Design of the material performance test apparatus for high temperature gas-cooled reactor

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Abstract Most materials can be easily corroded or ineffective in carbonaceous atmospheres at high temperatures in the reactor core of the high temperature gas-cooled reactor (HTGR). To solve the problem, a material performance test apparatus was built to provide reliable materials and technical support for relevant experiments of the HTGR. The apparatus uses a center high-purity graphite heater and surrounding thermal insulating layers made of carbon fiber felt to form a strong carbon reducing atmosphere inside the apparatus. Specially designed tungsten rhenium thermocouples which can endure high temperatures in carbonaceous atmospheres are used to control the temperature field. A typical experimental process was analyzed in the paper, which lasted 76 hours including seven stages. Experimental results showed the test apparatus could completely simulate the carbon reduction atmosphere and high temperature environment the same as that confronted in the real reactor and the performance of screened materials had been successfully tested and verified. Test temperature in the apparatus could be elevated up to 1600ºC, which covered the whole temperature range of the normal operation and accident condition of HTGR and could fully meet the test requirements of materials used in the reactor.

Key words Material performance test, High temperature gas-cooled reactor, Carbon reduction atmosphere

1 Introduction

The Very High Temperature Gas-cooled Reactor (VHTR) is a typical representation of Generation IV nuclear power system, which has being developed rapidly for its advantages like inherent safety, high efficiency, widely application as high-temperature heat source[1,2]. As the first Generation IV nuclear power commercial demonstration project in the world, a 200-MWt high temperature reactor pebble bed modules (HTR-PM) have be installing at the Shidaowan plant in Shandong Province of China[3,4]. At the meantime, many related researches have being carried out in universities to support the project[5,6].

Materials or devices are faced with a harsh environment in the reactor core of the HTGR. Except the nuclear radiation, the temperature of spherical fuel elements can reach 1200ºC under normal operation condition and should be limited under 1600ºC under accident condition[7,8]. In the meanwhile, because the matrix material of fuel elements and the surrounding reflector of reactor core are made from graphite, and a large number of graphite dusts have been produced due to friction loss during the fuel cycle process, a strong carbon reducing atmosphere has been formed in the reactor core[9,10]. Most materials, which are commonly used in high-temperature conditions, can be easily corroded or ineffective in carbonaceous atmospheres at high temperatures, including metal dusting and internal carburization[11,12]. Applicable materials should be screened out for the HTGR and related environment simulation experiments.

To solve this problem, a material performance test apparatus was built in Tsinghua University to provide reliable materials and technical support for subsequent HTGR relevant experiments. The purpose of the material performance test apparatus (MPTA) is

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to simulate a testing environment with high temperature and strong carbon reducing atmosphere similar as that confronted in the real reactor core of HTGR. Test temperature in the apparatus can be elevated up to 1600ºC, which covers the whole temperature range of the normal operation and accident condition of HTGR. Several essential materials and key designs, such as the heater, the thermal insulating layers and the temperature measuring elements that may be wildly used in subsequent HTGR relevant experiments, had been tested and validated.

2 Material performance test apparatus

The emphasis of the material performance test apparatus should be the simulation of two main factors of the environment of HTGR: temperature range and carbon reducing atmosphere. The MPTA consists of a material test zone and other support systems (Fig.1). The material test zone includes heating material test zone, thermal insulating material test zone, temperature measuring elements test zone. The support systems include cooling water system, vacuum system, hydraulic lifting system, power adjustment system, data acquisition system and supporting platform.

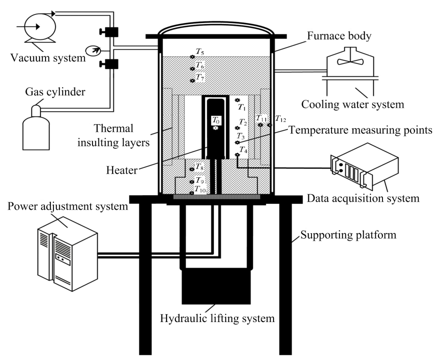

Fig.1 Structure schematic of the material performance test apparatus.

The MPTA takes the form of a graphite resistance furnace. In the center of the furnace is a high-purity graphite heater. The power comes from a high current low voltage DC power supply. A graphite sleeve is set outside the heater to reduce the heating nonuniformity along the circumference[13]. The surrounding thermal insulating layers are made of hard composite carbon fiber felt, while insulations at the top and bottom ends are much thicker than the side insulation in an effort to limit the heat transfer in the axial direction. The thicknesses of the top/bottom insulation and the side insulation are 500 mm and 200 mm, respectively. Outside the side insulating layer is a water-cooled jacket with cooling water running through the interlayer to take away most of the heat. The inside operating environment can be vacuum or inert gas protection atmosphere. Temperature measuring points are arranged in the furnace to acquire the temperature field. Thirteen thermocouples are used, including one on the surface of the heater, four in the annular test zone and eight in the insulating layers. Specially designed tungsten rhenium thermocouples are used to endure high temperatures in carbonaceous atmospheres[14,15]. The allowance of these thermocouples is ± 0.5%.

All the materials used inside the furnace including the heater, the temperature uniform sleeve and the insulating layers are carbon material in an effort to form a strong carbon reducing atmosphere inside the apparatus. In the meanwhile, most of the parts are designed to be detachable structures. It is convenient to replace damaged parts or test other materials. Main design parameters of the material performance test apparatus are listed in Table1.

Table 1 Main design parameters of the MPTA

Term	Value
Heating power	50 kW
Heating voltage (DC)	30 V
Testing temperature	1600ºC
Operating environment	Vacuum/N_2/He
Operating pressure	Micro-positive
Vacuum pressure	≤ 30 Pa
Height of annular test zone	1000 mm
Width of annular test zone	100 mm
Height of furnace body	~2000 mm
Diameter of furnace body	~900 mm
Total height	~5000 mm

3 Experimental results

The construction and commissioning of the MPTA started in July 2010 and was completed in June 2011. Fig.2 shows a photograph of the completed MPTA. Beneficial tests have been done or under way on the material performance test apparatus[16]. A typical experimental process will be described and analyzed here, which lasted 76 h including seven stages. The process of the experiment is as follows:

Firstly, a preheating was made. The furnace was vacuumed during the heating process to remove the air and the gas released by the carbon felt.

When the inside pressure dropped below 100 Pa, the furnace was charged with nitrogen to protect the graphite heater and thermocouples.

Then, we adjusted the heating power to raise the temperature inside the annular material test zone up to 1400ºC.

The temperature would be maintained for about 24 h.

After that, the heating power would be raised again to elevate the temperature inside the annular material test zone up to 1600ºC.

The temperature would be maintained for about 22 h.

At last, the heating power would be turned off. The furnace would be cooled down to the room temperature by the cooling water system.

Fig.2 Photograph of the completed MPTA.

The adjustment curve of the heating power during the experiment process is shown in Fig.3. The maintenance powers during 1400ºC and 1600ºC were 7.98 kW and 13.104 kW, respectively. Fig.4 shows the temperature profiles in the high temperature zone of the apparatus and these points, including the test point T_0 on the surface of the heater and test points T_1-T_4 in the annular test zone at various depths, are of the most concern. As shown in the figure, the temperature of test points changes according to the heating power.

Transient power adjustment does not reflect on it due to large thermal inertia. Test temperature in the annular test zone can be raised to 1600ºC, and kept for a long time. The tiny differences between T_1-T_4 shows good temperature homogeneity in the annular test zone and could fully meet the test requirements of materials used in the reactor.

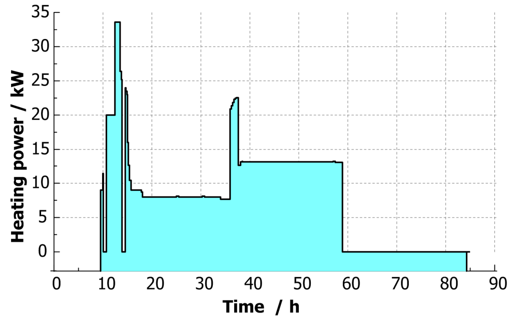

Fig.3 Heating power adjustment.

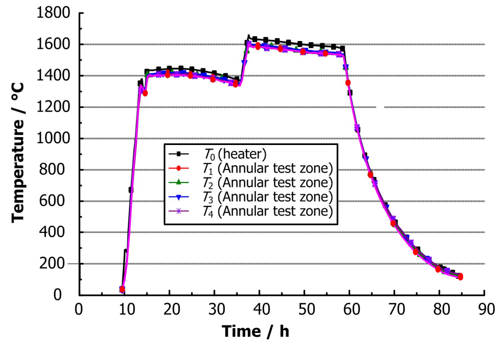

Fig.4 Temperature in high temperature zone.

Figure 5 shows the relationship between the resistance of graphite heater and temperature. As we can see, the resistance rises when the temperature goes up. But the amount of variation is relatively small under 1600ºC and the graphite heater work stably during the whole process.

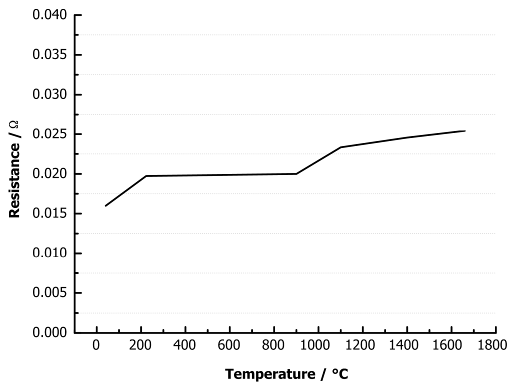

Fig.5 Resistance change of the heater.

Besides test points in the high temperature zone, temperature test points were also placed at different depths in the thermal insulating layers to assess the heat preservation capacity of the carbon felt.

Figs.(6)–(8) show the temperature profiles in the top, bottom and side thermal insulating layers, respectively.

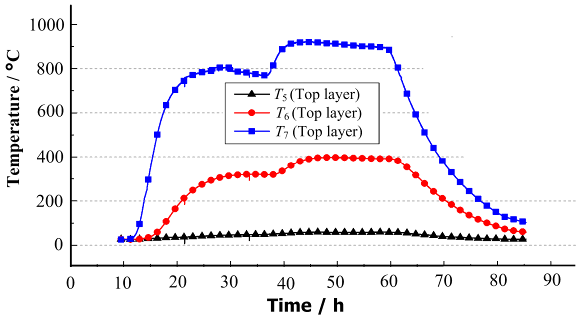

Fig.6 Temperature in the top insulating layer.

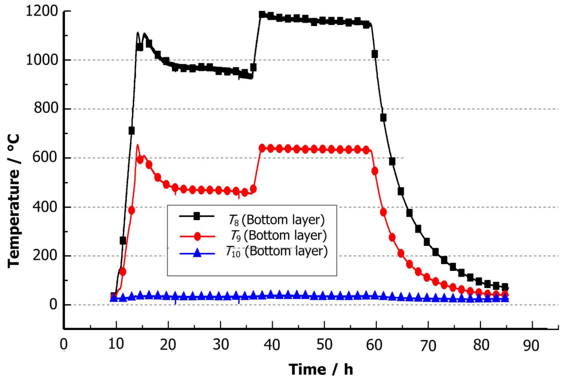

Fig.7 Temperature in the bottom insulating layer.

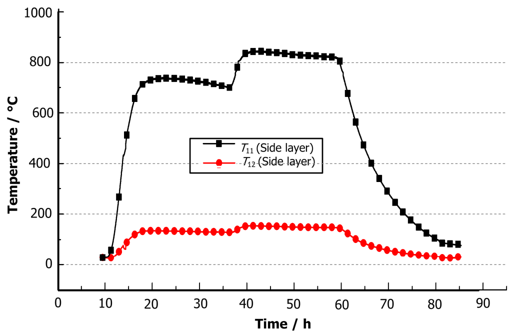

Fig.8 Temperature in the side insulating layer.

As shown in these figures, obvious temperature gradient has been created in the insulating layers and temperatures at the outside surface of the top and bottom layers are close to room temperature and the heat flux calculated is about 3×10^2 W/m^2, which indicates good heat preservation capacity of the chosen carbon felt material. Temperature at the outside surface of the side layer is relatively higher, for the thickness of the side layer is less than top and bottom layers. The water-cooled jacket outside will take away most of the heat. We can also notice that temperatures of test points in the bottom layer are higher than test points in corresponding positions of the top insulating layer. That is because heating electrodes are equipped through the bottom layer and more heat thus is conducted out from the bottom.

A set of data along the axial direction of the furnace at a moment of stage six is chosen, as shown in the Fig.9. As we can see, the temperature drop is mainly in the top and bottom insulating layers, while the temperature in the annular material test zone is quite uniform, which provides us a long enough constant temperature zone for material testing. Limited by the installation space and the thermocouple size, only 4 temperature test points was set in the test zone at different depths. However, the whole facility is axisymmetric and the test zone is under vacuum condition, thus the temperature distribution along the circumference can also be considered as uniform. In fact, the four thermocouples are all installed from the bottom of the facility, so they are actually at different radial angles. The tiny differences between their values verify the assumption.

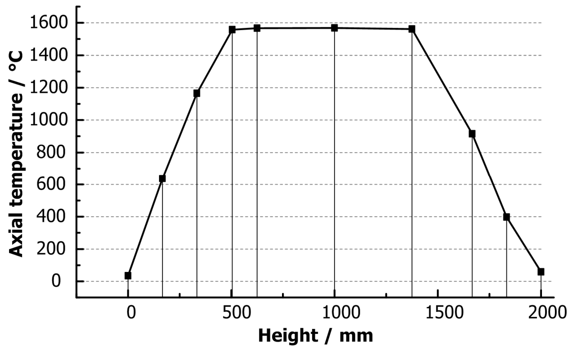

Fig.9 Temperature profile along the axial direction.

The HTR uses graphite blocks as construction components to build the reactor core cavity with thousands of fuel spheres which also use graphite as base materials in it. Materials or devices used in the reactor must have the ability to endure high temperatures in the carbonaceous environment. The simulation of carbonaceous environment in MPTA is realized by using central graphite heater, graphite sleeve and surrounding carbon fiber felt insulating layers that formed a strong carbonaceous atmosphere in the annular test zone. And moreover, graphite spheres or other graphite components can be placed into the annular test zone to realize direct contact with test materials. Fig.10 shows an alumina ceramic part which has been tested in the annular zone of the MPTA. Apparently, this part has been severely carburized because of its weak compactness. The carburization will lower its resistance and make it ineffective at last.

Temperature detectors are also important test objects in the apparatus. T_0-T_4 should endure the highest about 1600ºC in carbonaceous atmospheres.

Fig.10 An alumina ceramic part tested in the annular zone of the MPTA.

Other test points T_5-T_{12} may endure lower temperatures, but are directly embedded in the carbon material and can be easily corroded. Experimental results show that our specially designed tungsten rhenium thermocouples can work stably in such a rigorous temperature measuring environment.

4 Conclusion

To meet the material test need of the HTGR, a material performance test apparatus was built in Tsinghua University to provide reliable materials and technical support for relevant HTGR experiments. Experimental results showed the test apparatus could completely simulate the carbon reduction and high temperature environment the same as that confronted in the real reactor.

Test temperature in the apparatus could be elevated up to 1600ºC and had covered the whole temperature range of the normal operation and accident condition of HTGR. Temperature in the annular material test zone was uniform and the constant temperature zone was long enough. The performance of screened materials and structure designs, including the graphite heater, the carbon felt insulating layers and the tungsten rhenium thermocouples, had been successfully tested and verified that could work stably in strong carbon reduction environment at 1600ºC. Moreover, these parts were designed to be detachable structures and could be conveniently replaced to test other materials.

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