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Measurement on effective thermal diffusivity and conductivity of pebble bed under vacuum condition in High Temperature Gas-cooled Reactor

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ABSTRACT

A full-radius-scale heat test facility has been developed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China to measure the effective thermal diffusivity and conductivity of pebble bed in High Temperature Gas-cooled Reactor (HTGR). In present test, a separate-effect transient experiment under vacuum condition is conducted successfully up to 1200 °C. Through inverse method and experimental temperature data, this paper presents the process of determining these thermal parameters and compares the results with previous researches, which reveals that the results are comparable in low-temperature region and valid in high-temperature region. In addition, it also studies the experimental errors and the results' uncertainties in this test. The correct knowledge on effective thermal diffusivity and conductivity of pebble bed inside the reactor core is significant to ensure the valid design and inherent safety, which will give a better balance between safety and economic competitiveness.

1. Introduction

The High Temperature Gas-cooled Reactor has been studied for decades in INET of Tsinghua University in China for exploring and developing modular HTGR technology. The first 10 MW_{th} HTGR reached the criticality in 2000 and operated at full power in 2003, which validated the desirable characteristics of Generation IV nuclear power system: inherent safety feature; capability to provide high temperature. Furthermore, the demonstration plant, which is also called the high-temperature gas-cooled reactor pebble-bed module (HTR-PM), with 2×250 MW_{th} in Shidao Bay of China will connect to the grid at the end of 2017. The main technical goals of HTR-PM project should be as follows: demonstration of inherent safety; demonstration of economic competitiveness; confirmation of proven technologies; standardization and modularization (Zhang et al., 2009). In severe accidents, e.g. a loss-of-coolant and depressurized accident under full-power operation, the core temperature will increase above its normal-operation core temperature temporarily; besides, in the final step, the steady-state decay heat will result in a temperature distribution within reactor core. The inherent safety requires that the maximum fuel element temperatures will be always under the limiting temperature 1600 °C, i.e. no core melting, without employing any dedicated emergency systems when all conceivable accidents occur (Zhang et al., 2006, 2009). In present design, the normal-operation helium temperatures at reactor core inlet/outlet are 250/750 °C, and the produced steam state in the steam generator outlet is 13.25 Mpa/567 °C. The most crucial issue from a commercial perspective is the economic competitiveness, compared with the LWRs, which is the primary reactors in the world. According to the cost comparison, the present HTR-PM is 10%–20% more expensive than PWR at the same electric power if current HTR-PM parameters are employed (Zhang et al., 2016). In fact, the current reactor and fuel element technologies have the potential of reaching the 950 °C in helium outlet temperature, even 1000 °C, which is a typical temperature in very high-temperature gas-cooled reactor (VHTR). The improved temperature will enhance the efficiency and power of electricity generating and make it more competitive in economic cost. Moreover, a single reactor with larger thermal power can also be designed to enhance its economic competitiveness while the inherent safety can be reserved.

As stated above, the heat transfer design can ensure the inherent safety of HTR-PM in different powers and temperatures. Therefore, the correct knowledge on effective thermal diffusivity and conductivity of pebble bed, packed by 420,000 spherical fuel elements inside reactor core, is significant to ensure the valid design and inherent safety. Especially, the effective thermal diffusivity will determine the maximum dynamic temperature after the accident, and the effective

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thermal conductivity will determine the maximum steady temperature inside reactor core during the decay heat period. In fact, the pebble bed is a representative porous structure, and its heat transfer is a combination of solid heat conduction inside or between fuel elements, thermal radiation between the surfaces of adjacent spheres and the gas heat convection. According to other porous media researches, the radiation effect will account for more than 50% of total heat transfer at moderate temperatures in some porous media (Huang and Zhang, 2014; Stewart et al., 1986; Zhou et al., 2007), and radiation heat transfer will be apparently affected by different packing structure and density. Moreover, in the loss-of-coolant and depressurized accident, the gas heat convection isn't important. Two previous experiments on effective conductivity of graphite pebble bed had been conducted by the SANA facility in Germany in 1996 (Stöcker and Niesses, 1997) and the HTTF in South Africa (Rousseau et al., 2014; Rousseau and van Staden, 2008) in 2012 respectively. Since the carbon-reducing atmosphere exists and the thermal isolation is hard to maintain the steady temperature distribution in test facilities referring to a higher temperature, the effective thermal conductivities obtained by steady-state method were just up to 1000 °C in SANA and 1200 °C in HTTF, which is inappropriate to present the dramatic growth of effective thermal conductivity caused by radiation heat transfer at higher temperature.

The distinct knowledge on effective thermal diffusivity and conductivity of pebble bed contributes to realizing the heat transfer at higher thermal power and outlet helium temperature, which means a better balance between safety and economic competitiveness. A full-radius-scale heat test facility has been developed by INET of Tsinghua University in China to measure these two parameters up to 1600 °C under vacuum condition (20 Pa) and atmospheric pressure (10^5 Pa). Recently, we conduct the first experiment up to 1200 °C successfully, and the effective thermal diffusivity and conductivity can be derived through experimental dynamic temperatures among the pebble bed. The relevant data processing algorithm of inverse method has been studied theoretically in our previous work (Wu et al., 2017b), and this paper mainly focuses on the validation of inverse method on the practical experimental data. In the following sections, we present the experiment process, temperature distributions and improved methodology of data analysis on determining effective thermal diffusivity and conductivity.

2. Configuration of heat test facility

The more detailed description about the heating system, data acquisition, thermocouples, heat insulation and facility design can be found in previous works of Ren and Li et al. (Li et al., 2015; Ren et al., 2014a,b, 2015; Wu et al., 2017b). Here we present a brief overview of experimental facility for completeness.

Fig. 1 shows the overview of whole heat test facility. The steel vessel is 5 m in diameter and 7 m from ground to its header. The water jacket is embedded in the steel vessel, and the 20 Pa vacuum is maintained by four mechanical vacuum pumps at the same period. Fig. 2 shows a vertical cut through the whole vessel, where the circumambient thermal insulation of pebble bed are carbon felts with an approximate effective thermal conductivity 0.2 W/m°C (Li et al., 2014) to keep compatibility with carbonaceous atmosphere at high temperature and maintain a higher temperature in outside of pebble bed. Both of top and bottom insulations are 0.5 m in thickness to limit the heat transfer in the axial direction. 70 000 machined graphite balls are randomly and densely placed in bed region, which is an annular core configuration with 1 m in height, 1.2 m in internal diameter and 4.2 m in external diameter. A graphite heater in center of pebble bed is manufactured according to the power requirement, and its shape is presented in Fig. 4.

The dark points in Figs. 2 and 3 show the distribution of 90 thermocouples in pebble bed. There are five circumferential sets of thermocouples, indicated as C1 to C5, at each layer of three level. At each set, six thermocouples, indicated as T1 to T6 in Fig. 2 respectively, are

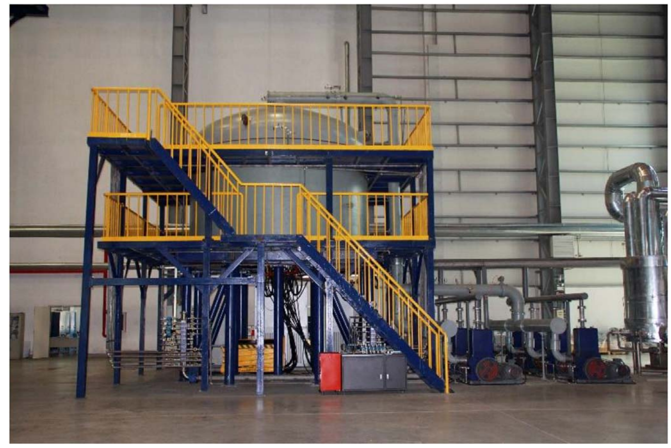

Fig. 1. Photograph of heat test facility.

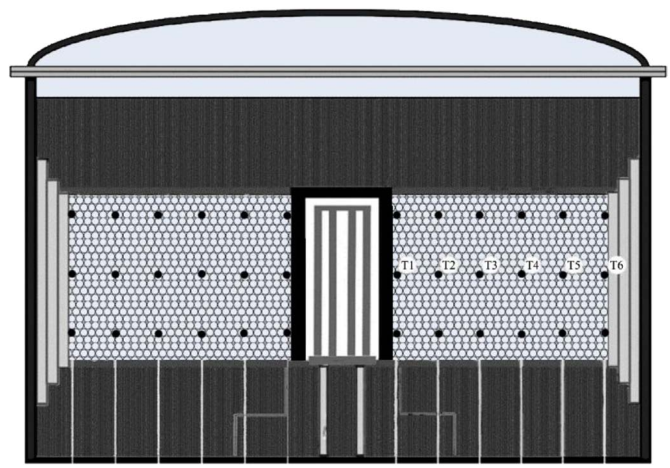

Fig. 2. Schematic of a vertical cut through the test facility.

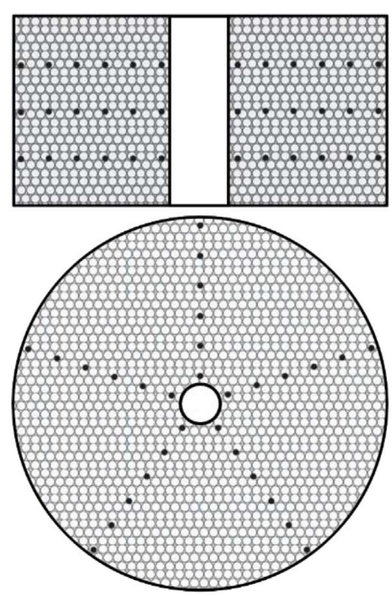

Fig. 3. Thermocouples distribution among the whole pebble bed.

distributed along the radial direction. Therefore, the number of thermocouples amounts to 90, which is calculated by 5 × 6 × 3, in entire pebble bed. In present test, the type K thermocouples are used to measure the temperature in the pebble bed. In addition, the