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Resuspension of multilayer graphite dust particles in a high temperature gas-cooled reactor

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ABSTRACT

The resuspension characteristics of graphite dust particles have a significant effect on the safe operation and source analyses of HTGR. The present study presents a theoretical model for the resuspension of multiple layers of graphite dust particles based on the Rock'n'Roll model and the multilayer approach of Friess and Yadigaroglu (2001). The model is then used to analyze the influences of various physical properties such as the number of particle layers, coolant temperature and operating pressure on the resuspension characteristics. The results show that as the number of particle layers increases, the resuspension fraction of the particles decreases up to a critical number of layers after which the resuspension fraction remains constant with increasing number of layers. After the second layer, the resuspension fraction of the particles increases from zero to a maximum and then decreases, with the maximum decreasing with increasing number of layers. Larger particles and particles with higher friction velocities more easily detach from the wall and resuspend. For the same helium pressure and friction velocity, the resuspension fraction decreases with increasing temperature. For the same helium temperature and friction velocity, a higher helium pressure will give rise to the resuspension of more graphite dust particles.

1. Introduction

Nuclear grade graphite has the advantages of strong thermal neutron moderating ability, weak absorption capacity, high purity, high thermal conductivity, small thermal expansion coefficient and isotropic properties, so it has been widely used in HTGR (high-temperature gas-cooled reactors) core (Marsden, 2000; Yu and Yu, 2010), such as materials for cladding fuel particles, core support members and reflection layers. However, mechanical wear and other effects produce sub-micron and micron size graphite dust particles (Humrickhouse, 2011). Moormann, 2008 analyzed the radioactive sources in an HTGR core and found that the graphite dust in an HTGR carries fission products and plays an important role in the transmission of fission products, which ultimately affects the radioactive material distribution in the core. Secondly, graphite dust particle deposition also affects reactor maintenance (Lind et al., 2010). Hence, the graphite dust transport is an important part of HTGR radioactive source analyses. In an HTGR, the graphite dust behavior includes the dust production mechanism, the amount of dust and the particle properties (Luo et al., 2010; Rostamian et al., 2013; Hiruta et al., 2013; Troy et al., 2012, 2015; Shen et al., 2015, 2016), the binding of fission products (Kissane, 2009) and the particle motion including diffusion deposition (Stempniewicz et al., 2012; Gutti and Loyalka, 2009; Peng et al., 2013b, 2016) and resuspension (Stempniewicz et al., 2008; Kissane et al., 2012; Barth et al., 2013; Kazuhiro et al., 1992; Peng et al., 2013a, 2014; Nguyen and Loyalka, 2015; Zhang et al., 2013). In the event of a LOCA (Loss of coolant accident), some of the dust particles that have been deposited on the surface of the primary loop will be resuspended with the loss of coolant which will lead to radioactive contamination of the surrounding environment. Therefore, the resuspension behavior of the graphite dust is an important part of analysis of graphite dust transport in an HTGR.

There were few studies focusing the resuspension behavior of graphite dust particles. A resuspension model based on the Vainshtein model was used by Stempniewicz et al., 2008 with the results agreeing well with a number of tests. Kissane et al., 2012 developed a resuspension model based on more realistic statistics from LES studies for the fluctuating components of the aerodynamic forces. Barth et al., 2013 experimentally investigated graphite dust deposition and resuspension in a small-scale test facility by means of positron emission

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tomography, with the results indicating that the graphite dust dynamics were similar to deposition and resuspension of other particle in turbulent flows. Kazuhiro et al., 1992 experimentally studied graphite dust resuspension during a depressurization accident, with the results indicating that the shear ratio concept could not accurately describe the dust behavior and more parameters should be included. Peng et al., 2013a experimentally studied the resuspension of graphite dust with the results showing that the resuspension fraction increases as the initial pressure increases. Peng et al., 2014 numerically investigated the resuspension of graphite dust in a steam generator with the results showing that the resuspension fraction is nearly zero for particles with diameters less than 1 μm and increases as the helium velocity increases for particles larger than 1 μm. Nguyen and Loyalka, 2015 used a numerical solution of the Reeks-Hall equation using the fractional resuspension rate in its original integral form with good agreement with experiment data. Zhang et al., 2013 developed a hybrid model for the resuspension of particles from multilayer deposits in the boundary layer of a fully developed turbulent flow. Analyses of the resuspension of graphite dust requires a good model of the adhesion force and its distribution for dust particles deposited on surfaces. However, the adhesion force and its distribution are difficult to determine in practice. Mokgalapa et al., 2014, 2016; Zhang et al., 2015 studied the adhesive force between a particle and the surface using an atomic force microscope (AFM) to show that the particle roughness and component surface condition strongly influenced the adhesive force. The studies (Stempniewicza and Komen, 2010; Merrill and Humrickhouse, 2011) indicated that the adhesion force must be divided into a number of computational bins with the model considering the resuspension of each bin separately.

In summary, previous studies on the resuspension behavior of graphite dust in an HTGR have been mostly semi-empirical models based on experiments or monolayer particle models. Only a few studies have considered the influence of multiple layers of deposit particles. An actual deposits of graphite dust particles on a wall normally have multiple layers since the HTGRs have very long run times. Therefore, the resuspension characteristics of multilayer graphite dust particles are very important. The present study focused on a preliminary and academic study, in which a theoretical model called the FY model which assumes that particles are resuspended one-by-one was used to analyze the basic resuspension characteristics of multilayer particle deposition in an HTGR.

2. Multilayer resuspension model

2.1. Introduction

Multilayer particle resuspension involves several problems that monolayer particle models cannot be describe: (1) Particles are masked by other particles so that only the particles on the top surface of the deposited layer can be influenced by the drag force and the lift force of the flow, so the masked particles cannot detach from the deposited layer. (2) Deposit layer structure: The compactness of the deposited layer structure and the particle layer thickness strongly affect the particle resuspension fraction. (3) Aggregation effect: The particles in the deposited layer may be aggregated; hence, the aggregated particle is larger than the particles before deposition.

The first multilayer resuspension model proposed by Paw, 1982 described the resuspension fraction by only the number of “turbulent crushing” events and a resuspension probability coefficient. Fromentin (1989) proposed a semi-empirical model based on the PARESS (PARticle RESuspension Study) test results. Lazaridis and Drossinos (1998) combined the RRH resuspension theoretical model and a multilayer resuspension rate model assuming that the resuspension probability coefficient of each layer of particles had a fixed value. Friess and Yadigaroglu (2001) used a recursive approach starting from the resuspension of the first layer of particles to gradually calculate the

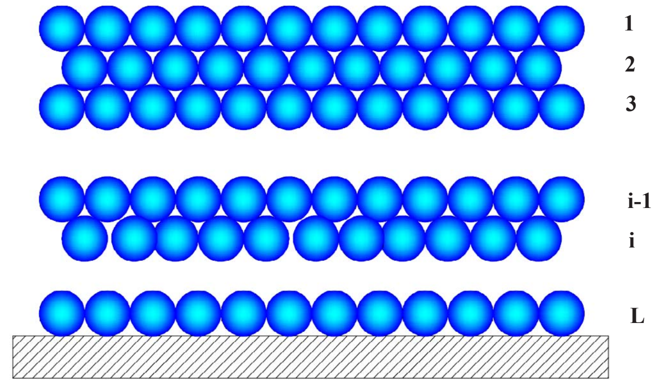

Fig. 1. Ideal deposition layer structure.

resuspension fraction of the whole deposition layer with a relationship between the PDF (probability density function) of the independent variable in the deposited layer and the multilayer structure to create a more accurate model.

Referring to Zhang et al. (2013), on the basis of our previous study of monolayer graphite particle (Zhang et al., 2017), the present study uses the Friess and Yadigaroglu (2001) in a multilayer resuspension model based on Rock'n'Roll resuspension theory model (Reeks and Hall, 2001). Due to the complexity of the multiple layers of particles, the present model is based on an ideal deposition layer structure formed by stacking equal size particles. The ideal deposition layer is illustrated in Fig. 1.

Assume that $s(\xi,t)$ represents the PDF of exposed particles that have not yet departed from the deposition layer. In the initial state, the particles are isotropic, i.e., the independent variable for each particle layer has the same PDF, $\varphi(\xi)$. For the first layer of particles, $s(\xi,0) = \varphi(\xi)$; for the second and subsequent layers, in virtue of the particles not being exposed, $s(\xi,0) = 0$.

The variation of the independent variables for each layer can be derived as follows:

$$\frac{\partial s_1(\xi,t)}{\partial t} = -p(\xi)s_1(\xi,t)(i = 1) \tag{1}$$

$$\frac{\partial s_i(\xi,t)}{\partial t} = -p(\xi)s_i(\xi,t) + \varphi(\xi)\int^{p}(\tilde{\xi})s_{i-1}(\tilde{\xi},t)d\tilde{\xi}\ (i \geqslant 2) \tag{2}$$

The Rock'n'Roll resuspension theory model is:

$$\varphi(f_a') = \frac{1}{\sqrt{2\pi}}\left(\frac{1}{f_a' ln\sigma_a'}\right)\exp\left(-\frac{1}{2}\left\{\frac{\ln(f_a'/\langle f_a'\rangle)}{ln\sigma_a'}\right\}^2\right) \tag{3}$$

$$P = \frac{1}{2\pi}\sqrt{\frac{<\dot{f}^2>}{<f^2>}}\exp\left\{-\frac{(f_a'F_a - <F>)^2}{2<f^2>}\right\}/\frac{1}{2}\left(1 + erf\left(\frac{f_a'F_a - <F>}{\sqrt{2<f^2>}}\right)\right) \tag{4}$$

Thus, for $i = 1$,

$$\frac{\partial s_1(f_a',t)}{\partial t} = -p(f_a')s_1(f_a',t) \tag{5}$$

$$\Lambda_1(t) = \int_0^\infty p(f_a')e^{-p(f_a')t}\varphi(f_a')d(f_a') \tag{6}$$

For $i \geqslant 2$,

$$\frac{\partial s_i(f_a',t)}{\partial t} + p(f_a')s_i(f_a',t) = \varphi(f_a')\int_0^\infty p(\tilde{f}_a')s_{i-1}(\tilde{f}_a',t)d\tilde{f}_a' \tag{7}$$

Multiplying both sides of the equation by $e^{p(f_a')t}$ gives