Hindawi
Science and Technology of Nuclear Installations
Volume 2020, Article ID 4754589, 8 pages
https://doi.org/10.1155/2020/4754589

Research Article

Research on Influence of Different Simulation Methods of Bypass Flow in Thermal Hydraulic Analysis on Temperature Distribution in HTR-10

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Received 19 February 2020; Accepted 5 June 2020; Published 26 June 2020

Academic Editor: Iztok Tiselj

In pebble-bed high temperature gas-cooled reactor, gaps widely exist between graphite blocks and carbon bricks in the reactor core vessel. The bypass helium flowing through the gaps affects the flow distribution of the core and weakens the effective cooling of the core by helium, which in turn affects the temperature distribution and the safety features of the reactor. In this paper, the thermal hydraulic analysis models of HTR-10 with bypass flow channels simulated at different positions are designed based on the flow distribution scheme of the original core models and combined with the actual position of the core bypass flow. The results show that the bypass coolant flowing through the reflectors enhances the heat transfer of the nearby components efficiently. The temperature of the side reflectors and the carbon bricks is much lower with more side bypass coolant. The temperature distribution of the central region in the pebble bed is affected by the bypass flow positions slightly, while that of the peripheral area is affected significantly. The maximum temperature of the helium, the surface, and center of the fuel elements rises as the bypass flow ratio becomes larger, while the temperature difference between them almost keeps constant. When the flow ratio of each part keeps constant, the maximum temperature almost does not change with different bypass flow positions.

1. Introduction

HTR-10 is a 10 MW pebble-bed high temperature gas-cooled experimental reactor with the characteristics of Generation IV nuclear reactors, which takes spherical elements with all-ceramic TRISO type coated particles as fuel, graphite as neutron moderator material and helium as cooling medium. A great number of graphite blocks are installed in the core vessel to shape the pebble bed for the fuel elements and the graphite balls, to moderate and reflect neutrons, and to form the flow path for the coolant. Carbon bricks are arranged between the graphite reflectors and the core vessel to reduce heat loss and to absorb heat neutrons [1].

The flow distribution in the reactor core is quite complex because the coolant is divided into multiple parts on the flow paths from the reactor pressure vessel (RPV) inlet to the outlet. The layout of the primary system of HTR-10 and flow direction of coolant in RPV are shown in Figure 1 [2]. The cold helium enters the RPV, flows down through the annular space between the RPV and the core vessel, and gathers in the helium cavity at the RPV bottom. A small part of the coolant flows into the discharge tube at the bottom of the reactor directly to cool the fuel elements there and then flows upwards into the hot helium plenum. Most of the remaining coolant flows upwards through the supporting structure at the bottom of the core vessel, enters the 20 cold helium boreholes in the side graphite reflectors, and flows upwards, and then gathers in the cold helium plenum in the top reflectors. In order to cool the control rods effectively, another small part of the cold helium flows through the control rod channels into a small plenum in the bottom graphite reflectors and finally enters the hot helium plenum. Most of

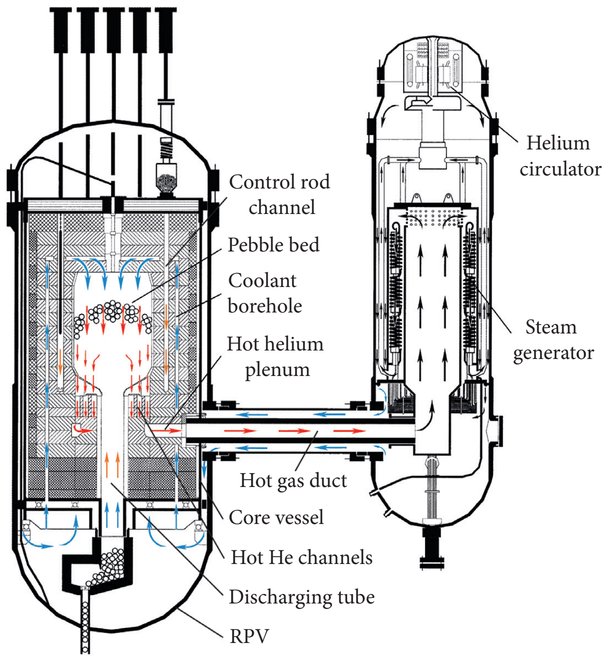


Figure 1: Layout of the primary system of HTR-10.

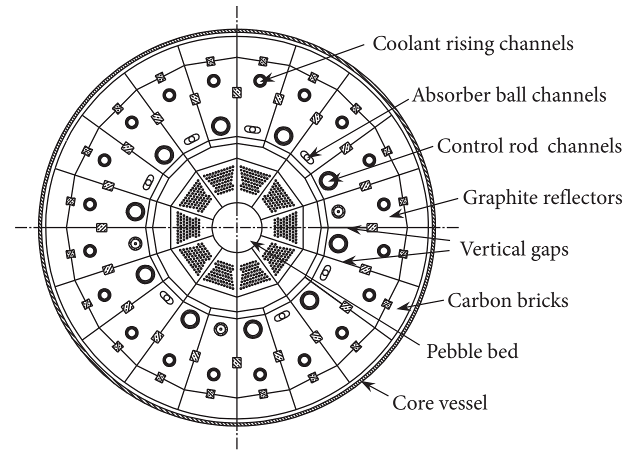


Figure 2: Cross-section of the HTR-10 reactor core structure.

the helium flows from top to bottom through the pebble bed piled up randomly, taking away the heat generated by the fuel, and enters the hot helium plenum at the bottom of the core. The coolant in the hot helium plenum mixes thoroughly and then flows out of the RPV.

In addition to the above-mentioned parts, another important part of the coolant may flow through the gaps between the graphite and carbon bricks and form the core bypass flow. Gaps are widely distributed between the graphite and carbon bricks, which are the main structural materials in the core vessel, as shown in Figure 2. Therefore, after the coolant enters the core vessel, the bypass flow may exist everywhere along the flow paths, especially between the cold and hot channels or plenums. The flow rate, position, and direction of the bypass flow are uncertain because of the quantity and diversity of the gaps [3].

In the previous study, Sun et al. [4] model the flow network based on the gap structure and the bypass flow mechanism to analyze the relationship between the gap size and the bypass flow rate in HTR-PM (High Temperature gas-cooled Reactor-Pebble-bed Module). The results show that the bypass flow ratio can reach 7% or 4% with the gaps of 3.0 mm width taking transverse flow into account or not. The bypass flow ratio becomes larger as the gap size becomes larger both around the core and in the height direction.

Sun et al. [5] use the commercial Computational Fluid Dynamic (CFD) software to investigate the bypass flow in a single narrow gap in the side reflectors. A three-dimensional model of 1/60 of the HTR-PM reactor core is established after confirming the models for the pebble bed, the bottom reflectors, the narrow gaps, etc. Cases with and without bypass flow were analyzed to find the effects on temperature distribution in the reactor core. The results show that even when the flow ratio is quite small (0.63%), the average temperature of the pebble-bed outlet coolant increases by 1.0%, and the maximum temperature of helium and the maximum temperature of the fuel element surface in the pebble bed both increase by 1.1%.

It can be inferred from the previous research [2–5] that the bypass flow in the side reflectors deserves attention because it accounts for a large share of about 10% in the total coolant flow, which plays an important role in the temperature distribution of both the pebble bed and the side reflector.

In the previous work [2, 3, 6, 7], several pebble-bed high temperature gas-cooled reactors are modeled and solved with the two-dimensional thermal hydraulic and safety analysis code THERMIX. In the original HTR-10 thermal hydraulic model, the core bypass flow is simulated equivalently and roughly below the pebble bed, as shown in Figure 3. This simulation takes into consideration that the bypass flow does not participate in the effective heat transfer in the pebble bed. However, the cooling effect in the side reflector cannot be simulated in this model.

In this paper, the flow composition of the coolant in the HTR-10 core is analyzed firstly. A new scheme to simulate the coolant flow process is proposed based on the flow distribution scheme of the original core thermal hydraulic analysis model and combined with the actual position of the core bypass flow. The THERMIX code is adopted to solve the thermal hydraulic models of HTR-10 with bypass flow channels simulated at different positions, and then the temperature distribution differences in the pebble bed and the side components in the reactor core are compared. The relationship between bypass flow ratio and temperature distribution is also analyzed in different conditions of the coolant flow process.

2. Model

2.1. Bypass Flow Analysis. In HTR-10, the coolant that finally flows into the hot helium plenum includes the following parts: the helium flowing downwards through the pebble bed from the top plenum, the helium flowing upwards through the fuel discharge tube from the bottom cavity, the coolant

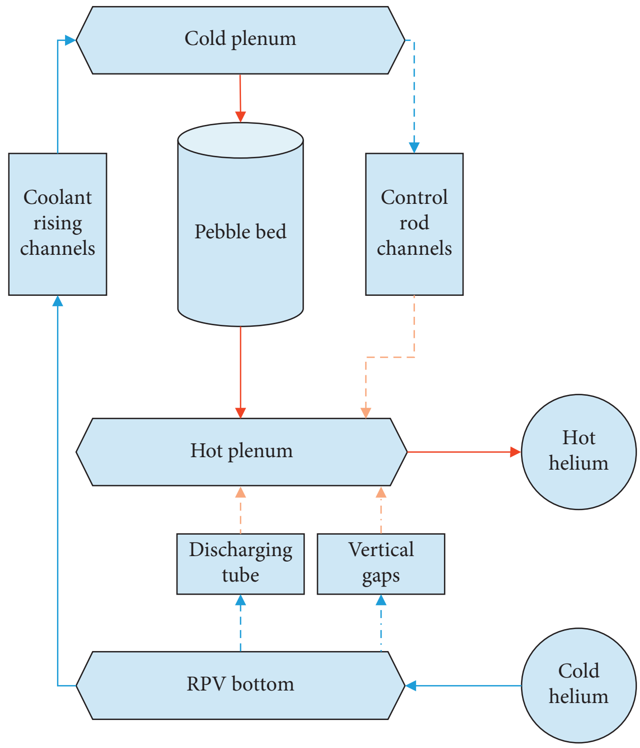


Figure 3: Brief flow process in the original HTR-10 thermal hydraulic model.

passing through the control rod channels, and the bypass flow in the gaps between graphite components. All the parts have defined flow areas and directions, except for bypass flow because of the widely distributed gaps. Because the sizes of the gaps are uncertain, the flow ratio of each part is also uncertain.

As shown in Figure 2, there are 20 pieces of graphite blocks and 20 carbon bricks per layer around the pebble bed in the side reflectors. The layout is similar in the top reflectors, in the bottom reflectors, and in the bottom carbon bricks. However, the 20 vertical gaps between the graphite blocks are connected with the top cold helium plenum directly in the top reflectors as shown in Figure 1, so that it is more possible for the coolant to flow into these gaps and through the top, side, and bottom reflectors to the hot helium plenum below the reactor core. In comparison, it is more difficult for the coolant to flow into those gaps below the reactor core and separate with the cavity in RPV bottom by steel and other structures.

Some conclusions in the previous research of the bypass flow characteristics in HTR-PM [4, 5] are also feasible in HTR-10 because HTR-PM has similar core structure, materials, and reactor concepts to HTR-10 [8].

The most typical bypass flow is from the cold plenum, through the vertical gaps, to the hot plenum, named P-P bypass flow [4]. Along the vertical gap, the pressure difference between the pebble bed and gaps may induce horizontal (radial) flows, which may change the P-P bypass flow rate. The results of the previous research about the P-P bypass flow rates considering the horizontal flows show that the total flow rate increases by over 58% [4], but in a single bypass flow path, after flowing through the entrance region, the flow rate does not change drastically any more [5].

In the present work, the bypass flow rate is considered totally in the thermal hydraulic simulation, including the flow rate change caused by the horizontal flows. During the coolant flowing in the bypass flow paths, its mass flow rate in total does not change.

In the improved thermal hydraulic model of HTR-10, considering the more possible bypass flow position, the bypass flow is divided into two parts: one part is below the reactor core at the same position of the original model, and the other part is in the reflectors between the pebble bed and the control rod boreholes. The brief flow process in the improved model is shown in Figure 4.

2.2. Calculating Model. The improved thermal hydraulic model is established based on the improved flow process shown in Figure 4, and the original model mainly consists of the one-dimensional fuel ball model, the two-dimensional rotation symmetric heat conduction model, and the gas convection model in r, z geometry.

The heat conduction model consists of 42 different material regions, divided into 35 radial and 61 axial mesh points, including the structures inside the concrete shell, such as the pebble bed, reflectors, carbon bricks, core vessel, RPV, discharging tube, cavity cooling system, and the helium or air space between them. The heat transfer of conduction, radiation, and natural convection in these regions is considered in this model.

The gas convection model consists of 20 different flow regions, divided into 18 radial and 39 axial mesh points, as shown in Figure 5. This model describes the coolant flow and forced convection in the reactor from the coolant inlet to the hot helium plenum, including the flow channels in the pebble bed and reflectors, the gas plenums, and the bypass flow, surrounded by the nonflow zones.

2.3. Parameters and Boundary Conditions. In the thermal hydraulic analysis, the parameters and formulas follow the German safety guide KTA 3102 1–3 [9–11], including the thermal material properties of helium, heat conductivity and surface heat transfer coefficient of spherical fuel elements, and the friction pressure loss in pebble-bed core. The equivalent thermal conductivity of the uniform pebble bed is calculated following the ZSB-R formula [12] and based on the empirical correlations of thermal conductivity of graphite under radiation conditions. The thermal physical properties of reflector graphite and carbon bricks are provided by German researchers.

The flow rate distribution in the model follows the design guidelines of HTR-10 to meet the safety requirements [2], which is listed in Table 1. The mass flow ratio of each part is the portion of its mass flow rate to the total coolant mass flow rate at the reactor inlet.

In the present study, an operating point during the temperature measurement experiment of the HTR-10 reactor core is selected and simulated. The main parameters

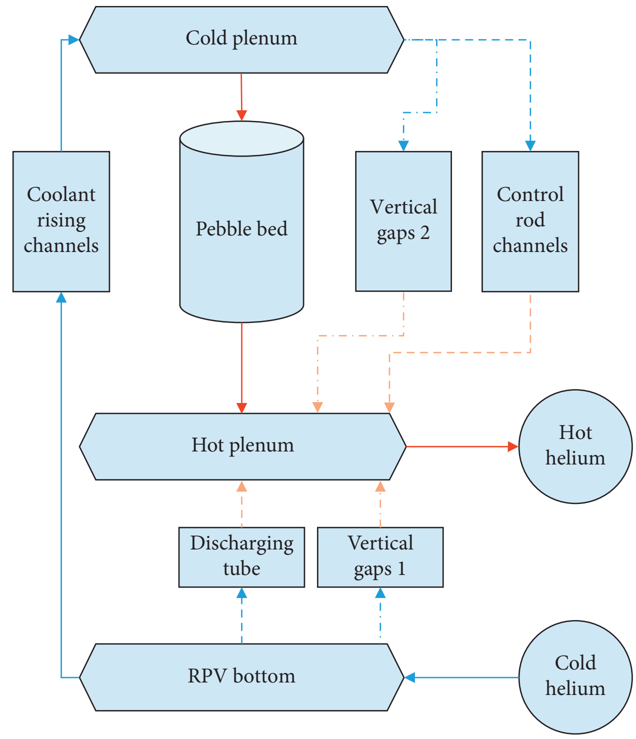


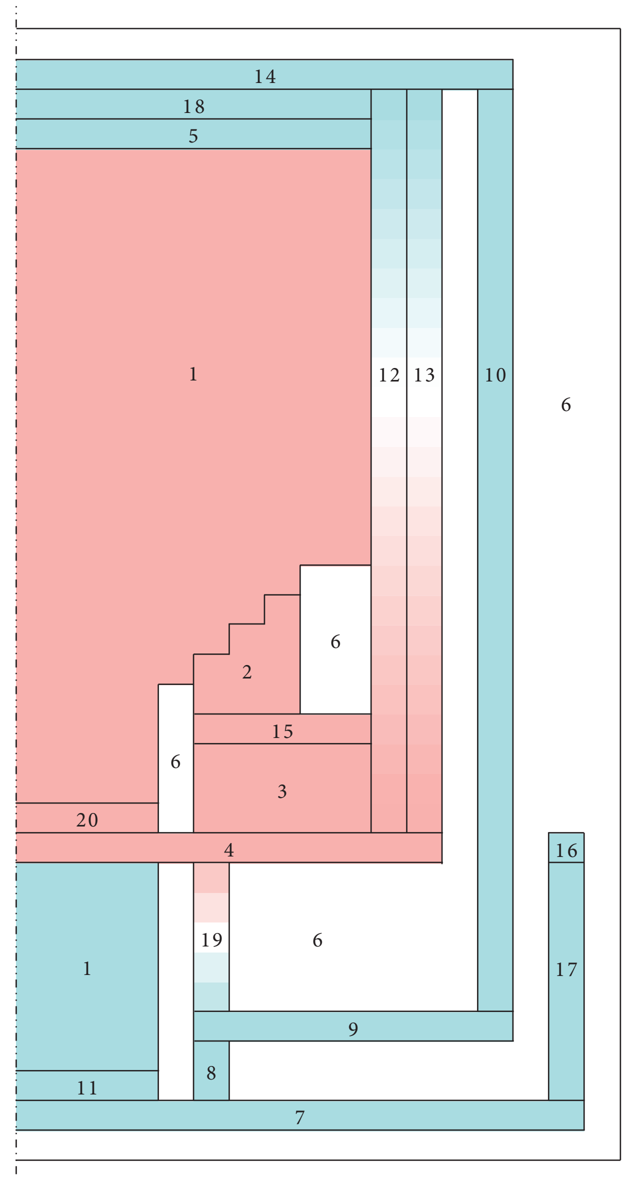
Figure 4: Brief flow process in the improved HTR-10 model.

and boundary conditions of the calculating model are set according to the operating parameters listed in Table 2. Region 16 in the model, which represents the coolant inlet, is set velocity inlet, where the mass flow rate is 1.53 kg/s and the temperature is 183.73°C. The outer fluid boundary temperature is set at 20°C, and the pressure of the coolant in RPV is set at 16.92 bar.

In the present thermal hydraulic analysis, the heat generated by the fuel elements is calculated based on the power distribution provided by the reactor physical analysis and calculation. The power density profile of HTR-10 mainly depends on the refueling scheme and fuel composition. The Several-Passages-through-the-Core cycle is chosen as the procedure for the fuel handling inside the core for HTR-10. The refueling scheme is that the fuel elements are 5 times cycled through the reactor before they reach their specified burnup. At present, HTR-10 is still in the transition period from the initial core to the equilibrium core. Its power distribution in the simulated condition is shown in Figure 6, whose thermal power is 3.20 MW in total.

3. Results and Discussion

3.1. Bypass Flow Ratio. Several cases to discuss the relationship between the maximum temperature in the pebble bed, including the fuel elements and the coolant and the ratio of the main coolant flow through the pebble bed, are calculated. The porosity of the reflector with bypass flow paths, the hydraulic diameter, and the local resistance parameter of the bypass flow channels are adjusted to change the bypass flow proportion from about 11% to 5.2%, which correspondingly makes the main flow ratio change from about 86% to 91.8%.



(1) Pebble bed core,
(2, 3) Flow channels in bottom reflector,
(4) Hot helium outlet plenum,
(5) Plenum between the top reflector and the pebble bed,
(6) Non-flow zone,
(7) RPV bottom cavity,
(8, 9) Bottom flow channels,
(10) Coolant rising channels in the side reflector,
(11, 20) Throttle plate,
(12) Bypass flow in the side reflector,
(13) Control rod channels,
(14) Plenum in the top reflector,
(15) Plenum in the bottom reflector,
(16) Inlet cavity in RPV,
(17) Annular flow channel in RPV,
(18) Flow channels in top reflector,
(19) Bypass flow in the bottom structures.

Figure 5: Gas convection model for HTR-10.

The maximum core temperature for different mass flow distribution is shown in Figure 7. The dots of different shapes show the temperature of helium, fuel ball surface, and fuel ball center. Different colors represent the results of

Table 1: Flow Distribution of the coolant.

Flow paths	Mass flow ratio
Pebble-bed and bottom reflector	No less than 86.00%
Control rod boreholes	About 2%
Discharging tube	About 1%
Bypass flow in total	No more than 11%

Table 2: Main parameters and boundary conditions in the calculation.

Parameters and boundary conditions	Unit	Value
Reactor thermal power	MW	3.20
Primary helium pressure	bar	16.92
Primary helium mass flow	kg/s	1.53
Helium temperature at the reactor inlet	°C	183.73
Helium temperature at the reactor outlet	°C	569.71
Ambient temperature	°C	20.00

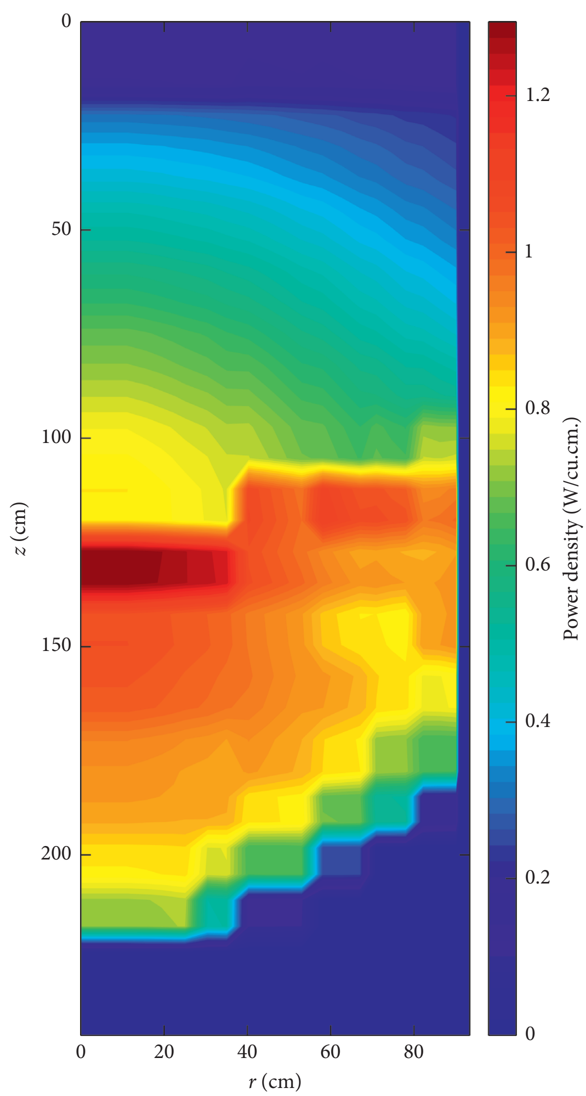


Figure 6: Power density profile of the simulated condition.

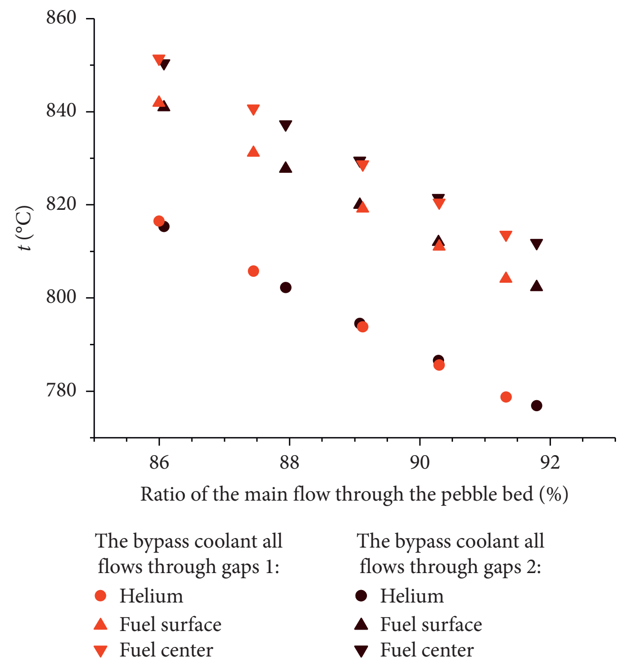


Figure 7: The relationship between maximum core temperature and flow distribution schemes with different mass flow ratios and with different bypass flow positions.

models with different bypass flow positions, as shown in Figure 4.

The highest temperature of each component decreases as the ratio of the main flow increases because when the bypass flow becomes smaller, more coolant contributes to cooling the fuel elements in the pebble bed effectively. The results show that, for every 1% increase in the main flow ratio, the maximum temperature drops by about 7°C.

The temperature differences between helium, the surface, and center of fuel elements are generally consistent when the ratio changes. The heat transfer from the fuel element center to the surface is conduction, where the temperature difference can be calculated based on the Fourier heat conduction formula. The heat generated by the fuel ball does not change, so the heat flux keeps constant. The thermal conductivity of the fuel ball does not change significantly here with the temperature change within 50°C. The heat transfer from the fuel ball surface to helium can be calculated based on Newton's cooling formula, where the heat flux decreases with the main flow increasing and the fuel temperature decreasing, and it is directly proportional to the convective heat transfer coefficient of helium flowing pass the fuel ball surface.

3.2. Bypass Flow Position. The temperature of the P-P bypass flow coolant without sufficiently heated is much lower than the graphite reflectors at the bypass path inlet. When the bypass flow, which accounts for about 1/10 of the total coolant flow, passes through different positions in the core vessel, it will affect the temperature distribution of nearby structures greatly, which may also influence the temperature distribution in the pebble bed.

The relationship between the bypass flow positions and the temperature distribution in the reactor core is analyzed in detail. In the following six cases, the bypass flow coolant flows into both the two gaps and the total bypass mass flow ratio is kept constant at 11%. In the first case, all the bypass coolant flow into Gaps 2, and 20% of all the bypass coolant is moved into Gaps 1 in the next every case until all the bypass coolant flows into Gaps 1.

The radial temperature distribution in the reactor core vessel with the bypass coolant flowing through different positions is shown in Figure 8. In this figure, the two sets of curves show the temperature distribution at two heights of 80 cm (an upper part) and 170 cm (a lower part) below the top surface of the pebble bed, respectively. Along each curve, the temperature at the core axis is the highest and gradually decreases outwards with the progressive heat transfer from the pebble bed to the side reflectors and the carbon bricks.

The bypass coolant passing through the side reflectors reduces the overall core radial temperature more effectively. The temperature difference is not obvious in the pebble bed, especially at the lower part, where more heat is generated by the fuel elements. The maximum temperature difference appears at the inner surface of the side reflectors facing the pebble bed, which is about 40°C at the upper part and about 70°C at the lower part. The reason is that Gaps 2 is located between the pebble bed and the control rod channels. The temperature of the bypass flow coolant is much lower than that of the graphite bricks in the side reflectors, so the temperature of the structures near Gaps 2 decreases significantly as the side bypass flow increases. As heat is transferred outwards in the structures that do not generate heat, the temperature difference decreases gradually.

The axial temperature distribution in the side structures in the core vessel with the bypass coolant flowing through different positions is shown in Figure 9. In this figure, the four sets of curves show the temperature distribution of four regions of graphite reflectors with and without bypass coolant, the contact surface of side reflectors and carbon bricks, and the carbon bricks from the inside out, respectively.

As the bypass coolant moves from bottom to side, the maximum temperature moves downwards from the height of the bottom of the cylindrical part of pebble bed to the height of the plenum in the bottom reflectors, because the bypass coolant through the side reflectors transfers more heat from the coolant in the bottom reflectors outwards to the side components. The maximum temperature difference occurs at the cylindrical bottom, which is 70°C in the reflectors with bypass channels and about 40°C in the reflectors without bypass flow paths between the control rod channels and the cold helium rising channels. As the heat transfers radially outwards, the temperature difference in the side structures between different cases gradually decreases. Similarly, in the reactor bottom, the temperature of the structures is the lowest in the case with the most bypass coolant flowing through the bottom gaps. All the coolants passing through different channels flow into the hot plenum

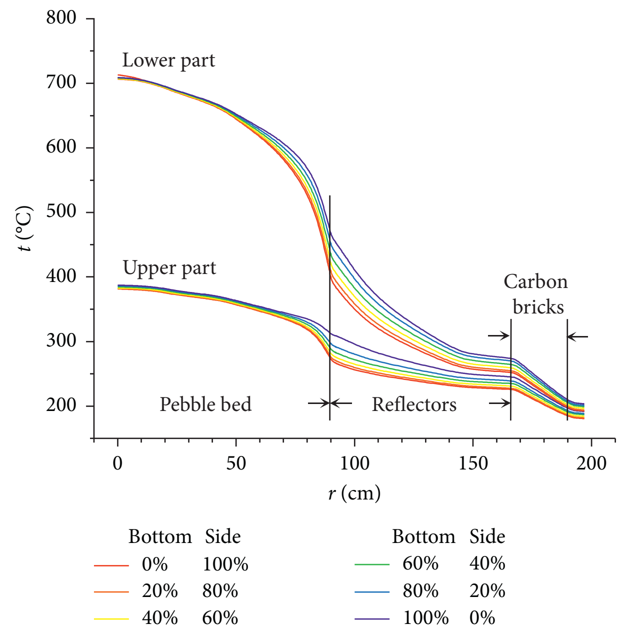


Figure 8: Radial temperature distribution in the reactor core vessel with different bypass flow positions.

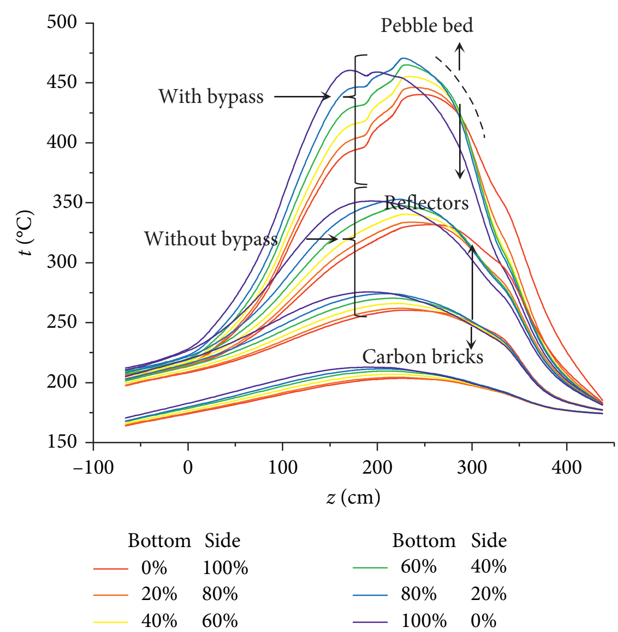


Figure 9: Axial temperature distribution in the reactor core vessel with different bypass flow positions.

and are mixed substantially there before flowing out of the reactor core. The temperature generally becomes the same at the height of the hot helium plenum.

The temperature of the fuel ball surface at the pebble-bed axis in the cases is shown in Figure 10. As more coolants move from bottom to side, the temperature of the fuel ball surface decreases by within 10°C from the upper part to the middle of the pebble bed and then becomes almost the same from the middle of the core to the discharging tube inlet. In the discharging tube, the temperature is lowest in the cases

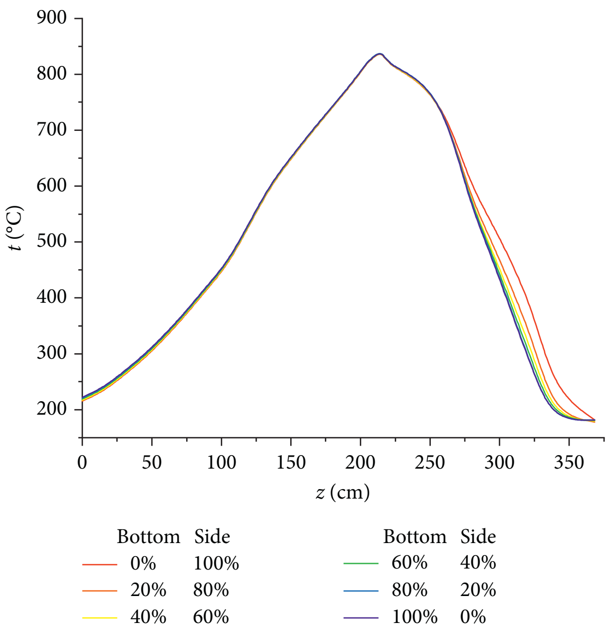


FIGURE 10: Relationship between fuel ball surface temperature at the pebble bed axis and bypass flow positions.

with the most coolant passing through the bottom bypass channels. The temperature difference is bigger than that in the upper part of the core, but the heat in total is almost the same because the amount in the discharging tube is much less than that in the pebble bed.

The highest temperature of the fuel and the coolant in the pebble bed is also compared when the bypass coolant flows through Gaps 1 below the reactor pebble bed and through Gaps 2 in the side reflectors around the pebble bed. The results are as shown in Figure 7. The highest temperatures, which are located at the core axis, hardly change with the bypass flow position. When the bypass flow ratio keeps constant, together with the control rod cooling flow and the discharging tube cooling flow, the mass flow of the coolant flowing through the pebble bed does not change. The mass flow distribution at the axis of the pebble bed hardly changes because no parameters to calculate the friction pressure loss in pebble bed change significantly. The heat transfer condition in the pebble-bed axis is almost not changed.

4. Conclusions

Thermal hydraulic analysis of HTR-10 with the bypass coolant with different positions and ratios is conducted in the present work. The temperature distribution in both the pebble bed and the reactor internals is affected, especially in the side graphite reflectors. The main conclusions are achieved as follows:

(1) The bypass coolant flowing through the reflectors enhances the heat transfer of the nearby components efficiently. The temperature of the side reflectors with all the bypass coolant flowing through the side gaps is up to 70°C lower than that with all the bypass coolant through the bottom gaps.

(2) The temperature distribution of the central region in the pebble bed is affected by the bypass flow positions slightly, while that of the peripheral area is affected significantly.

(3) The maximum temperature of the helium, the surface, and center of the fuel elements rises by about 7°C for every 1% increase in the bypass flow ratio, while the temperature difference between them almost keeps constant.

(4) When the flow ratio of each part keeps constant, the maximum temperature almost does not change with different bypass flow positions.

In future researches, based on this study, the thermal hydraulic model of HTR-10 can be calibrated with the experimental results from the temperature measuring points set in the side reflectors to ensure the portions of the side and the bottom bypass flow.

Data Availability

The data used to support the findings of this work are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National High Technology Research and Development Program of China (863) (Grant no. 2014AA052701) and the National S&T Major Project (Grant no. ZX069), which are gratefully acknowledged. The authors also would like to thank Dr. Bing Xia for providing power distribution data.

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