Experiment study on thermal mixing performance of HTR-PM reactor outlet

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A B S T R A C T

A model experiment is proposed to investigate the thermal mixing performance of HTR-PM reactor outlet. The design of the test facility is introduced, which is set at a scale of 1:2.5 comparing with the design of HTR-PM reactor outlet. The test facility using air as its flow medium includes inlet pipe system, electric heaters, main mixing structure, hot gas duct, exhaust pipe system and I&C system. Experiments are conducted on the test facility and the values of thermal-fluid parameters are collected and analyzed, which include the temperature, pressure and velocity of the flow as well as the temperature of the tube wall. The analysis results show the mixing efficiency of the test facility is higher than that required by the steam generator of HTR-PM, which indicates that the thermal mixing structure of HTR-PM fulfills its design requirement.

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1. Introduction

In December 2012, Pebble-bed Module High Temperature gas-cooled Reactor (HTR-PM) (Dong and Gao, 2006; Zhang et al., 2009), one of Chinese National S&T Major Project, started it First Concrete Date (FCD) in Rongcheng, Shangdong Province. HTR-PM is the world’s first fourth-generation commercial nuclear power plant with high thermal efficiency and inherent safety features. In China, Tsinghua University is now conducting the studies for developing and validating the key equipments and technologies related to the demonstration project based on project of HTR-10 (10MW High Temperature Gas-cooled Reactor Test Reactor) (Wu et al., 2002; Xu and Zuo, 2002).

For High Temperature Gas-cooled Reactor (HTR), the radial temperature difference of the coolant helium out of the cylindrical reactor core is up to above 100 °C. In addition, much higher temperature difference can be introduced to the main coolant flow by the small cold leakages into the bottom of reactor vessel. In order to ensure the technical feasibility and safety of steam generator by limiting the thermal loads on the heat exchanging component, a thermal mixing structure is proposed to 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 where the temperature difference of coolant is reduced through a turbulent mixing process. Due to the complexity of the flow path and high speed turbulence with Reynolds number exceeding 10^5, the accurate performance of thermal mixing structure is difficult to be obtained through pure numerical calculation. In order to validate the design of the thermal mixing structure, usually a scale or full size experiment is applied to study its thermal mixing performance and pressure drop by combining related numerical calculation.

The air simulation tests in a 1:2.9 scaled plexiglass model were conducted to evaluate the mixing performance of the hot gas header and the hot gas duct of the HTR-module reactor (Damm and Wehrlein, 1992). For High-Temperature engineering Test Reactor (HTTR), 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 (Inagaki et al., 1990, 1992, 2004). Thermal mixing performance of the coolant in the hot gas chamber of HTR-10 is experimentally investigated on a 1:1.5 scale model with air (Huang, 1995; Yao et al., 2002).

Due to the rapid development of software and hardware of computer science and related fields, especially CFD (Computational Fluid Dynamics), numerical simulation is also carried out to analyze the thermal mixing performance of HTR reactor outlet. The flow field in the hot gas chamber of HTR reactor is studied with CFDS software (Wang et al., 2006). Analysis of the flow filed indicates that the turbulent twisting flow results in the high thermal...
mixing efficiency. With the CFD software, several turbulent models, such as the classical k-ε model, advance two-equation models and Reynolds-stress model are compared by considering their accuracy for simulating the related flow in the mixing structure (Von Lavante and Laurien, 2007).

This paper introduces the design of the test facility which is applied to evaluate the performance of thermal mixing structure at HTR-PM reactor outlet. Then, results of three kinds of experiments are demonstrated, which includes experiments of constant flow rate versus variable temperature difference, constant temperature difference versus variable constant flow rate as well as constant temperature difference and constant flow rate versus variable hot/cold flow ratio. Finally, some conclusions are given based on the experiment results.

2. Main parameters of test facility

The design criteria and the main parameters of the test facility are determined according to the self-modeling and similarity analysis (Zhou et al., 2011, 2014). The test facility is set as a scale of 1:2.5 compared with the design of thermal mixing structure at HTR-PM reactor outlet. The experiment uses air instead of helium as the working fluid. The main parameters of the model experimental system and the mixing structure of HTR-PM under rated condition are shown as Table 1. The aluminum alloy (ZL101A) is chosen as internal structural material of the installation because it's important physical characters, such as density, specific heat capacity and thermal conductivity, etc., are close to those of the graphite adopted in HTR-PM. In addition, the aluminum alloy has some additional advantages such as low density and easy processing.

Prandtl number and Reynolds number are found to be the two main parameters influencing the thermal mixing performance of the related structures by previous studies (Damm and Wehrlein, 1992; Inagaki et al., 1992; Yao et al., 2002; Zhou et al., 2011). Usually the mixing structure of the test facility is similar in geometry with that of real HTR. In this situation, Prandtl number and Reynolds number of the flow in hot gas duct are adopted as the key measures to indicate the similarity between the real mixing structure and the test structure. In this section, the Prandtl number, Reynolds number and other parameters are related with the flow in hot gas duct unless additional notification. For our study, the similarity of Prandtl numbers between HTR-PM and test facility is excellent since the Prandtl number of air at experiment condition is close to that of helium in HTR-PM.

Reynolds number of the flow in hot gas duct can be more than 3 \times 10^6 for some HTRs such as HTR-PM, and therefore it is difficult to make a test facility get the same Reynolds number. The main reason is that the Mach number of flow in the test facility will become much higher where the compressibility of the air flow will severely hurt its similarity with the helium flow in the real HTR where the Mach number of the helium flow is only around 0.03.

Thus, the maximum Reynolds number of the model experiment is usually around 1.0 \times 10^6. The previous study related with HTR-module indicated that the mixing performance would decrease slightly when extrapolating the situation of low Reynolds number (1.6 \times 10^6) in the model experiment to the situation of high Reynolds number (3.2 \times 10^6) in the real HTR-model (Damm and Wehrlein, 1992). The study on HTR also showed that the thermal mixing performance with a low Reynolds number of the experiment condition are close to that with a high Reynolds number of real HTTR based on theoretical analysis and experiments (Inagaki et al., 1990, 1992, 2004). In addition, the results of experiment on HTR-10 revealed that thermal mixing performance would become approximately stable when the Reynolds number was higher than around 2 \times 10^5 (Yao et al., 2002). Some simulation calculation (Wang et al., 2006; Zhou et al., 2014) also confirmed this situation.

This phenomenon can also be found according to theory analysis (Inagaki et al., 1990; Zhou et al., 2011). For incompressible turbulent flow under steady-state conditions, the energy equation can be given as following with non-dimensional variables:

\[ U_i \frac{\partial T^*}{\partial X^*_i} = \left( \frac{1}{R e Pr} + \frac{\nu_i}{Re Pr_t} \right) \frac{\partial^2 T^*}{\partial X^*_i^2} \]  

where, \( U \) indicates the flow rate; \( T \) indicates the temperature; \( X \) indicates the coordinate; \( Re \) is the Reynolds number; \( Pr \) is the Prandtl number; \( \nu \) indicates the kinematic viscosity with unit of m^2/s; superscript * indicates the non-dimensional variable; \( - \) indicates the time-averaged value; subscript i indicates the direction of coordinate whose values are 1, 2 and 3; subscript t indicates the turbulent parameter.

If all channels in the two mixing structure (test facility and HTR-PM) are independently considered, a statistics work based on the previous work (Zhou et al., 2014) shows that all of the Reynolds numbers of the flow in all channels are above 3.0 \times 10^4 under the rated condition. Because there is no clear answer for the value of \( \nu/v \) for the flow in the complex mixing structure, the situation of fully developed turbulence in the center of a pipe can be adopted here (Inagaki et al., 1990; Zhou et al., 2011) where Reynolds number should be bigger than 5 \times 10^3:

\[ \frac{\nu_i}{v} = a \ Re^\alpha, \quad a = 0.01 - 0.1, \quad n = 7/8 - 1 \]  

where, \( n \) increases with the increase of Reynolds number and \( a \) is constant, Here, the conservative value of 7/8 for \( n \) is used, and then we can get:

\[ U_i \frac{\partial T^*}{\partial X^*_i} = \left( \frac{1}{Re Pr_t} + a \ Re^{7/8} \right) \frac{\partial^2 T^*}{\partial X^*_i^2} \]  

Since \( Pr_t \) and \( Pr_t \) are all around 1 and \( Re \) is bigger than 5 \times 10^3, this equation can be changed to following which is similar to the previous work (Inagaki et al., 1990):

\[ U_i \frac{\partial T^*}{\partial X^*_i} = a Re^{-1/8} Pr_t^{-1} \frac{\partial^2 T^*}{\partial X^*_i^2} \]  

For the rated condition of HTR-PM, the Reynolds number equals to 3.67 \times 10^6 and \( Pr_t \) equals to around 0.85 (Lauder and Spalding, 1974), then we can get:

\[ U_i \frac{\partial T^*}{\partial X^*_i} = 0.178a \frac{\partial^2 T^*}{\partial X^*_i^2} \]  

For the rated condition of test facility, the Reynolds number equals to around 1 \times 10^5 and \( Pr_t \) equals to around 0.85, then we can get:

\[ U_i \frac{\partial T^*}{\partial X^*_i} = 0.209a \frac{\partial^2 T^*}{\partial X^*_i^2} \]  

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HTR-PM</th>
<th>Test facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>7</td>
<td>0.1</td>
</tr>
<tr>
<td>Diameter of hot gas duct (mm)</td>
<td>750</td>
<td>300</td>
</tr>
<tr>
<td>Flow media</td>
<td>Helium</td>
<td>Air</td>
</tr>
<tr>
<td>Quality flow rate (kg/s)</td>
<td>96</td>
<td>5</td>
</tr>
<tr>
<td>Flow rate in hot gas duct (m/s) (rated)</td>
<td>66.47</td>
<td>68.63</td>
</tr>
<tr>
<td>Mach number of flow in hot gas duct</td>
<td>0.033</td>
<td>0.185</td>
</tr>
<tr>
<td>Temperature in hot gas duct (°C)</td>
<td>750</td>
<td>70</td>
</tr>
<tr>
<td>Viscosity of flow in hot gas duct (10^{-5} Pa·s)</td>
<td>4.45</td>
<td>1.99</td>
</tr>
<tr>
<td>Reynolds number of flow in hot gas duct</td>
<td>3.67</td>
<td>1.03</td>
</tr>
<tr>
<td>Reynolds number of flow in hot gas duct (10^6)</td>
<td>(0.23–1.05)</td>
<td></td>
</tr>
<tr>
<td>Prandtl number of flow in hot gas duct</td>
<td>0.667</td>
<td>0.694</td>
</tr>
</tbody>
</table>
In addition, the value \( n \) is close to 1 rather than 7/8 if Reynolds number is bigger than \( 5 \times 10^3 \) according to Eq. (2) and, therefore, the difference of non-dimensional temperature distributions between the mixing structures of HTR-PM and test facility will become even smaller. In this way, it can be concluded that the thermal mixing performance of test facility can credibly reflect the performance of mixing structure at HTR-PM reactor outlet, which is similar with the previous studies (Damm and Wehrlein, 1992; Inagaki et al., 1992; Yao et al., 2002; Wang et al., 2006).

3. Structure of model experiment system

The overall design is shown as Fig. 1 which is determined with the calculation analysis by considering the size of experiment site and equipment. The whole test facility can be divided as three regions: inlet room, main experiment room and exhaust room.

3.1. Inlet room

The inlet room is used to place the air blowers and their control cabinet, whose inner wall are installed with wooden acoustic boards for heat insulation and sound absorption. There are three air blowers and their corresponding frequency transformers in this room. Two big blowers provide air to hot gas branch and cold gas branch, respectively, and the small one provides air to the branch simulating the leakage flow. The shock absorbers are equipped at the bottom of the blowers and the metallic bellows are applied to connect the outlet of blowers and following stainless steel pipeline in order to eliminate the influence of shock of the blowers to other components of the installation. The metal filters are installed on the windows of the inlet room and the inlet of the blowers in order to ensure the safety and accuracy of the sensors in the test facility by removing the dust in the air.

3.2. Thermal mixing test facility

The whole test facility (Fig. 1) for thermal mixing includes: inlet pipe system, electric heaters, main mixing structure, hot gas duct, exhaust pipe system and I&C system. Most equipment is installed in the main experiment building except some components of inlet system and exhaust system. The inlet system consists of air blowers, their control cabinet and related pipeline and valves. The inlet air mainly consists of a hot gas branch and a cold gas branch. For the hot gas branch whose flow indicated by the red arrows in Fig. 1, the air flows from the outlet of the air blower to the high power electric heater, and then goes into main mixing structure through the central inlet of it after being heated by the electric heater. In the cold gas branch whose flow indicated by the green arrows in Fig. 1, the air flows from another air blower to the low power electric heater, and then goes into the main mixing structure through the surrounding inlets of it without being heated by the electric heater. The hot air and cold air are mixed in the main mixing structure, and then flow to the pipelines in the exhaust room through the exhaust pipe system. Finally, the air is exhausted through the chimney on the exhaust room. The flow of exhausted air is indicated by yellow arrows in Fig. 1.

The I&C system consists of main control station, local control devices, sensors and related wiring, which mainly is used for operation control of the test facility and collection of experiment data. Various sensors are connected with several data acquisition cards produced by NI (National Instruments) which are installed in two main control stations.

3.3. Main mixing structure

The main mixing structure is the key component of test facility which consists of the inlet chamber, the narrow cross channel and the hot gas chamber which is shown as Fig. 2. The air of hot gas
branch and cold gas branch flows into the inlet chamber through
the big central inlet and the four small surrounding inlets at
the upper cap, respectively. The inlet chamber mainly consists
of an inner sleeve and an outer sleeve which separate the hot air and
cold air before entering the main mixing structure. The narrow
cross channel includes two set of horizontal channels and three set of
vertical channels which are established by three layers (inner annular
part) or four layers (outer annular part) of aluminum blocks. The air
flows through the narrow inlet between the petal-shape aluminum
blocks into the annular plenum of hot gas chamber at the bottom
of the main mixing structure. Another branch of hot gas flows to
the narrow inlet through the central hole filled with small balls which
simulates the tube for unloading the fuel sphere. After being
collected at hot gas chamber, the air flows to hot gas duct through the
inlet of it.

The outside surface of the main mixing structure is covered with
thermal insulators to reduce heat losses to the atmosphere. The
gaps between outsider sleeve of the main mixing structure and
aluminum blocks as well as the gaps between aluminum blocks
themselves are filled with rubber seals to prevent the linkage to
the hot gas chamber through these gaps.

3.4. Hot gas duct

Fig. 3 shows the design of the hot gas duct which is made of
stainless steel pipe. The hot gas duct connects the upstream hot
gas chamber and the downstream exhaust pipe with pipe flanges.
Four sets of thermocouple exhaust are installed in the cross section
at the entrance of hot gas duct each of which consists of five
thermocouples in a small tube. In addition, eight sets of them are
installed at the exit of hot gas duct. At the exit of hot gas duct, there
are two sets of pitometers and several pressure sensors to get the
velocity and the pressure of the air flow there.

3.5. Measurement system

The thermal-fluid parameters needed for the thermal mixing
experiment includes: air flow rate, air temperature, wall temperature,
air pressure and air velocity. Table 2 shows the information for various sensors adopted in this test facility.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range</th>
<th>Precision</th>
<th>No.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex flowmeter</td>
<td>350–4000 m³/h</td>
<td>1.5%FS</td>
<td>1</td>
<td>LUGB-2330</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>1100–160,000 m³/h</td>
<td>1.5%FS</td>
<td>5</td>
<td>LUGB-2315</td>
</tr>
<tr>
<td>Differential pressure</td>
<td>20 KPa</td>
<td>0.2%FS</td>
<td>18</td>
<td>CYG1601</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>−40 °C to 250 °C</td>
<td>0.2 °C</td>
<td>110</td>
<td>T</td>
</tr>
<tr>
<td>Thermal resistor</td>
<td>−50 °C to 300 °C</td>
<td>0.2 °C</td>
<td>15</td>
<td>Pt100</td>
</tr>
</tbody>
</table>
4. Results of experiment

The experiment is carried out to get the value of various parameters for thermal mixing of HTR-PM reactor outlet on the test facility mentioned above. There are three series of experiments: constant flow rate versus variable temperature difference at inlet, constant inlet temperature difference versus variable flow rate as well as constant temperature difference and flow rate versus variable hot/cold flow ratio at inlet.

4.1. Experiments of constant flow rate versus variable temperature difference at inlet

In this series of experiments, the flow rates of hot gas branch and cold gas branch keep constant at rated value of 2.5 kg/s and the temperature differences between them are changed from 30 °C to 100 °C with a step of 10 °C. Table 3 shows the experiment result at various temperature differences. Fig. 4 indicates the performance of thermal mixing at the outlet of hot gas duct versus the temperature differences. The performance of thermal mixing are indicated with temperature as the following equation:

\[
\eta = \left(1 - \frac{|\Delta t_o|_{\text{max}}}{\Delta t_i}\right) \times 100\%
\]

where, \(\Delta t_o\) indicates the temperature difference at the cross section of hot gas duct outlet with unit of °C; \(\Delta t_i\) indicates the temperature difference between hot gas branch and cold gas branch with unit of °C.

It can be found that the performance of thermal mixing is constant at around 98% with the change of the temperature differences indicating that the air is mixed well through the main mixing structure and hot gas duct of the test facility at the experiment conditions.

4.2. Experiments of constant temperature difference versus variable flow rate at inlet

In this series of experiments, the temperature difference between hot gas branch and cold gas branch keeps constant as 100 °C and the flow rates of hot gas branch and cold gas branch are changed by adjusting the rotation rates of the two blowers. Table 4 shows the experiment result at different flow rates. Fig. 5 indicates the performance of thermal mixing at the outlet of hot gas duct versus the Reynolds number of air flow in the hot gas duct.

It can be found that the performance of thermal mixing is constant at around 98% with the change of the flow rate in hot gas duct indicating that the air is mixed well through the main mixing structure and hot gas duct of test facility at the experiment conditions. The stable mixing performance with Reynolds numbers from around 2.5 × 10^5 to 1.0 × 10^6 accords with the results of related analysis in Section 2.

4.3. Experiments of constant temperature difference and constant total flow rate versus variable hot/cold flow ratio at inlet

In this series of experiments, the temperature difference between hot gas branch and cold gas branch keeps constant as 100 °C and the total flow rate of hot gas branch and cold gas branch keeps at around 3.1 kg/s while the flow ratio between hot gas branch and cold gas branch is changed. Table 5 shows the experiment results at different flow ratios. Fig. 6 indicates the performance of thermal mixing of the mixing structure versus the different flow ratios between hot gas flow and cold gas flow.

It can also be found that the performance of thermal mixing is constant at around 98% with the change of the flow ratios which indicates the air is mixed well.
5. Conclusions

By using the designed and constructed test facility, the experiments are carried out to get the values of various parameters for analysis of the efficiency of mixing structure at HTR-PM reactor outlet. There are three series of experiments: constant flow rate versus variable temperature difference, constant temperature difference versus variable flow rate as well as constant temperature difference and total flow rate versus variable hot/cold flow ratio.

The analysis of experiment results shows the mixing efficiencies of all experiments are around 98%. Compared with the required mixing efficiency (94.5%) based on the temperature deviation at reactor outlet and the temperature limitation at inlet of steam generator, it can be concluded that the thermal mixing structure at HTR-PM reactor outlet can fulfill the requirement of thermal mixing.

Acknowledgment

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References