the HTR-PM. Figure 4 shows temperature and pressure profiles in the horizontal planes at different heights. Heights of the three planes are 0.4, 1.5 and 2.4 m from the bottom of the gas mixing chamber. The top plane is located in the inlet of the hot gas mixing structure of the HTR-PM. The second plane is located in the middle layer of the radial channels, and the bottom plane is in the middle of the mixing chamber. From inlet of the radial channels to outlet of the

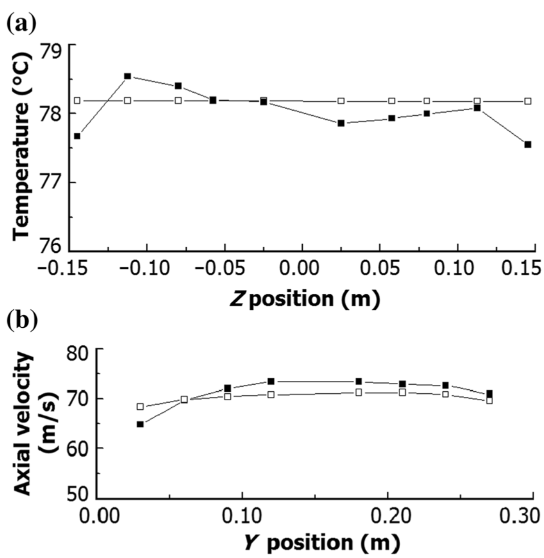

Fig. 3 Simulated (*square*) and measured (*black square*) radial profiles of temperature (**a**) and axial velocity (**b**) at outlet of the hot gas duct

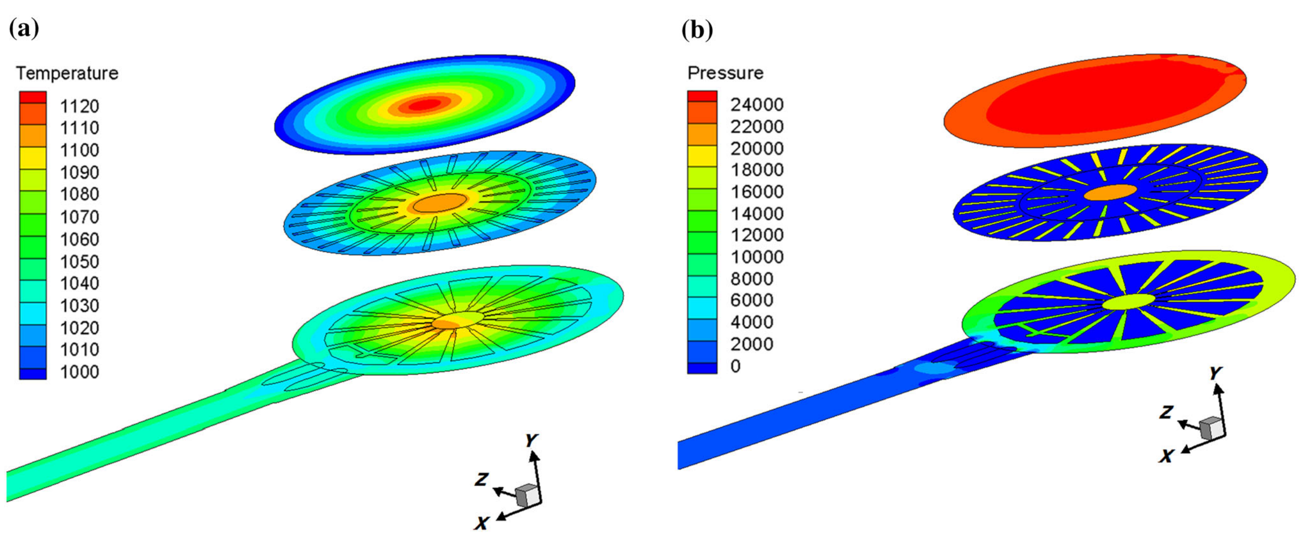

Fig. 4 (Color online) Temperature (**a**) and pressure (**b**) distributions in the horizontal planes with different height positions

gas mixing chamber, the maximum temperature difference reduces from 140 K to 30 K, indicating that thermal mixing occurs mainly in the radial channels and the annular gas mixing chamber. Figure 4 shows that great pressure drop occurs in the hot gas mixing structure of the HTR-PM due to the considerable flow resistance in the narrow radial channels and the annular gas mixing chamber. The maximum pressure gradient occurs in the outlet of the mixing chamber, where there is a sudden narrowing of flow area due to the two support blocks there.

Figure 5 shows that velocity vectors in the meridian plane are perpendicular to the hot gas duct. The velocity of hot helium flow increased when it entered the radial channels from the outlet of reactor core because of the decreased flow area in the narrow channels. The large-scale secondary flow vortices appear in the gas mixing chamber in the bottom of the hot gas mixing structure. These swirling flows in curved duct cause chaotic advection and strengthen mass and momentum exchange between the helium flows at different temperatures, hence the increased thermal mixing of helium in the gas mixing chamber. Figure 6 shows stream lines and turbulent kinetic energy distributions in the middle plane of the mixing chamber. The irregular streamlines in the plane indicate that the lateral flow occurs in the annular duct, which can enhance the mass and thermal mixing in the annular mixing chamber. The turbulent kinetic energy in the annular duct is much higher than that in the radial channels, indicating that strong turbulence accelerates the heat transfer between air flows at different temperatures, and is beneficial for temperature mixing of the hot and cold gas. The maximum turbulent kinetic energy occurs near the outlet of the annular duct, where two support blocks are placed and lead to sharp narrowing of the flow area.

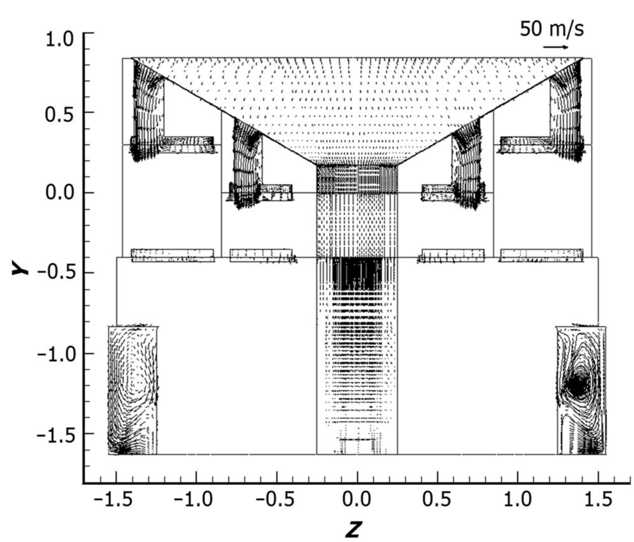

Fig. 5 Velocity vectors in the meridian plane which is perpendicular to the hot gas duct

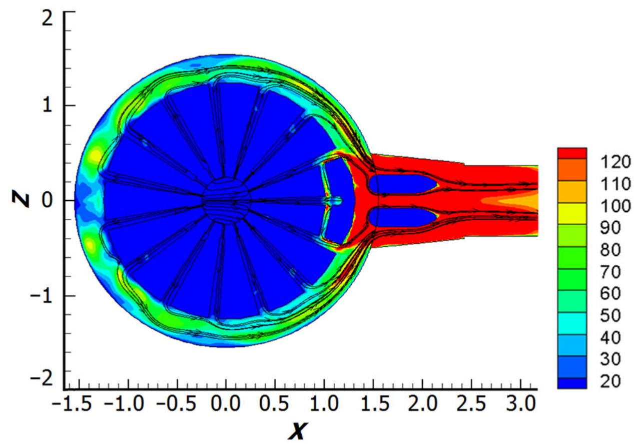

Fig. 6 (Color online) Streamlines and turbulent kinetic energy distributions in the middle plane of the mixing chamber

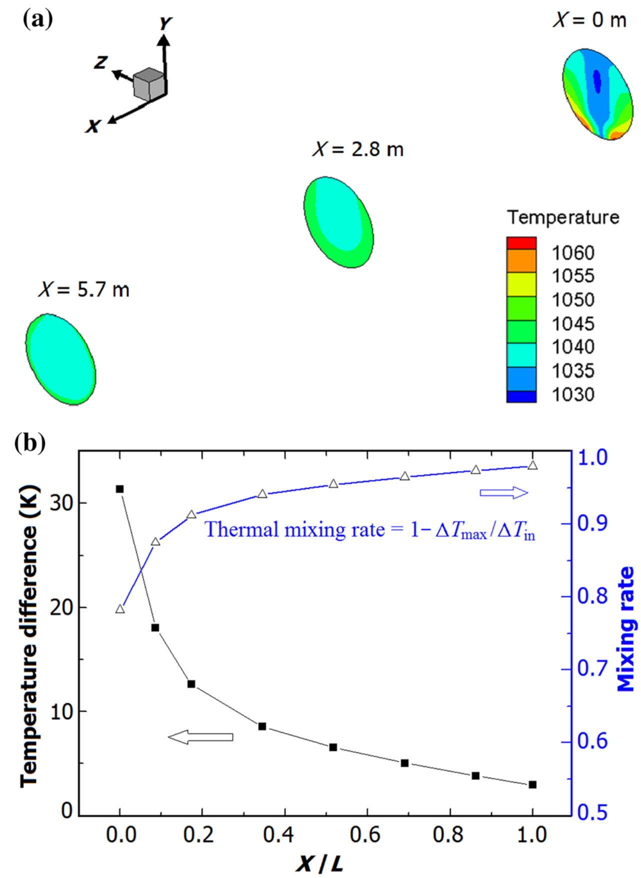

Fig. 7 (Color online) Profiles of temperature difference (**a**) and mixing rate (**b**) in the hot gas duct at various positions

Figure 7(a) shows temperature profiles in the hot gas duct at various positions. $X = 0$ is the inlet of hot gas duct, and $X = 5.7\,\mathrm{m}$ is the outlet of hot gas duct. Maximum temperatures in the three positions are 31, 7 and 3 K, respectively. The results revealed that the hot temperature region lays in the bottom at entrance of the hot gas duct.

Over a length of 1–4 m, the temperature in the bottom region of the duct decreased gradually, and the temperature difference from the bottom region to the hot gas duct outlet was only 3.0 K. From Fig. 7(b), the maximum temperature difference decreased along axial direction of the hot gas duct, indicating that further thermal mixing was carried out in the hot gas duct. Here, the dimensionless temperature-mixing degree (TMD) is defined as the thermal mixing rate in order to describe the mixing efficiency between hot gas and cold gas:

$$\mathrm{TMD} = 1 - \frac{\Delta T_{\max}}{\Delta T_{\mathrm{in}}}, \tag{4}$$

where $\Delta T_{\max}$ is the maximum gas temperature difference at the measuring cross section, and ΔT_{in} is the maximum temperature difference in the inlet of gas mixing structure. The thermal mixing of gases at different temperatures is the process of momentum and energy exchanges. The temperature-mixing rate in the hot gas duct increased with the distance from the hot gas duct inlet. While the distance exceeds 50 % of the hot gas duct length, the thermal mixing rate is over 95 %. The maximum thermal mixing rate at outlet of the hot gas duct is about 98 %.

Axial velocity distributions and lateral velocity vectors in the cross section of the hot gas duct inlet and outlet are shown in Fig. 8. The axial flow velocity profile in the hot gas duct inlet is not uniform due to the sharp narrowing of the flow area. A rotating vortex pair can be seen in the cross plane, and these large-scale swirling flow structures enhance the thermal mixing at the entrance of the hot gas duct. The non-uniformity of the axial velocity and the amplitude of the lateral velocity in the outlet cross section are much lower than those in the inlet cross section, which evidences that intensive mixing is realized in the outlet of the hot gas duct.

The relation between the thermal mixing efficiency and the Reynolds number of the fluid in the hot gas duct is shown in Fig. 9. The thermal mixing rate decreases slightly with increasing Reynolds number of the helium flow in the hot gas duct, indicating that the influence of the Reynolds number of the fluid in the hot gas duct on the thermal mixing is minor, which is consistent with the previous experimental data [7].

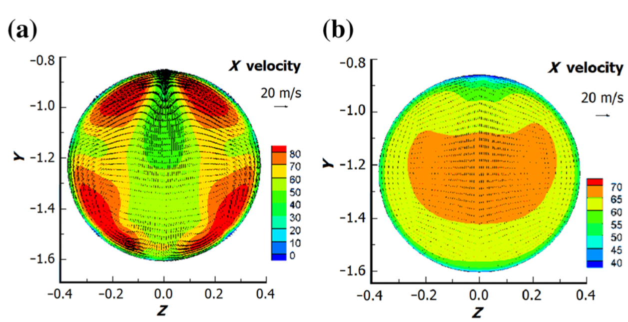

Fig. 8 (Color online) Axial velocity distributions and lateral velocity vectors in the cross sections of the hot gas duct inlet (**a**) and outlet (**b**)

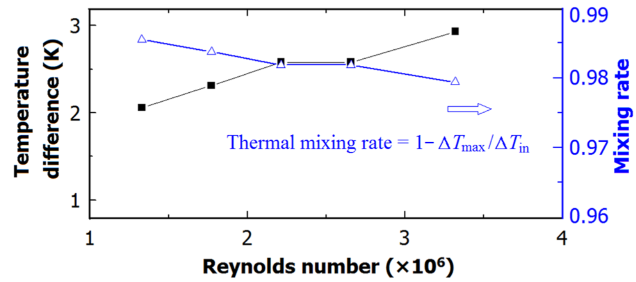

Fig. 9 (Color online) Relationship between the thermal mixing rate and Reynolds number

5 Conclusion

For the high-temperature gas-cooled reactor (HTR), the radial temperature difference in the coolant helium out of the cylindrical reactor core is as high as 100 K. In addition, much higher temperature differences can be introduced to the main coolant flow by the small cold leakages into the bottom of the reactor vessel. In order to ensure the technical feasibility and safety of the steam generator by limiting the thermal loads on the heat-exchanging component, a thermal mixing structure is proposed to enhance the thermal mixing of the coolant helium out of the reactor. The thermal mixing performance and flow structure in the hot gas mixing structure are obtained using 3D numerical simulations of CFD. The accuracy and reliability of the simulations were validated by comparison with the results of model experiments. The computational results showed that the helium with different temperatures in the hot gas mixing chamber and the hot gas duct mixed intensively. The maximum temperature in the outlet of the hot gas duct was about 3 K, and the thermal mixing rate reached 98 %. By contrast, the maximum temperature difference in the inlet of the mixing structure was around 140 K. The flow fields based on numerical simulations showed that large-scale swirling flow structures and strong turbulence occurred in the hot gas mixing chamber and entrance of the hot gas duct, which enhanced the momentum and energy exchange between gas flows with different temperatures. The thermal mixing rate increased with increasing distance between the hot gas duct and the hot gas chamber. The simulation data also showed that the effect of Reynolds number on the thermal mixing rate in the hot gas mixing structure is very small. To further study the transient process and detail of vortex structures in the thermal mixing structures, the large eddy simulation (LES) will be applied to analyze the unsteady turbulent in the future work.

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