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Wear behavior of graphitic matrix of fuel elements used in pebble-bed high-temperature gas-cooled reactors against steel

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ABSTRACT

Graphite dust can impact the operation of pebble-bed high-temperature gas-cooled reactors. Wear of fuel elements during collisions in the transport pipes of fuel handling and storage systems is a significant source of graphite dust generation; however, very little work on the wear behavior of this scenario has previously been reported. The present work investigated high contact loads of spherical fuel elements during collisions against pipe inner surfaces. Friction and wear tests, with the graphitic material sliding against steel, in a similar loading range were carried out. The coefficients of friction (COF) and wear rates were systematically investigated as a function of the sliding speed, applied load, steel surface roughness, and atmosphere. The COFs were found to be independent of the sliding speed and applied load, but initially decreased and then increased with increasing steel surface roughness; the wear rate of graphitic material increased with increasing load and steel surface roughness. Test results also showed that helium caused higher COFs and wear rates than air. Microscopic observations showed that the nature of the atmosphere can affect the generation of a lubrication layer at the contact area. These results could be applied in developing quantitative predictive models of dust generation during fuel handling and storage processes.

1. Introduction

The utilization of spherical fuel elements (FE) is one of the unique characteristics of pebble-bed high-temperature gas-cooled reactors (HTGR) (Zhang et al. 2016). The diameter of these spherical FEs is 60 mm. The coated fuel particles are embedded in a graphitic matrix (GM) of the spherical FE; the 5-mm thick outer shell of the spherical element is made of pure GM material without fuel particles (Tang et al. 2002). In the on-line refueling process of a pebble-bed HTGR, the spherical FEs are charged into the reactor core from the top, flow slowly down through the pebble bed, and are discharged from the core at the bottom. Each discharged spherical FE will be either transported back into the core by the fuel-handling system if its fuel burnup is lower than the required limit or transported to the spent fuel storage system as a spent fuel element (Liu et al. 2002; Zhang et al. 2009). During both transport processes, the spherical FEs travel through steel pipes with inner diameters nearly equal to those of the spherical FEs, driven by pneumatic force. Their maximum instantaneous speed in the pipes can be as high as ~8.8 m/s in rare cases, which is much faster than that in the core (Table 1). In fact, an FE does not travel strictly along the axis in the pipe: it also vibrates in the pipe's radial direction because of the non-uniform fluid field and changing pipe route (Liu et al. 2015); consequently, spherical FEs can collide and become worn when interacting with inner walls of transport pipes, thereby generating graphite debris and dust (Shen et al. 2015). This dust-generation behavior in transport pipes, which is a highly interesting dust issue (Moormann 2008), differs significantly from that in the core (Cogliati et al. 2011; Troy et al. 2015) where the spherical FEs flow slowly past each other and against the graphite components (Table 1). Besides, the slow corrosion of graphite components (Cerullo and Lomonaco 2012) and the GM of FEs (Yu and Yu 2010) by trace impurity gases in the primary circuit may also contribute to the dust production, although the FEs stay much shorter in the core than graphite components.

Beside these working conditions in the transport pipes, the matrix material of the FE is also of particular interest. The GM for HTR-10 (Zhao et al. 2006) and HTR-PM (Zhou et al. 2013) FEs and the German A3-3 material are similar in production process and heat treatment. The GM material is, in fact, not completely graphitized because the final heat treatment temperature is below 2000 °C. Consequently, its mechanical properties differ from those of the nuclear graphite materials

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Table 1
Graphite dust-generation scenarios in pebble-bed HTGR.

Position	Ambience	Ambient Pressure (MPa)	Ambient Temperature (°C)	Counterpart	Speed (m/s)	Dust generation mechanism
Core	He	3–7	250–750	FE vs. FE; FE vs. graphite structure	$\sim 2 \times 10^{-6}$	Friction
Fuel element discharge tube	He	3–7	250	FE vs. inner wall of discharge tube	$\sim 7 \times 10^{-5}$	Friction
Transport pipes and handling facility in fuel-handling system	He	3–7	25–250	FE vs. inner wall of the pipes and facility	0–6	Friction and collision
Transport pipes and handling facility in spent fuel storage system	Air	± 0.05	25–50	FE vs. inner wall of the pipes and facility	0–8.8	Friction and collision

Table 2
Physical parameter values used in calculations.

	Graphitic matrix	Steel pipe
Elastic modulus (Pa)	1×10^{10}	19.5×10^{10}
Poisson's ratio	0.15	0.31

employed in the reactor core structure.

Several researchers have explored wear behavior of the GM material against itself in surface contact (Li et al. 2016). Others have used nuclear graphite, such as IG-11, to investigate the wear rate of graphite spheres against itself (Hiruta et al. 2013; Luo et al. 2017) or stainless steel. The wear rate of a 60-mm diameter IG-11 graphite sphere against the lateral surface of a 60-mm diameter stainless steel cylinder was approximately $6 \times 10^{-5}\,mm^3/(N{\cdot}m)$ under 20 N load at 0.04 m/s (Tokuhiro et al. 2013). Luo et al. 2004 studied the wear behavior of a convex spherical surface of IG-11 against the concave spherical surface of stainless steel by reciprocating sliding. These studies were mainly conducted to explore the dust generation within the pebble-bed core. The generated dust would be transported in the primary circuit and accumulate at the dead-end zones of main components such as the heat exchanger whose efficiency can be reduced consequently (Peng et al. 2016). The dust could also absorb and carry fission and activation products, which is a high concern in the analysis of potential radioactivity release (Stempniewicz et al. 2012; Kissane et al. 2012).

To date, however, the wear of the GM against the inner surface of a transport pipe and consequent dust generation has not yet been extensively studied. The dust production rate in the transport pipes is still unknown (Rostamian et al. 2012) but is expected to be significant (Stempniewicz et al. 2012) compared with that in the core. The dust could adhere to the surfaces of pipes and devices or be carried into the primary circuit, and thereby affect the safety of the fuel-handling system and even the reactor operation. It is therefore important to understand the friction and wear behaviors of FEs and the mechanism of consequent dust generation in the transport pipes. Depending on these results, the amount of dust could be estimated more accurately and further used in maintenance planning and safety analysis (Stempniewicz et al. 2012).

This study set out to investigate the friction and wear process of FEs in the transport pipes of a pebble-bed HTGR. The collision and wear processes of FEs in the pipes were analyzed. A set of experiments was designed to explore the effects of sliding speed, applied load, surface roughness, and atmosphere on the friction and wear behavior. The mechanisms of friction and wear were further characterized. The results obtained could be used for future estimation of dust generation in the transport pipes.

2. Collision analysis

During the short duration of FE collisions against a pipe wall, if the FE slides with a relative tangential velocity to the contact zone, the dynamic frictional force would lead to wear of the FE. The dynamic frictional force certainly depends on the impact force, while the impact force is impulsive within a short time frame—typically of the order of 1 ms. According to the technical specifications of HTR-10 and HTR-PM (Zhou et al. 2013), an FE should be able to be dropped from 4 m height (or at an approaching speed of 8.8 m/s) onto a pebble bed more than 50 times without failure occurring. Consider (i) an FE collision against another FE in the pebble bed and (ii) perpendicular collision against the inner wall of a 65-mm diameter steel pipe at this approaching speed. The collision duration, the normal force, and the stress can be obtained from Hertz's theory using the physical parameters given in Table 2. The results listed in Table 3 show that the normal forces in both cases are unsurprisingly lower than the crushing strength of the FE, which is required to be over 18 kN (Zhou et al. 2013). In addition, the compressive stress during an FE collision against the inner pipe wall is less than that against another FE, because the convex inner wall of the pipe allows a larger contact area. However, the number of FE collisions that occur in a pipe is much larger than that of drops onto the pebble bed; therefore, it is necessary to explore the friction and wear behavior before predicting the dust generation in the transport pipeline. With the estimated range of normal forces under operating condition, friction and wear experiments could be correspondingly carried out.Table 4.

3. Material and methods

The experimental spheres used in this work were made of a GM similar to that of the matrix of spherical FEs of HTR-PM. A slight difference was that the impurities in these spheres were not as strictly controlled as those of authentic elements; fortunately, the total impurity concentration in these spheres was still below 0.1 mass% and would therefore not affect the friction and wear properties.

Tribological tests were performed on a universal micro-tribotester (UMT-2, Center for Tribology Inc., California, USA) with a ball-on-disc configuration. The ball was fixed as the upper piece and pressed on the disc by the given load. The lower disc rotated at a certain speed during the test. The distance from the center of the disc to the ball and the rotation speed were adjusted to obtain different sliding line speeds in the range of 1–6 m/s (the maximum line speed was unable to achieve 8.8 m/s, because of the rotational speed of the tribotester and diameter of the experimental spheres). In future studies, a direct determination of the COF and wear rate at higher sliding speeds over 6 m/s is needed

Table 3
Calculated parameters of collisions at a perpendicularly approaching speed of 8.8 m/s.

Parameters	FE vs. FE collision		FE vs. steel pipe collision	
Coefficient of restitution	0.4	0.6	0.4	0.6
Collision duration (ms)	0.324	0.311	0.249	0.238
Time-average normal force (kN)	7.6	9.1	9.9	11.82
Time-average compressive stress (MPa)	356	424	168	179