Introduction to the Chinese HTR-PM pebble bed equivalent conductivity test facility

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Abstract: The first two 250-MWt high temperature reactor pebble bed modules (HTR-PM) have been installing at the Shidaowan plant in Shandong Province, China. The values of the effective thermal conductivity of the pebble bed core under different temperatures are essential parameters for the design of HTR-PM, which are needed to analyze the maximum fuel temperature, temperature distribution and residual heat releasing ability in reactor core. For this purpose, Tsinghua University in China has proposed a full-scale heat transfer experiment to conduct comprehensive thermal transfer tests in packed pebble bed and to determine the effective thermal conductivity through the pebble bed under vacuum condition and helium environment. The design of HTR-PM pebble bed equivalent conductivity test facility is introduced in detail in this paper. Validation experiments have verified the feasibility of the related materials and structures. Test temperature can be elevated to 1600°C, which covers the whole temperature range of the safety analysis of HTR-PM.

Key words: high temperature gas-cooled reactor; pebble bed; effective thermal conductivity; heat transfer

1. Introduction

As a typical representation of Generation IV nuclear power system, the High Temperature Gas-cooled Reactor (HTGR) is in the path of rapid development in China for its advantages like inherent safety, high efficiency, and wide application as high-temperature heat source [1, 2]. The first two 250-MWt high temperature reactor pebble bed modules (HTR-PM), as one of the 16 top priority projects of the “Chinese Science and Technology Plan” for the period 2006-2020, have been installing at the Shidaowan plant in Shandong Province, China [3, 4].

HTR-PM has a cylindrical core with a diameter of 3000mm, while thousands of spherical fuel elements are randomly packed inside, as shown in fig.1. The packing structure of spheres is called as “pebble bed”. Pebble bed has broad applications in systems involving heat transfer, such as high temperature reactors, catalyst bed, fluidized bed, tritium breeding module and thermal insulator [5, 6]. However, because the pebble bed is formed by random packing of a large number of particles, its microstructure is quite complex. When studying its macroscopic properties, pebble bed is usually considered as quasi homogeneous medium and local average parameters, also known as effective parameters, are used. The effective thermal conductivity is one of them, which is used to represent the macroscopic heat transfer ability of the pebble bed. The values of the effective thermal conductivity of the pebble bed core of HTR-PM under different temperatures are essential parameters required in thermal calculation and safety analysis of the reactor, which will be used in simulation models to predict the maximum fuel temperatures and temperature distributions in reactor core. Most of the main technical characteristics of the HTGR have been closely related to the effective thermal conductivity [7, 8].
Fig. 1. Pebble bed core of the high temperature gas-cooled reactor

Juelich Laboratory of Germany once designed a relevant experiment named SANA-1 in history for validation of the afterheat removal capacity of HTGR \cite{9}. But the size of the pebble bed in SANA-1 was much smaller than that of HTR-PM core, which would have a significant effect on the final measured values. Moreover, the highest test temperature in SANA-1 was confined below 1000°C, unable to cover the whole temperature range of the safety analysis of HTR-PM (0–1600°C).

For this reason, in order to support the HTR-PM project, Tsinghua University in China has been constructing a full-scale test facility for pebble bed equivalent conductivity measurement (TF-PBEC) to conduct comprehensive thermal transfer tests in packed pebble bed under the whole temperature range (0–1600°C) \cite{10}. The aim of the TF-PBEC is to create a full-size pebble bed to simulate the complicated thermal transfer condition in the real reactor core of HTR-PM and to determine the effective thermal conductivity through the pebble bed under vacuum condition and helium environment with temperature up to 1600°C. This paper will introduce the detailed design and recent research progress of the TF-PBEC. This project is one of the subtopics of “Research on Important Safety Issues of High Temperature Gas-cooled Reactor”.

2. Design of the TF-PBEC

2.1 general structure

The TF-PBEC is an integrated experimental system, which consists of furnace body, central heater, graphite temperature uniform sleeve, insulating layers, vacuum system, cooling water
The facility adopts the structure of the internal heating type resistance furnace. The heater locates at the center of the furnace cavity, two heating units of which are powered by two separate supplies with delta-connection. The heat transfers to a cylindrical graphite sleeve by radiation and then transfers to the target randomly packed pebble bed (not shown in fig.2). Besides the temperature uniform function, the graphite sleeve also separates the pebble bed from the heater. Packed by about 70000 graphite spheres with a diameter of 60 mm, the pebble bed is arranged in a ring-shaped space. The temperature distribution in the pebble bed under helium atmosphere or vacuum conditions will be measured and the effective thermal conductivity will be calculated by heat conduction differential equations. The pebble bed is surrounded by insulating layers, while the side layers are much thinner than the top/bottom layers in order to lead most of the heat transfer along the radial direction. The cooling water running in the interlayer of the furnace wall will finally take the heat away. Temperature measuring points are also embedded in insulating layers in order to modify the final data. The whole facility is mounted on a two-floor platform. A lifting equipment is located under the facility in order to unload the central heater for maintenance. The three-dimensional modeling of the TF-PBEC is shown in fig.3. Table.1 lists the main parameters of the TF-PBEC.
Table 1 Main design parameters of TF-PBEC

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating mode</td>
<td>resistance heating</td>
</tr>
<tr>
<td>Heating power</td>
<td>450+450 kW</td>
</tr>
<tr>
<td>Power supply</td>
<td>AC</td>
</tr>
<tr>
<td>Maximum test temperature</td>
<td>1600 °C</td>
</tr>
<tr>
<td>Inside environment</td>
<td>helium/vacuum</td>
</tr>
<tr>
<td>Pressure</td>
<td>atmospheric pressure</td>
</tr>
<tr>
<td>Vacuum rate</td>
<td>( \leq 30 \text{ Pa} )</td>
</tr>
<tr>
<td>Height of pebble bed</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Width of annular pebble bed</td>
<td>1500 mm</td>
</tr>
<tr>
<td>Number of spheres</td>
<td>about 70000</td>
</tr>
<tr>
<td>Diameter of spheres</td>
<td>60 mm</td>
</tr>
<tr>
<td>Total height</td>
<td>about 7000 mm</td>
</tr>
</tbody>
</table>

2.2 pebble bed

Inside the TF-PBEC, a randomly packed annular pebble bed will be created to simulate the fuel packing structure in the HTR-PM reactor core.

About 70000 machined graphite spheres with a diameter of 60mm (the same as the real fuel element) will be randomly packed in an annular test zone bounded by inner and outer walls. The radius of the inner wall is set to be 600mm and the radius of the outer wall is 2100mm, which
means the whole thickness of the pebble bed is 3000mm (regardless of the inner wall), the same as
the HTR-PM core size. Hence, the pebble bed inside the TF-PBEC can be considered as the
representation of the packing structure in the real reactor core. The reason for the annular
configuration of the pebble bed is that a set of heat electrodes have to be contained in the inner
wall to provide a temperature gradient in the radial direction through the pebble bed, while the real
reactor core can produce heat itself. The height of the bed is set to be 1000mm in order to limit the
size and the cost of the facility. The spheres are made from isostatic graphite rods by lathe work
and the finished products are shown in fig.4. The parameters of graphite spheres are listed in Table 2.

Fig.4 Isostatic graphite spheres used in the TF-PBEC

<table>
<thead>
<tr>
<th>parameters</th>
<th>value</th>
<th>parameters</th>
<th>value</th>
<th>parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity</td>
<td>8.6%</td>
<td>elasticity modulus</td>
<td>11.5 GPa</td>
<td>resistivity</td>
<td>11-13 μΩ.m</td>
</tr>
<tr>
<td>average granularity</td>
<td>25 μm</td>
<td>tensile strength</td>
<td>24.2 MPa</td>
<td>thermal expansion</td>
<td>4.5 10⁶/K</td>
</tr>
<tr>
<td>Shore hardness</td>
<td>58</td>
<td>bending strength</td>
<td>48.7 MPa</td>
<td>thermal conductivity</td>
<td>133 W/(m.K)</td>
</tr>
<tr>
<td>ash content</td>
<td>50-200 ppm</td>
<td>compression strength</td>
<td>89 Mpa</td>
<td>density</td>
<td>1850 kg/m³</td>
</tr>
</tbody>
</table>

Thermocouples are arranged in the pebble bed zone to acquire the three-dimensional
temperature field information. A total of 90 temperature measuring points are evenly divided into
6 layers along radial direction, 5 parts along circumferential direction and 3 layers along axial
direction of the pebble bed, as shown in Fig.5. These points are the most important observation
targets and will endure the highest temperature about 1600°C in carbonaceous environment. In
the face of such a rigorous temperature measuring environment, tungsten rhenium thermocouples
with forged molybdenum protection tubes are chosen as main detectors. Tungsten-Rhenium (WRe)
thermocouples can work stably at 2000°C in appropriate conditions; however can be liable to be
carbonized in carbonaceous atmosphere. Forged molybdenum tubes can have a good hermeticity
to delay the corrosion.

Fig. 5 Temperature measuring points arranged in the pebble bed

2.3 insulation layers

The design of the thermal insulating layers, including the top layer, the side layer and the
bottom layer, affects the temperature distribution in the pebble bed zone, as shown in fig.6. The
side insulating layer consists of three layers. Each of them is a wholly-shaped hard carbon felt
shell. The outside layer is fixed on the furnace wall, while the middle layer and inside layer are
detachable to adjust the thickness of side insulating layer and form different heat preservation
effects. The top and bottom insulating layer are also carbon felt but more thicker than the side
layer to reduce axial heat loss. The connection between side layer and top, bottom layers takes the
form of step joint to reduce direct radiation heat loss and avoid the furnace wall damage.
2.4 central heater

The design of central heater is a key part of the TF-PBEC. Due to the large scale of the pebble bed and the highest required test temperature up to 1600°C, the material selections and structure designs of each part of the central heater thus should be considered carefully, which include structure design of single heating unit, bonding type of heating units, insulation technique and installation process.

The central heater will be design to be a relative independent structure in order to get convenient replacement or maintenance. Two alternative heaters have been designed, as shown in fig.7. Design (a) chooses graphite as material. The whole heater consists of nine tubular graphite electrodes, which are connected by graphite plates and bolts and powered by an AC supply with delta-connection. Design (b) chooses carbon/carbon composites as material, which has less weight, higher strength and larger resistivity than graphite. The whole heater consists of two concentric heating cylinders, which are powered respectively by two separate AC supplies with delta-connection. Due to advantages in weight, strength and power adjustment, the later design has been determined as the final solution.
3. Preliminary validation experiments

As we know, most materials, which are commonly used in high-temperature conditions, can be easily corroded or ineffective in carbonaceous atmospheres at high temperatures. Due to the large scale of the pebble bed and the high test temperature in the TF-PBEC, the fabrication of the facility and the temperature measurement elements become very difficult.

To guarantee the success, a scaled-down validation facility was built in advance to provide reliable materials and technical support for the design of the final experimental facility\cite{11, 12}. All of the essential materials and key structure designs used in the TF-PBEC, such as that of the heater, the thermal insulating layers, the temperature measuring elements, the furnace body, the vacuum system and the water cooling system was tested and validated in the validation facility. The picture and the structure diagram of the validation facility are shown in fig.8 as below.
This bench-scale facility had the same structure designs and the axial size with the TF-PBEC. Only the radial size was reduced because of the lack of pebble bed and the reduction of the diameter of the central heater. The construction and commissioning of the validation facility was completed in 2011. Beneficial tests had been done or under way on the validation facility. Fig. 9 shows the temperature profile of all the temperature measuring points in the validation facility during one of the tests.

As shown in the figure, the temperature of these test points changed according to the heating power. Test temperature in the annular test zone could be raised to 1600°C. The tiny differences
between T1~T4 showed good temperature homogeneity in the annular test zone along the axial direction. Obvious temperature gradient had been created in the insulating layers and temperatures at the outside surface of layers were close to room temperature. Experimental results also indicated that our specially designed thermocouples could work stably in such a rigorous temperature measuring environment.

4. Project schedule

After these validations, the design and construction of the TF-PBEC started in March 2012. Up to now, the construction of the facility has been completed and the facility enters the stage of installation and commissioning. Fig.10 shows a photograph of the completed TF-PBEC. Relevant experiments will be done in the future.

![Fig.10 Photograph of the completed TF-PBEC](image)

5. Conclusion

A thorough knowledge of the mechanisms of heat transfer through a packed bed of spheres is of crucial importance in the design of a high temperature pebble bed reactor. The TF-PBEC aims at measuring the effective thermal conductivity of pebble bed type reactor core of the high temperature gas-cooled reactor. The design of the facility is introduced in detail, including the pebble bed, the temperature detector, the insulation structure, the central heater and so on. Validation experimental results show test temperature could be elevated to 1600°C, which covers the whole temperature range of the normal operation and accident condition of HTGR and could fully meet the test requirements.

ACKNOWLEDGMENTS

The authors acknowledge the support of the National S&T Major Project of China under Grant No. ZX06901 and the Specialized Research Fund for the Doctoral Program of Higher Education under Grant No. 20130002120015.

References


