Design of the Material Performance Test Apparatus for High-Temperature Gas-Cooled Reactor (Postprint)

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Abstract

Most materials are susceptible to corrosion or degradation in carbonaceous atmospheres at the high temperatures characteristic of high-temperature gas-cooled reactor (HTGR) cores. To address this challenge, a material performance testing apparatus was developed to provide reliable materials and technical support for HTGR-related experiments. The apparatus employs a central high-purity graphite heater surrounded by thermal insulation layers composed of carbon fiber felt, thereby establishing a strongly reducing carbonaceous atmosphere within the chamber. Specially designed tungsten-rhenium thermocouples, capable of withstanding high temperatures in carbonaceous environments, are utilized to control the temperature field. A typical experimental process, spanning 76 hours and comprising seven distinct stages, was analyzed in this study. Experimental results demonstrated that the test apparatus could accurately simulate both the reducing carbonaceous atmosphere and high-temperature environment encountered in actual reactor conditions, and that the performance of candidate materials was successfully evaluated and validated. The apparatus can achieve test temperatures up to 1600°C, encompassing the entire temperature range of normal operation and accident conditions in HTGRs, thus fully satisfying the testing requirements for reactor materials.

Full Text

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 become ineffective in carbonaceous atmospheres at high temperatures in the reactor core of the high temperature gas-cooled reactor (HTGR). To address this problem, a material performance test apparatus was built to provide reliable materials and technical support for relevant HTGR experiments. The apparatus uses a central 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 that can endure high temperatures in carbonaceous atmospheres are used to control the temperature field. A typical experimental process lasting 76 hours including seven stages was analyzed in the paper.

Experimental results showed that the test apparatus could completely simulate the carbon-reduction atmosphere and high-temperature environment identical to that confronted in the actual reactor, and the performance of screened materials was successfully tested and verified. Test temperature in the apparatus could be elevated up to 1600°C, which covers the entire temperature range of normal operation and accident conditions 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

Introduction

The Very High Temperature Gas-cooled Reactor (VHTR) is a typical representative of Generation IV nuclear power systems, which has been developing rapidly due to its advantages such as inherent safety, high efficiency, and wide application as a high-temperature heat source. As the world's first Generation IV nuclear power commercial demonstration project, a 200-MWt high-temperature reactor pebble-bed module (HTR-PM) is being installed at the Shidaowan plant in Shandong Province, China. Concurrently, many related research efforts have been carried out in universities to support the project.

Materials and devices in the HTGR reactor core face an extremely harsh environment. In addition to nuclear radiation, the temperature of spherical fuel elements can reach 1200°C under normal operation and should be limited to under 1600°C under accident conditions. Meanwhile, because the matrix material of fuel elements and the surrounding reflector of the reactor core are made from graphite, and a large number of graphite dusts are produced due to friction loss during the fuel cycle process, a strong carbon-reducing atmosphere forms in the reactor core. Most materials commonly used in high-temperature conditions can be easily corroded or become ineffective in carbonaceous atmospheres at high temperatures, including metal dusting and internal carburization. Applicable materials must be screened for HTGR applications through relevant environment simulation experiments.

To solve this problem, a material performance test apparatus was built at Tsinghua University to provide reliable materials and technical support for subsequent HTGR experiments. The purpose of the Material Performance Test Apparatus (MPTA) is to simulate a testing environment with high temperature and strong carbon-reducing atmosphere similar to that confronted in the actual reactor core of HTGR. Test temperature in the apparatus can be elevated up to 1600°C, which covers the entire temperature range of normal operation and accident conditions of HTGR. Several essential materials and key designs, such as the heater, thermal insulating layers, and temperature measuring elements that may be widely used in subsequent HTGR experiments, have 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 HTGR environment: temperature range and carbon-reducing atmosphere. The MPTA consists of a material test zone and other support systems [Figure 1: see original paper].

The material test zone includes the heating material test zone, insulating material test zone, and temperature measuring elements test zone. The support systems include a cooling water system, vacuum system, hydraulic lifting system, power adjustment system, data acquisition system, and supporting platform.

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 heating nonuniformity along the circumference. 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 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. The allowance of these thermocouples is $±$0.5%.

All 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. Meanwhile, most parts are designed to be detachable structures, making it convenient to replace damaged parts or test other materials. Main design parameters of the material performance test apparatus are listed in Table 1 .

3. Experimental Results

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

First, a preheating was performed. The furnace was evacuated during the heating process to remove the air and 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 1400°C. The temperature was maintained for about 24 hours. After that, the heating power was raised again to elevate the temperature inside the annular material test zone up to 1600°C. The temperature was maintained for about 22 hours. Finally, the heating power was turned off, and the furnace was cooled down to room temperature by the cooling water system.

The adjustment curve of the heating power during the experiment process is shown in [Figure 3: see original paper]. The maintenance powers during 1400°C and 1600°C were 7.98 kW and 13.104 kW, respectively. [Figure 4: see original paper] shows the temperature profiles in the high-temperature zone of the apparatus, and these points, including the test point T0 on the surface of the heater and test points T1–T4 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 1600°C and kept for a long time. The tiny differences between T1–T4 show good temperature homogeneity in the annular test zone.

[Figure 5: see original paper] shows the relationship between the resistance of the 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 1600°C and the graphite heater works stably during the whole process.

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

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. The heat flux calculated is about 3$\times 10^{2}$ 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 because the thickness of the side layer is less than the 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 is thus 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 [Figure 9: see original paper]. 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 a long enough constant temperature zone for material testing. Limited by the installation space and the thermocouple size, only four temperature test points were 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 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.

The HTR uses graphite blocks as construction components to build the reactor core cavity with thousands of fuel spheres that also use graphite as base materials. 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 a central graphite heater, graphite sleeve, and surrounding carbon fiber felt insulating layers that form a strong carbonaceous atmosphere in the annular test zone. Moreover, graphite spheres or other graphite components can be placed into the annular test zone to realize direct contact with test materials. [Figure 10: see original paper] shows an alumina ceramic part that 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. T0–T4 should endure the highest temperatures of about 1600°C in carbonaceous atmospheres. Other test points T5–T12 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 needs of the HTGR, a material performance test apparatus was built at Tsinghua University to provide reliable materials and technical support for relevant HTGR experiments. Experimental results showed that the test apparatus could completely simulate the carbon-reduction and high-temperature environment identical to that confronted in the actual reactor.

Test temperature in the apparatus could be elevated up to 1600°C and covered the entire temperature range of normal operation and accident conditions 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 tungsten-rhenium thermocouples, had been successfully tested and verified to work stably in a strong carbon-reduction environment at 1600°C. Moreover, these parts were designed to be detachable structures and could be conveniently replaced to test other materials.

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Note: Figure translations are in progress. See original paper for figures.