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Performance of thermal mixing structure of HTR-PM regarding bypass flow and power effect

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ABSTRACT

The temperature of bypass flow not flowing through the reactor core is obviously lower than that of the main coolant helium in a High Temperature Gas-cooled Reactor (HTGR). In addition, change and deviation of reactor power will introduce higher radial temperature difference of main coolant helium. In order to investigate the effects of bypass flow and power change and deviation on radial temperature difference of the helium flow, model experiments and simulation calculations are proposed to evaluate the temperature profiles and Thermal Mixing Performance (TMP) of the thermal mixing structure at Pebble-bed Module High Temperature gas-cooled Reactor (HTR-PM) core outlet. We gave three definitions of TMP by describing the thermal nonuniformity of the inlet flow of the mixing structure in different ways. The TMP defined by the temperature difference between main flow and bypass flow is within the range of 97.5 ± 1.1% under all considered conditions which is suitable for evaluating the experiment and simulation results. The new definition of TMP integrating specific heat, flow rate and inlet position needs further improvement. In addition, the maximum radial temperature difference at the outlet of the mixing structure fulfils the requirement of steam generator, less than 30 °C (± 15 °C). Furthermore, future works are discussed.

1. Introduction

China is now developing and verifying the key technologies for the Pebble-bed Module High Temperature gas-cooled Reactor (HTR-PM) (Dong and Gao, 2006; Zhang et al., 2009, 2016), a demonstration plant designed by Institute of Nuclear and New Energy Technology (INET), Tsinghua University. The construction of the HTR-PM started its First Concrete Date (FCD) in December of 2012 at Rongcheng, Shangdong province, China. HTR-PM is considered as world's first fourth-generation commercial nuclear power plant with high thermal efficiency and inherent safety features based on the project of HTR-10 (10 MW High Temperature Gas-cooled Test Reactor) (Wu et al., 2002; Xu et al., 2002).

Usually, the radial temperature difference of the coolant helium out of the cylindrical reactor core is up to above 100 °C for a High Temperature Gas-cooled Reactor (HTGR). In addition, the small cold bypass flow into the bottom of reactor vessel introduces much higher temperature difference to the main coolant flow (Sun et al., 2012). In order to ensure the technical feasibility and safety of steam generator by limiting the thermal loads on the heat-exchanging components, a well-designed thermal mixing structure can mix the coolant helium out of the reactor. Usually, the thermal mixing structure consists of three components: narrow cross channel, hot gas chamber and hot gas duct in which a turbulent mixing process reduces the temperature difference of coolant. To validate the design of the thermal mixing structure for a HTGR, usually a scale or full size experiment is adopted to study its Thermal Mixing Performance (TMP) and pressure drop together with related numerical calculations.

A serial air tests in a 1:2.9 scaled plexiglass facility were conducted to evaluate the mixing performance of the hot gas header and the hot gas duct of the HTR-Module reactor (Damn and Wehrlein, 1992). Thermal hydraulic tests on the core and core-bottom structure were carried out on the Helium Engineering Demonstration Loop (HENDEL) under simulated reactor operating conditions of High-Temperature engineering Test Reactor (HTTR) (Inagaki et al., 1990, 1992, 2004). TMP of the hot gas chamber of HTR-10 was experimentally investigated on a 1:1.5 scaled plexiglass facility with air (Huang, 1995; Yao et al., 2002). Some basic experiments had been finished on a Test Facility -

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Hot Gas Mixing (TF-HGM) for HTR-PM (Zhou et al., 2014, 2016a).

Moreover, numerical simulation was conducted to analyze the TMP of HTGR reactor outlet. The flow profile in the hot gas chamber of HTGR is investigated using CFX5 software (Wang et al., 2006), which indicated that the turbulent twisting flow resulted in the high thermal mixing efficiency. Several turbulent models, such as the classical k-ε model, advanced two-equation models and Reynolds-Stress model were compared by considering their accuracy for simulating the flow in the mixing structure (Von Lavante and Laurien, 2007). The TMP of HTR-PM core outlet was analyzed using Fluent software (Zhou et al., 2016b).

This paper discusses the performance of thermal mixing structure at HTR-PM core outlet considering the effects of bypass flow and power change and deviation. Firstly, this paper introduces three kinds of definition of TMP. Then, we show the special designs and the related experiment results of TF-HGM for HTR-PM taking into account the bypass flow and power deviation. After it, the results of simulation calculations on the mixing structures of the TF-HGM and HTR-PM are investigated using Fluent software, where bypass flow and power change and deviation are considered. Finally, discussions and conclusions are introduced based on the results of the experiments and simulation calculations and some future works are predicted.

2. Definitions of TMP

For the issue of definition of TMP, the paper mainly concerns the differences of the way to obtain the maximum temperature difference of different inlet flow in the mixing structure. The inlet flow of the mixing structure consists of three branches, hot gas branch, cold gas branch and bypass gas branch, which will be explained in Section 3 of this paper in detail. When only considering the inlet temperature difference between hot gas branch and cold gas branch, the TMP is defined as the following equation:

$$TMP = \left(1-\frac{\Delta t_o}{\Delta t_i}\right)\times 100\%,\ \ \Delta t_i = t_{i,h}-t_{i,c} \tag{1}$$

where, Δt_o indicates the maximum temperature difference at the cross section of the outlet of the mixing structure with K as its unit; Δt_i indicates the maximum temperature difference at the inlet of the mixing structure with K as its unit; $t_{i,h}$ and $t_{i,c}$ indicate the inlet temperature of hot gas branch and cold gas branch respectively with K as their units.

In addition, we can also calculate Δt_i according to the inlet temperature difference between hot gas branch and bypass gas branch:

$$\Delta t_i = t_{i,h}-t_{i,b} \tag{2}$$

where, $t_{i,b}$ indicates the inlet temperatures of bypass gas branch with K as its unit.

Since the temperature, mass flow rates and specific heats of the gas in hot gas branch, cold gas branch and bypass gas branch may be quite different, the simple temperature difference sometimes cannot indicate the thermal nonuniformity at the inlet. A new way to calculate the maximum temperature difference at the inlet is proposed as the following equation:

$$\Delta t_i = \frac{\alpha\sum|((t_j C_{p,j}-t_a C_{p,a})v_j\beta_j|}{\sum(v_j C_{p,j})} \tag{3}$$

where, α indicated the correction factor considering the thermal uniformity between inlet gas and outlet gas. t_j, v_j, $C_{p,j}$ and β_j denote temperature, mass flow rate, specific heat capacity at constant pressure and location correction factor of the jth inlet gas branch respectively. Their units are K, kg/s and J/(kg·K) respectively. t_a is the average temperature of the inlet gas with unit of K and $C_{p,a}$ is its specific heat capacity at constant pressure with unit of J/(kg·K).

$$t_a = \frac{\sum(t_j v_j C_{p,j})}{\sum(v_j C_{p,j})} \tag{4}$$

When the temperature distribution of the inlet gas is continuous, the Eqs. (3) and (4) are in an integral form.

When the Eq. (3) is applied to calculate the maximum temperature difference of the gas at the outlet, the Δt_o equals to $\alpha(t_{o,Max}-t_{o,Min})/4$ by assuming that the temperature distribution of the outlet gas is uniformed with mass. Therefore, the value of α is set as 4 at present if the Δt_o obtained by Eq. (4) is set as the same value as that by the old way, $t_{o,Max}-t_{o,Min}$. The values of β for hot gas branch and cold gas branch are set as 1 and the value of β for bypass gas branch is set as 2 because the inlets of bypass gas branch are nearer to the outlet of the mixing structure.

The TMP using the inlet temperature difference between hot gas branch and cold gas branch is labeled with "(1)" and the TMP using the inlet temperature difference between hot gas branch and bypass gas branch is labeled with "(2)". The TMP according to the new way to determine the inlet temperature difference is labeled with "(3)". The TMPs in following figures and tables are same situation unless additional hints.

3. TF-HGM considering bypass flow and power deviation

3.1. Bypass flow and power deviation of HTR-PM

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 flow at 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 flow reaches 750 °C. After flowing through 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 flows into the reactor pressure vessel, where it is heated again. In this way, the primary loop realizes a closed cycle of helium flow.

After the cold helium flow goes into the reactor pressure vessel, it goes up to the cold gas chamber on top of the reactor core through the ascend channels in the side reflector. Then, the main coolant helium flows to hot gas chamber via reactor core and bottom reflector. At the same time, a small part of helium goes through the gaps between the graphite blocks of the side reflector, and then flows to bottom reflector and hot gas chamber. Furthermore, another small part of helium flow goes through the control rod channels, and then flows to hot gas chamber. The last two parts of helium flow are called as bypass flow, since they do not go through the reactor core. The temperature of bypass flow is obviously lower than that of main helium flow passing the reactor core. Although the bypass flow is only a minor share of the whole coolant helium, it is an important fact affecting the temperature profile of helium flowing to the steam generator.

When the HTR-PM runs with a power lower than its rated power during its normal operation, the temperature and flow rate of helium coolant in the reactor may be different from those under the rated power condition. In addition, the strategy to move the control rod for power regulation results in the radial power deviation in HTR-PM reactor core that leads to the radial temperature deviation of helium flow when it flows out of the reactor core and goes to the steam generator. A study for HTTR showed that the radial temperature deviation of the coolant influenced the TMP of the mixing structure (Inagaki et al., 1990).

In summary, the bypass flow and power change and deviation can result in the radial temperature deviation of helium flow where it goes out of the reactor core. There are demands to investigate the TMP of the mixing structure of HTR-PM with the consideration of the effects of