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Computational and experimental prediction of dust production in pebble bed reactors, Part II

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HIGHLIGHTS

- Custom-built high temperature, high pressure tribometer is designed.
- Two different wear phenomena at high temperatures are observed.
- Experimental wear results for graphite are presented.
- The graphite wear dust production in a typical Pebble Bed Reactor is predicted.

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ABSTRACT

This paper is the continuation of Part I, which describes the high temperature and high pressure helium environment wear tests of graphite–graphite in frictional contact. In the present work, it has been attempted to simulate a Pebble Bed Reactor core environment as compared to Part I. The experimental apparatus, which is a custom-designed tribometer, is capable of performing wear tests at PBR relevant higher temperatures and pressures under a helium environment. This environment facilitates prediction of wear mass loss of graphite as dust particulates from the pebble bed. The experimental results of high temperature helium environment are used to anticipate the amount of wear mass produced in a pebble bed nuclear reactor.

1. Introduction

The Pebble Bed Reactor (PBR) is a High Temperature Gas-Cooled Reactor (HTGR). Because of its unique online refueling design, PBR is counted on less shut-down time for maintenance and more efficient operation. The pebble bed in such reactors is comprised of thousands of billiard-sized graphite-matrix spheres as fuel elements. Each pebble contains the Tristructural-isotropic (TRISO) nuclear fuel particles. These pebbles travel from the top of the reactor to the bottom. They are exposed to pressurized helium coolant and high temperatures ranging from 650 °C to 950 °C. As the pebbles traverse downward through the reactor, the amount of graphite dust produced under frictional contact and thus circulated and eligible for release under a postulated accident like depressurization and subsequent air ingress, is a design review safety concern. Graphite dust production in previously built PBRs have always been considered as a potential safety concern (Moormann, 2009). Multiple observations are reported for the German Arbeitsgemeinschaft Versuchsreaktor (AVR, 1960–1980) on the accumulated dust. However, the phenomena of dust production have never been closely examined experimentally and computationally. Computational prediction (Rostamian et al., 2010, 2011, 2012) of graphite particulate formation at room temperature has been conducted for room temperature experiments. These works showed a very good agreement with a review on the results by Xiaowei et al. (2005) and by Cogliati et al. (2011). Part I of this paper is a computational micromechanics study of graphite wear, which introduces a nonlinear wear model for graphite (Rostamian et al., 2013). This model predicts the experimental data from a custom-designed tribometer. Since high temperature properties of graphite other than its module of elasticity, are not available, high temperature finite element simulations have not been conducted to produce a nonlinear wear law for graphite at high temperatures.

In the literature of wear of brittle materials, temperature effects have not widely been discussed. And in those discussing the temperature effects, specific cases based on the target application were reported (e.g. Grigor'ev et al., 1983). In the present experimental

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study, however, wear of graphite in a wide range of temperatures (20–750 °C) have been studied. In an effort to quantify the frictional wear mass loss from graphite pebbles in the pebble bed, a custom-designed tribometer has been developed to measure the wear of graphite pebbles in helium atmosphere at pressures and temperatures expected in modern Graphite-Moderated Gas-Cooled Reactors (GM-GCR). This paper describes in details the design, deployment of the device and the experimental data of nuclear grade graphite. The graphite dust mass produced from the tribometer is then used to predict the mass produced in a PBR during a full working year as discussed by Cogliati et al. (2011).

2. Experiment

2.1. Experimental apparatus

The majority of the test data is below the higher outlet temperatures expected under normal PBR operation. Also, there is no test data for graphite matrix or graphite at the temperatures and pressures expected in a PBR. To conduct wear tests under such conditions, a custom test apparatus was designed. In this section, the design requirements and the experimental setup are explained in details.

2.2. Design requirements

The tribological properties of graphite depend on several factors. Therefore, the ability to perform tests on separate effects to simulate the real conditions of a PBR is considered important in obtaining accurate wear rates for graphite. The design parameters that were selected are listed in Table 1.

2.3. Tribometer design

The motion requirements for sliding between two spherical objects led to the selection of a twin disk tribometer. The apparatus is essentially a small twin-disk tribometer housing in a furnace that is completely encompassed by a pressure vessel. With a water cooling loop removing the heat outside the furnace, the concurrent, demanding design requirements of high pressure and temperature were effectively decoupled. The large pressure vessel allowed for no mechanical feedthroughs and for real-time measurement of the particulate mass and the normal force applied with only non-mechanically actuated penetrations through the pressure boundary. The frame of the tribometer is mounted to the underside of the top removable lid of the pressure vessel (see Fig. 1).

Table 1
Design parameters for the testing apparatus.

Testing parameter	Description	Source
Maximum temperature	750–900 °C	Reactor outlet temperature (Nelson et al. (2011))
Maximum pressure	6.5 MPa	Primary loop pressure (Nelson et al. (2011))
Helium environment	99.998%	HTGR standards, airgas catalog
Normal force	10–50 N	Past Chinese studies (Xiaowei et al. (2005))
Velocity	<0.1 m/s	Cogliati et al. (2011)
Total distance	∼500 m	Xiaowei et al. (2005), Kadak and Bazant (2004)
Contact geometry	Sphere–sphere	Pebble–pebble contact

2.4. Experimental material

The main carbonaceous components in the PBR are the spherical fuel elements and the core reflectors. The latter is made from nuclear grade graphite while the fuel elements themselves are made from what is referred to as graphite-matrix. This graphite matrix classically comprised of natural graphite, synthetic-graphite, and a phenolic resin binder. This mixture is then isomolded or quasi-isostatically molded into its final spherical shape. It is then carbonized in heat treatment of up to 800 °C, and

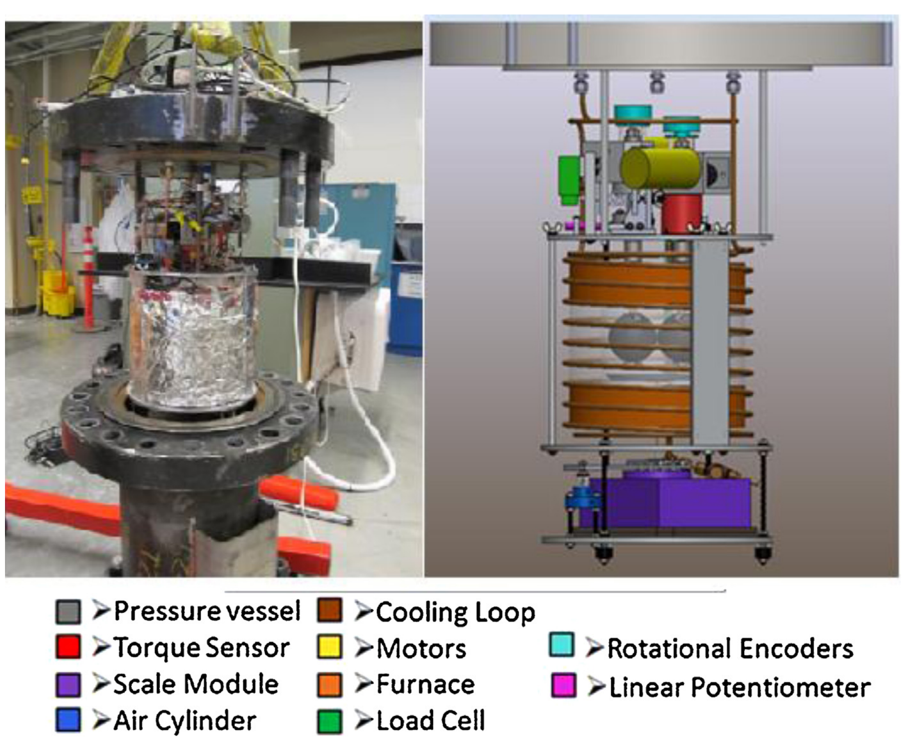

Fig. 1. Tribometer (left) and its schematic (right) with pebbles in contact and the modular analytical balance.