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Predictions of the Bypass Flows in the HTR-PM Reactor Core

Sun Jun, Chen Zhipeng, Zheng Yanhua, Shi Lei, Li Fu
Institute of Nuclear and New Energy Technology, Tsinghua University
the key laboratory of advanced reactor engineering and safety, Ministry of Education
Nengke Building B207, Tsinghua University, Beijing 100084, China
Phone: +86-10-62784826, sunjun@tsinghua.edu.cn

Abstract – *In the HTR-PM reactor core, the basic structure materials are large amount of graphite reflectors and carbon bricks. Small gaps among those graphite and carbon bricks are widespread in the reactor core so that the cold helium flow may be bypassed and not completely heated. The bypass flows in relative lower temperature would change the flow and temperature distributions in the reactor core, therefore, the accurate prediction of bypass flows need to be carried out carefully to evaluate the influence to the reactor safety. Based on the characteristics of the bypass flow problem, hybrid method of the flow network and the CFD tools was employed to represent the connections and calculate flow distributions of all the main flow and bypass flow paths. In this paper, the hybrid method was described and applied to specific bypass flow problem in the HTR-PM. Various bypass flow paths in the HTR-PM were reviewed, figured out, and modeled by the flow network and the CFD methods, including the axial vertical gaps in the side reflectors, control rod channels, absorber sphere channels and radial gap flow through keys around the hot helium plenum. The bypass flow distributions and its flow rate ratio to the total flow rate in the primary loop were also calculated, discussed and evaluated.*

I. INTRODUCTION

As the demonstration nuclear power plant for the high temperature gas-cooled reactor technology, the HTR-PM (high temperature reactor pebble bed module) is designed by INET (Institute of Nuclear and New Energy Technology), Tsinghua University [1], and has poured the first concrete on December 9th, 2012.

In the reactor core design, a large number of graphite and carbon bricks are piled up to circle a cylindrical structure, in the middle of which are filled with hundreds of thousands of spherical fuel elements, i.e., the pebble bed. Also served as the neutron reflectors, the graphite bricks are dug and shaped to form many flow paths for the coolant. The cold helium gas at the temperature of 250℃ is driven by the main helium blower and flows into the reactor pressure vessel through the outer tube of the horizontal coaxial double tube, named hot gas duct. Then, the helium flow in the lower head is separated into 30 rising channels inside the side reflectors, goes upward and is collected in the cold helium plenum above the pebble bed. A majority of the cold helium, main flow, flows through the pebble bed downward to bring out the huge fission heat, being heated up to 800-900℃, and is fully mixed in the hot helium plenum below the pebble bed. The rising channels for the cold helium and the pebble bed are the main flow paths in the reactor core. Meanwhile, a minority of the cold helium may flow through narrow gaps, slots, or channels inside the graphite reflectors and carbon bricks, thus, it cannot be heated adequately from the pebble bed and becomes the bypass flow relative to the main flow through the pebble bed. The bypass flow in lower temperature finally enters into the hot helium plenum and mixes with the main flow. The mixed hot helium flows through the inner tube of the hot gas duct and exchanges heat with the water or steam flow in the secondary loop. The important nuclear island equipment and systems and the main helium flow directions are illustrated in Figure 1.

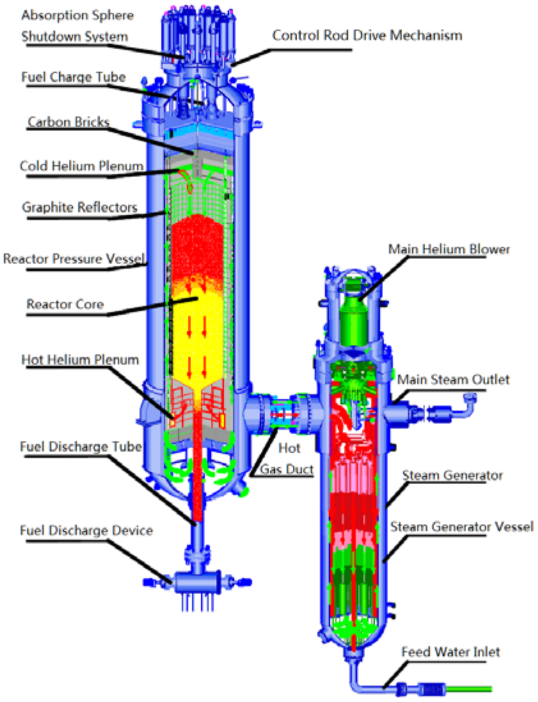

Fig. 1: Drawing of the main nuclear island systems and structures in the HTR-PM.

The bypass flow is part of flow in the primary side so that the ratio of bypass flow rate to the primary flow rate affects the effective flow through the pebble bed, and then the temperature distributions in the reactor core. If more flow is bypassed from the pebble bed, main flow is less and not so effective to bring out the heat from the pebble bed. The maximum temperature of fuel pebbles as well as the average temperature in the reactor core becomes higher. It at least induces two problems to the reactor safety. One is about the fission products inside the fuel pebbles, which may have larger possibility to diffuse into the flow in the primary loop to increase the radioactive level. The other problem is the less temperature safety margin for the normal operation and accident conditions of the reactor. Therefore, the predictions of the bypass flow ratio of the primary flow and the bypass flow distribution in the reactor core are very important issues in the thermal hydraulic design of the high temperature gas-cooled reactors.

Knowledge of the bypass flow and its effects on the reactors have also been noticed in many kinds of high temperature gas-cooled reactors. In the commissioning phase of the THTR (Thorium high temperature reactor), evident bypass flow was indicated and evaluated to about 23% of the total flow rate in the primary loop, in which, leakage around the hot gas duct was the major bypass path. In the test reactor HTR-10 [2], which is also designed and operated by INET, the conservative estimation of the bypass flow ratio to the primary loop flow was less than 14%. In the preliminary safety analysis of the HTR-PM, the bypass flow ratio was about 10%. Experimental means are difficult that data related to the bypass flow are still inadequate. Thus, numerical calculations are feasible to understand the bypass flow in the reactor core. System codes were used to calculate the effect of the bypass flows in HTR-Modul [3] and the HTR-PM [4]. Although the system codes were the primary design tools for the thermal hydraulics, the bypass flow paths and their resistances were input models and should be determined a prior. In other words, it could not predict the amount and distribution of the bypass flow only with the system codes. With the development of computer technologies both in the software and hardware, the CFD (computational fluid dynamics) methods have been more widely applied in the thermal hydraulic analyses in the nuclear engineering. For the high temperature gas-cooled reactors, more detailed models were established to study the bypass flow for the AVR (Arbeitsgemeinschaft Versuchsreaktor) [5] and PBMR (Pebble Bed Modular Reactor) [6-7]. Limited by the huge computational cost, the bypass flow was not able to be predicted with all of them in the reactor core model using CFD tools. Only part of the bypass flow paths were modeled or simplified. A compromised method should be employed to balance the computational costs and data fidelity so that the bypass flow can be predicted and evaluated.

Since the reactor core of the HTR-PM is the loose structure consist of large amount of graphite and carbon bricks from top to bottom and from the inside out, many gaps among those bricks are possible bypass flow paths. Those gaps are widely distributed and connected so that the bypass flow paths should be described with their positions and interconnections. Furthermore, the number of gaps are too large to be modeled in detail so that proper simplifications should be made to solve the bypass flow problem. Moreover, the pressure distribution in the reactor core is mainly formed by the main flow so that the bypass flow paths should be modeled together with the main flow paths. Therefore, based on these characteristics, we have found the hybrid method of using the flow network and the CFD to predict the bypass flow in the HTR-PM in a practical way [8]. The flow network method is used to represent the simplified flow paths and their connections, including the main flow paths and bypass flow paths. Then, typical resistance of each flow path should be determined by empirical formula or calculated in the CFD simulations. Finally, the flow rates and distributions in all the flow paths are calculated in the flow network. In INET, we have analyzed many kinds of bypass flow paths in the HTR-PM, such as bypass flow introduced in the fuel discharge tube [8], the vertical gaps between side reflectors [9], and bypass flow in the control rod channels [10].

In the current paper, the hybrid method of the flow network and the CFD was further clarified in Section II. Following that was mainly the analyses and results about the bypass flow recently studied in Section III, in the beginning of which, previous researches were also reviewed. The last part was the conclusion and future work.

II. METHODOLOGY

The bypass flow problem in the HTR-PM reactor core is characterized in three aspects:

1. The gaps, possible bypass flow paths, are widespread, interconnected and in a large number;
2. Shared the helium pressure background inside the reactor pressure vessel, the bypass flow is interacted with the main flow;
3. The gap structures vary and are irregular affected by installation, thermal expansion and irradiation in the reactor core, and may change in the long time operation life.

Due to these special features, the flow network combined with the CFD tools is the practical method to solve the bypass flow problem in the HTR-PM reactor core. The flow network method, also called pipe network or pipe flow network, is the simplification of flow field into flow nodes and flow links so that the interconnections of the gaps and their connections with pebble bed are easy to represent. Meanwhile, the computational costs by the flow network method are reduced significantly from the detailed models in the CFD simulations so as to solve all the main flow and bypass flow in the same model. The CFD tools are only used to model partial or local flow channels with complex or irregular shapes to obtain the flow resistances. With explicit resistances of every flow link and boundary conditions, the flow network can be solved to show the flow and pressure distributions. In this section, the methodology of the bypass flow problem was introduced in the following two parts: the flow network and the CFD.

II.A. Flow Network

The flow network was a kind of simplification in numerical solution of fluid dynamics widely applied in pipe flows. Three-dimension flow field was treated as multiple one-dimension flow paths, interconnected to form a network. The control volumes of the flow field were then replaced by flow nodes and flow links in the space discretization. Flow nodes were characterized with mass, pressure and temperature, while flow links with resistance and flow rate. In this way, linear equations of flow rate and pressure were deduced so that the computational cost was much decreased. Different from the mass, momentum balance equations in three-dimension flow, the linearized pressure equation set of the flow network is much more simplified and formed by combining the mass balance equations of the flow nodes and the momentum balance equations of the flow links. The common form of the linearized pressure equation at the time (*t*+1) was

$$-\left(\sum_{i=1}^{m} R_{b,i} + \sum_{j=1}^{n-m} R_{b,m+j} + \frac{V}{\tau}\frac{\partial\rho}{\partial p}\right)_t p_{t+1} + \sum_{i=1}^{m} R_{b,i}\, p_{i,t+1} + \sum_{j=1}^{n-m} R_{b,m+j}\, p_{m+j,t+1} = \sum_{i=1}^{m} C_{b,i} - \sum_{j=1}^{n-m} C_{b,m+j} - \left(\frac{V}{\tau}\frac{\partial\rho}{\partial p}\right)_t p_t \quad \text{(eq. 1)}$$

in which, p, ρ and V were the flow node's pressure, density and volume, τ was the time step between time $t+1$ and t. This typical flow node had m upstream flow nodes and n-m downstream flow nodes. The parameters representing the resistance of flow links, R_b and C_b, were

$$R_b = \frac{1}{\dfrac{f}{\rho A^2}|w|} \quad \text{(eq. 2)}$$

$$C_b = -\left(\frac{f}{2\rho A^2}|w|w + \rho g H\right) \Big/ \left(\frac{f}{\rho A^2}|w|\right) \quad \text{(eq. 3)}$$

in which, f, A, H and w were the resistant coefficient (including the local and friction ones), cross section area, height difference and mass flow rate of the flow link, g was the gravitational acceleration.

Within the flow network, all the flow nodes' equations formed the equation set, in which, the coefficient matrix was usually sparse. With given boundary conditions and determined resistance of each flow path, the coefficient matrix was known and could be solved by many efficient methods to obtain the pressure and flow distributions.

Before solving the flow network, one of the important steps was to determine the resistances of various flow paths, which directly affected the flow distribution. Main flow paths could use empirical correlations to calculate the resistant coefficients, such as the KTA rule [11] for the flow through the pebble bed, or the common used inner circular tube flow resistance formula:

$$f = f_{local} + \frac{L}{D}\frac{0.3164}{\mathrm{Re}^{0.25}} \quad \text{(eq.4)}$$

in which, the resistant coefficient was the sum of the friction and local ones. L and D were the channel's length and the hydraulic diameter of the cross section area. Re was the Reynolds number of the channel. Usually, the local resistant coefficients could also be inquired in many reference books.

For irregular channels or channels with complex shapes, the flow resistance should be calculated by CFD simulations, described in the next part.

For the bypass flow problem of the HTR-PM, the vPower simulation platform was the modeling and solving software, developed by Beijing Neoswise Sci. & Tec. Co., Ltd. Many graphical modules were embedded in the vPower with specific algorithms to represent flow nodes, flow links, pebble flow resistance, inner tube flow resistance, etc. New modules with resistance algorithms related to complicated bypass flow paths could be easily developed and integrated into the vPower system. The vPower has been successfully applied and validated in building the real time simulation reactor model for the engineering simulator [12] using the flow network. The previous researches [8-10] of the bypass flow also used the flow network to understand the characters of the bypass flow, which was shown in the next section.

In addition, the admittance (*ADM*) of the flow link was commonly used in vPower to represent the resistance,

$$ADM = \frac{w}{\sqrt{\Delta p + \rho g H}} \quad \text{(eq.5)}$$

in which, large admittance meant low resistance. In flow links, the admittance values could be directly assigned or calculated by functions or correlations in attached modules on the flow links.

Typical scheme diagram of the modeling page in the vPower was shown in Figure 2 indicating a simple project of how to use the vPower. Detailed models of various bypass flow paths were described in the next section.

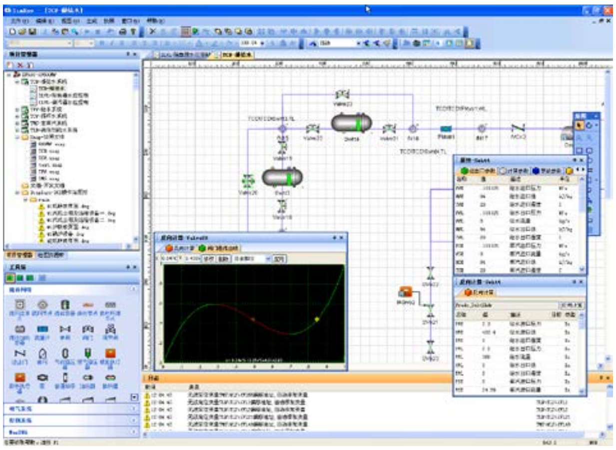

Fig. 2: The simple project of using the vPower.

The bypass flow problem is more than solving the flow distribution in the reactor core. The temperature distribution as well as its feedback to the power distribution is also related. The bypass flow should be modeled with the heat transfer part and the reactor physics part so that the influences among these three parts could be considered in a more realistic way. However, the previous researches and the analyses in current paper were still simplified that only the flow network was modeled. Flow paths in the flow network model were given proper fluid temperatures according to the flow paths' positions to calculate fluid properties, such as the densities and viscosities. The fluid temperatures in specific positions were derived from results in the Preliminary Safety Analysis Report of the HTR-PM [13].

The simplified flow network model for the bypass flow problem was the first step to solve the bypass flow problem, in which, the main purposes currently were to preliminarily understand the bypass flow distribution, the effects of gap sizes, and the relative importance of gap positions.

II.B. CFD

With the development of computational tools, the CFD was more and more applied in the thermal hydraulic analyses. Since the basic conservation equations of mass, momentum and energy were the foundation of the CFD theory, irregular channels or gaps in the bypass flow problem should be simulated in CFD as an effective means.

For a bypass flow path, the geometrical structure could be modeled in Gambit and discretized into meshes. Then, the mesh information in the mesh file was imported into the ANSYS Fluent to select fluid and solid materials, turbulent models, solving algorithms, to set initial and boundary conditions, and to induce the flow resistance from the convergent results at last. Usually, many cases were simulated for the same channel with a group of boundary conditions, such as various pressure differences at the inlets and outlets. The group of flow rates and pressure difference could calculate the admittances of the channel from the results.

Since the gaps inside the graphite reflectors were interconnected to form the gap networks or gap combinations, specific gap and its boundary conditions was not easy to clarify. In the bypass flow problem, we tried to analyze the gaps or their combinations with clearer boundary conditions, given constant pressures at the cross sections of the inlets or outlets of the CFD models.

In addition, the gap sizes in the bypass flow paths were as small as 1mm or smaller so that the Reynolds number of the gaps were about several thousand, the values of which were seemed to be at the transition level from laminar flow to turbulent flow. Since the cross sections of these channels were not circular, we believed that the complex shapes and variations of the cross sections (such as bend, expansion or contraction) in those gaps induced turbulent flow so that the turbulent model, such as the standard k-e model, was more appropriate with balanced accuracy and computational cost. Only the gaps with extreme small sizes, smaller than 0.1mm, and with simple shapes, such as flat straight channels, were considered to use the laminar flow model in the CFD simulations, in which, the flow rates were much smaller and could be neglected in the bypass flow problem. The laminar models used for extreme small sized and flat straight channels were compared and validated in experiments [14].

III. BYPASS ANALYSES

With the hybrid method of the flow network and the CFD, the bypass flow can be modeled and analyzed in the following major steps:

1. Clarify the possible bypass flow paths and their connections in the reactor core;
2. Build flow network models of all flow paths, with proper discretization of the flow nodes and flow links;
3. Determine the flow resistance of each flow path, use CFD simulations if necessary;
4. Solve the flow network.

From the cross section figure of the HTR-PM reactor core structure in Figure 3 and the schematic diagram of bypass flow paths in Figure 4, possible bypass flow paths at least include:

1. Vertical gaps between graphite reflectors;
2. Control rod channels;
3. Adsorbed sphere ball channels.

As for the vertical gaps between graphite reflectors, bypass flow directions may be axial or radial. In the axial direction, pressure difference of the cold helium plenum and hot helium plenum will induce bypass flow there, which was discussed in Section III.A. Since the space outside of the carbon bricks has the pressure almost equivalent to that at the lower head of the reactor pressure vessel, which is much higher than the pressure in the pebble bed. The bypass flow in the vertical gaps may be in radial direction from outside of the carbon bricks to the pebble bed. Of the radial bypass flow paths, the largest bypass flow rate, which is of greatest interest, may occur around the hot helium plenum with largest pressure difference. Thus, only the bypass flow around the hot helium plenum was discussed in Section III.D.

In this section, previous work, including flow in the vertical gaps and control rod channels, was reviewed and further analyzed at first. Following these steps, some recent results were shown about the bypass flow in adsorbed sphere channels and bypass flow around the hot helium plenum.

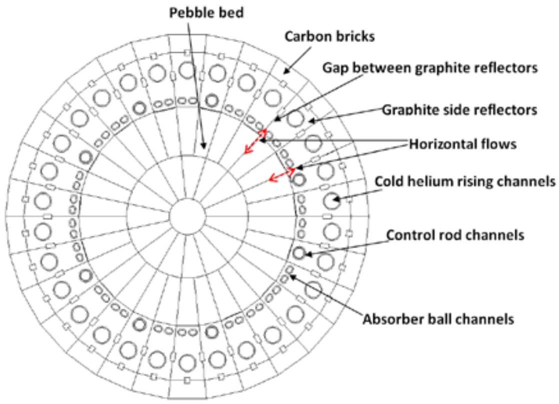

Fig.3: Cross-section of the reactor core structure in the HTR-PM.

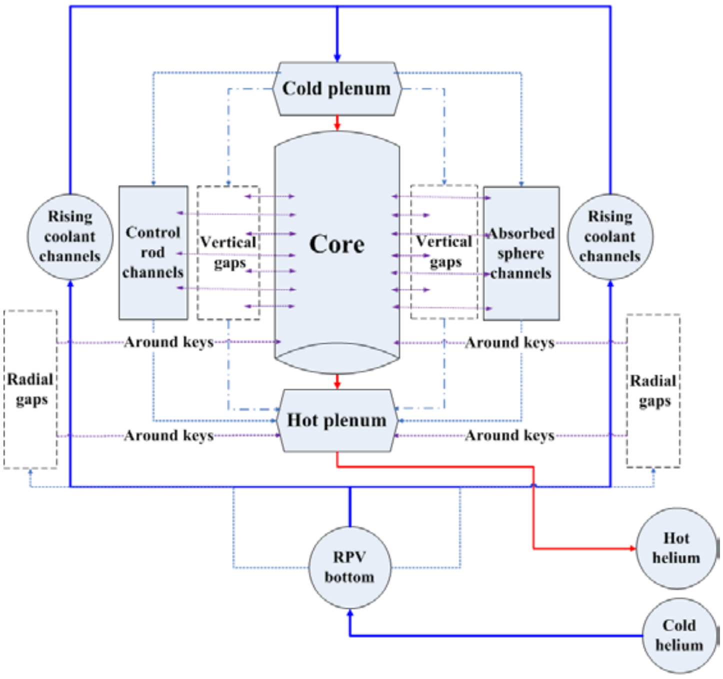

Fig.4: Possible bypass flow paths in the reactor core of the HTR-PM.

III.A. Axial Bypass Flow in Vertical Gaps between Side Reflectors

Due to the vertical gaps between side graphite reflectors and the connections from the cold helium plenum to the hot helium plenum, the axial bypass flow was modeled and analyzed in our previous research [9]. Since the vertical gaps were adjacent to the pebble bed, potential horizontal flow (Figure 5) could exchange the main flow in the pebble bed with the axial bypass flow in the vertical gaps, the direction of which was from the gaps to the pebble bed or in opposite depending on the pressure distribution there. It revealed that the horizontal flows around those vertical gaps had strong effect on the axial bypass flow so that their flow network model were necessary.

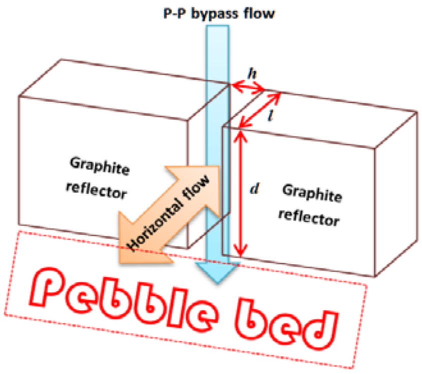

Fig. 5: Schematic diagram of axial bypass flow and horizontal flow in a gap between two graphite bricks

Not only the sizes but also the size distributions of these vertical gaps were important. From the flow directions shown in Figure 6 in the result of the flow network, the horizontal flow was into the pebble bed at the top while out of the pebble bed at the bottom, in which, larger gaps induced larger pressure difference of the vertical gaps and the pebble bed, and more horizontal flow. In the middle of the pebble bed, the horizontal flow rates were smaller than those at the top or the bottom due to smaller pressure difference. Even there was a turning point of horizontal flow direction that the flow rate was almost zero. Thus, the gap size in the middle was not the dominant factor.

Also from the flow network in Figure 6, flow paths in the pebble bed and the vertical gap shared the inlet and outlet flow nodes, located at the cold helium plenum and hot helium plenum respectively. The flow rates might be different for the bypass flow paths into the vertical gap at the top and out of the vertical gap at the bottom. If the vertical gap sizes were the same from top to bottom, the flow rates into and out of the bypass flow path were also the same, which meant the net exchanged horizontal flow rate of the pebble bed and the vertical gaps were zero. While the gap sizes were not always the same, there were horizontal flow into or out of the pebble bed that flow rate at the top bypass path was not equal to that at the bottom bypass flow path, which was also confirmed in Ref. [9]. Then the mass flow rate balance equation for the axial bypass flow in the vertical gaps was

Inlet + Σ(horizontal flow out of pebble bed) – Σ(horizontal flow into pebble bed) = Outlet	(eq.6)

Since the real structures of the gaps were not the same from top to the bottom, it brought a problem that how to define the bypass flow rate ratio. Using only the inlet bypass flow rate or outlet could not represent the bypass effect completely. While a more conservative option was to use the sum of inlet and all the horizontal flow out of the pebble bed. Further research of vertical gap bypass flow should be with more detailed model using best estimate method.

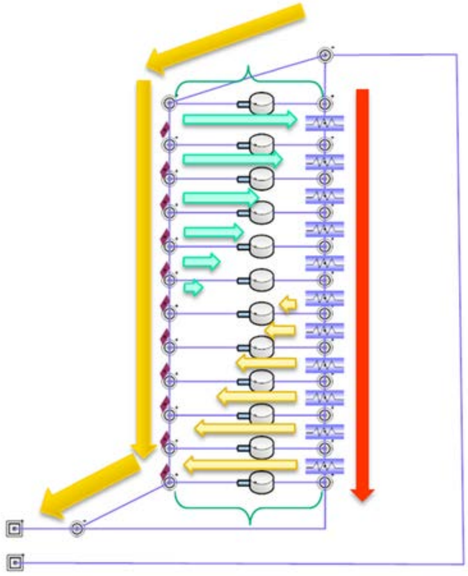

Fig. 6: Flow network results of axial bypass flow and horizontal flow in a gap between two graphite bricks

III.B. Bypass Flow in Control Rod Channels

The bypass flow in the control rod channels was used to cool down the structure material of the control rods. Small holes were dug in the graphite reflectors to lead in flow from the cold helium plenum, and to lead them out to the hot helium plenum. The bypass flow network was also built and analyses in Ref. [10] considering the control rod channels, pebble bed and potential horizontal flow through gaps between upper and lower graphite reflectors. The bypass flow in the control rod channels was mainly dominated by the large flow resistances at the inlet and outlet that the sizes of the small holes could be designed to obtain enough amount of bypass flow rate. The inlet and outlet holes were also simulated in the CFD to calculate the resistant coefficients and admittances. Unlike the horizontal flow of the vertical gaps in previous section, the horizontal gap flow of the control rod channels could be well limited by sealing structures in between two graphite reflectors, which were also modeled and simulated in the CFD. Although it also showed exchanged horizontal flow into and out of the pebble bed with the control rod channels (Figure 7), the flow rate was much lower than that with the open vertical gaps.

In addition, the horizontal flow directions were different from those in vertical gaps. Since the flow resistances in the inlet and outlet flow paths were larger than that in the pebble bed, horizontal flow went out of the pebble bed to the control rod channels at the top and into the pebble bed at the bottom.

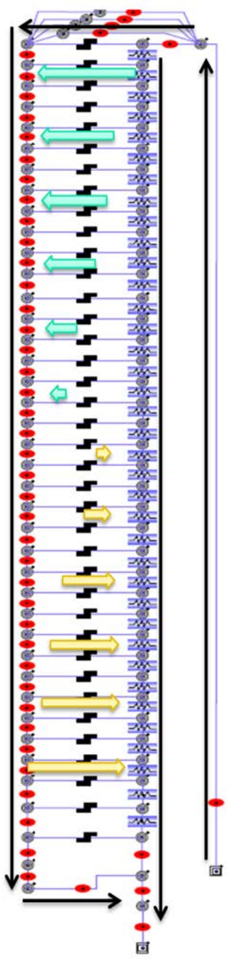

Fig. 7: Flow network results of bypass flow and horizontal flow of the control rod channels

III.C. Bypass Flow in Absorber Sphere Channels

The absorber sphere channels are another kind of vertical channels inside the side reflectors. In normal operations of the HTR-PM, they are empty. Only in accidents or shutdown conditions, the channels are filled with absorber spheres to ensure the cold shutdown of the reactor.

In the beginning of the start-up process, absorber spheres should be driven back to the tanks above the absorber sphere channels by a helium gas blower. Since the main helium blower is not running in the pneumatic conveying step, the pressure difference between the pebble bed and the absorber sphere channels are nearly negligible. Thus, the bypass flow in the start-up process was not important and interested.

In normal operation conditions, the absorber sphere channels are also parallel flow paths to the pebble bed without evident inlet or outlet. The flow network result of the bypass flow in the absorber sphere channels was shown in Figure 8 with only one absorber sphere channel, in which, the meanings of the graphical modules in the flow network were the same as those in Ref. [10]. The horizontal flow was similar to that in the control rod channels, in which, the sizes of the gaps between upper and lower graphite bricks were small and well-sealed. Therefore, the bypass flow in the absorber sphere channels was just the horizontal flow out of the pebble bed, which was balanced with the flow into the pebble bed.

When the absorber sphere channel without the sealing structure (Figure 9) was simulated in the CFD, the admittances and bypass flow rates in one channel were obtained for several sizes of the horizontal gaps, shown in Table 1. The gaps were between two upper and lower graphite bricks so that the normal sizes could not be larger than 0.2mm due to the design tolerances. The bypass flow rate in one absorber channel was not larger than 0.1kg/s as the sum of all horizontal flow out of the pebble.

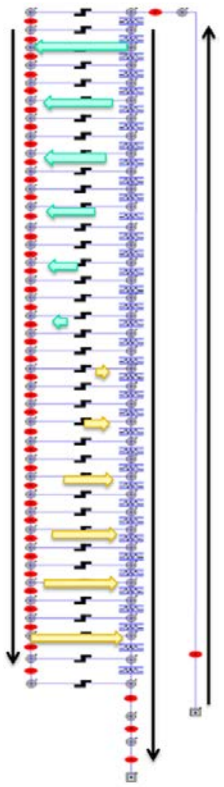

Fig. 8: Flow network results of bypass flow and horizontal flow in absorber sphere channels

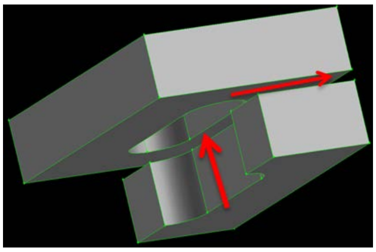

Fig. 9: Schematic diagram of bypass flow and horizontal flow in absorber sphere channels

Table 1: Bypass flow results of various horizontal gap sizes in the absorber sphere channels without sealed structure.

Gap sizes (mm)	Admittance	Bypass flow rate in one channel (kg/s)
0.1	2.2E-6	0.01
0.2	1.9E-5	0.09

With the sealed structure in the absorber sphere channels, the bypass flow rate could be more limited even for larger horizontal gaps. The three gaps in the sealed structure were similar to that in the control rod channels [10] (Figure 10, with three gaps and their widths indicated). As the gap sizes were larger in such combinations in Table 2, the bypass flow rates were also controlled in low values, indicating that the bypass flow was not significant in the absorber sphere channels even when the gaps became larger by long time irradiation.

In all the cases, assuming the six absorber sphere channels to have the same conditions, the bypass flow rate ratio to the total flow rate in the primary loop was less than 0.6%.

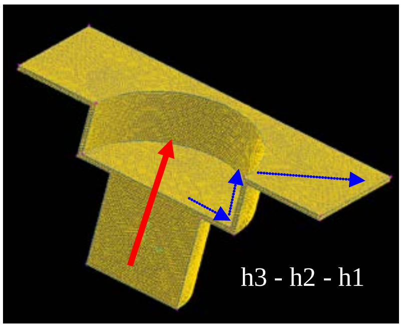

Fig. 10: Schematic diagram of bypass flow and horizontal flow in absorber sphere channels.

Table 2: Bypass flow results of various horizontal gap sizes in the absorber sphere channels with sealed structure.

Gap sizes (h1-h2-h3, mm)	Admittance	Bypass flow rate in one channel (kg/s)
6.0-0.1-0.1	2.2E-6	0.015
6.0-0.1-1.0	4.6E-6	0.031
6.0-1.0-0.1	6.5E-6	0.045

III.D. Radial Bypass Flow around the Hot Helium Plenum

As mentioned in the start of Section III, the vertical gaps may have radial bypass flow. The radial bypass flow is limited by inserting keys in the vertical gaps between each two adjacent graphite reflectors (Figure 11). As the vertical gaps extend along the side reflectors from the top to the bottom, the keys are also installed in the whole height of side reflectors. In this part, the radial bypass flow was modeled in the CFD by simulating the flow through the vertical gap around the key. Typical flow admittance was obtained for the flow around the key. Then, we only discussed the radial bypass flow around the hot helium plenum where the pressure difference was the largest and the flow path was the shortest.

The CFD model of the flow around the key was shown in Figure 12 with half of the flow path in symmetry, in which, the existence of the key made the radial flow path bend twice. Since the key was designed to fix the graphite reflectors and limit the bypass flows, the gaps around the key was smaller than the design tolerance 0.1mm, while the gap between two graphite reflectors was about 1.5mm before and after the key. Several cases were calculated with pressure differences from 50kPa to 100kPa, and the admittance of this flow path was less than 3.0E-5.

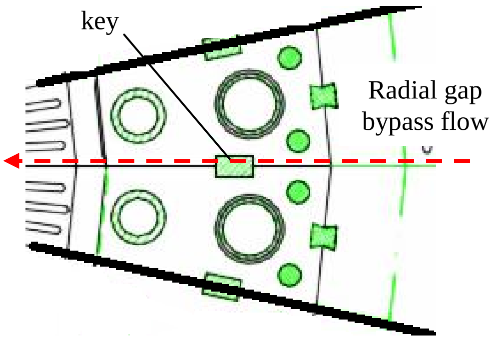

Fig. 11: Schematic diagram of radial bypass flow around the key in vertical gaps.

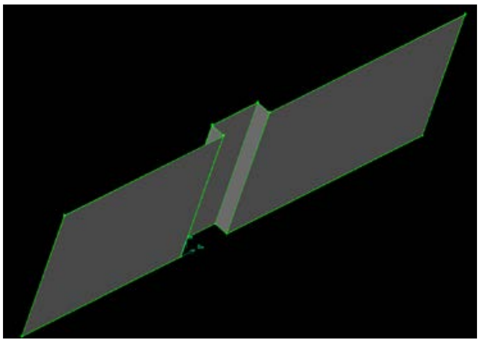

Fig. 12: Radial bypass flow path model around the key in vertical gaps.

For the bypass flow around the hot helium plenum, the most possible path was from the space between the carbon bricks and side metal internals, through the keys, and into the hot helium plenum. Connecting the flow path from the lower head of reactor pressure vessel, to the metal internals at the bottom, with the space between the carbon bricks and side metal internals, the radial bypass flow rate was calculated to be 0.024kg/s in each vertical gap with the 100kPa pressure difference. In this case, the total 30 radial bypass flow in the circle around the hot helium plenum was less than 0.8% of the total flow in the primary loop.

IV. CONCLUSIONS

The bypass flow problem in the HTR-PM was described and preliminarily solved using the hybrid method of the flow network and the CFD. The flow network method was appropriate to represent the connections of all the main flow paths and bypass flow paths, and could solve the bypass flow distributions practically. The CFD tools were used to model irregular or complex bypass flow paths, usually gaps or gap combinations, and obtain the flow resistances or admittances, which were adopted and integrated into the flow network for solving the flow rates and distributions finally. The most possible bypass flow paths included the axial and radial vertical gaps in the side reflectors, control rod channels and absorber sphere channels, in which, the bypass flow in axial vertical gaps and control rod channels were reviewed and further analyzed, while bypass flow in the absorber sphere channels and the radial gap flow through keys around the hot helium plenum were calculated and discussed. The bypass flow rate ratio to the total flow rate in the primary loop were also calculated and evaluated.

In the future, the flow network will be modeled together with the heat transfer network and reactor physics part so that the flow and temperature distributions can be solved more realistically. Other possible bypass flow paths will also be taken into account in achieve the more complete model.

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