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Resuspension models for monolayer and multilayer deposits of graphite dust

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ABSTRACT

Graphite dust that will be generated in a multi-pass pebble-bed HTR (high temperature reactor), for example the Chinese HTR-PM and the South African PBMR, during normal reactor operation will be deposited inside the primary system and will become radioactive due to sorption of fission products. A significant amount of radioactive dust may be resuspended and released from the reactor cooling system in case of a depressurization accident. Therefore, accurate particle resuspension models are required for HTR/PBMR safety analyses.

A review of available resuspension models applicable for monolayer and multilayer deposits is presented in this paper. It is demonstrated that for both multilayer and monolayer deposits, the main problem is the lack of data on adhesion forces and particle-to-particle contact forces.

For monolayer deposits, a simple resuspension model, based on a moment balance, referred to here as KS-MB, is proposed and compared with several available resuspension models and available experimental data. It is concluded that a key factor in successful resuspension predictions is a good knowledge of the adhesion force distribution for dust particles deposited on rough surfaces. We demonstrate that relatively simple, quasi-static models, such as the KS-MB model, are as useful as the more complicated dynamic models for resuspension calculations in lack of precise data concerning adhesion forces.

For multilayer deposits, resuspension modelling is even more complex. Several models exist, but there is no sufficiently extensive validation. Furthermore, the models may even give contradicting trends of the resuspension rates. The KS-MB resuspension model applicable for multilayer deposits is proposed here and validated against available experimental data. It is concluded that important factors are deposit structure as well as adhesion forces and particle-to-particle contact forces. Furthermore, it is not possible to positively identify the trend of resuspension rates in multilayer deposits. The effect of the multiple layers is overwhelmed by uncertainties in the adhesion force definitions. The main recommendation from the current work is that further measurements of adhesion forces, preferably done for the actual materials and conditions (temperatures, pressures) of the analyzed system (for example HTR-PM) are crucial for development of models and accurate prediction of resuspension.

1. Introduction

Graphite dust that will be generated in a multi-pass pebble-bed HTR (high temperature reactor), for example the Chinese HTR-PM and the South African PBMR, during normal reactor operation will be deposited inside the primary system and will become radioactive due to sorption of fission products. A significant amount of radioactive dust may be resuspended and released from the reactor cooling system in case of a depressurization accident. Therefore accurate particle resuspension models are required for HTR/PBMR safety analyses.

A review of available resuspension models applicable for monolayer and multilayer deposits is presented in this paper. New resuspension model for monolayer and multilayer deposits are presented. As will be demonstrated, for both multilayer and monolayer deposits; the main problem is the lack of data on adhesion forces and particle-to-particle contact forces.

The work was sponsored by a Dutch R&D program. The models described in this paper were applied for long term dust analysis in HTR-PM, performed using the SPECTRA code.

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2. Resuspension

2.1. Definitions

We use the following definitions:

- *Adhesion forces* – forces binding a particle to the surface
- *Aerodynamic forces* – drag and lift force exerted by the flowing gas on the deposited particles
- *Resuspension model* – mathematical relation between the adhesion forces and the aerodynamic forces that determines if a particle remains on the surface or becomes resuspended.

2.2. Adhesion forces

An adhesion force, F_a, is the force binding the dust particles to the surface. The main difficulty in calculating the resuspension is a relatively weak knowledge of the adhesion forces and the fact that on typical surfaces there is a wide spread of the adhesion forces, especially for rough surfaces. Due to this spread, the adhesion forces are usually represented by distribution functions. The log-normal distribution is most frequently used. The log-normal distribution is characterized by the following two parameters:

- the mean adhesion force: $\langle F_a \rangle$
- the standard deviation, often referred to as adhesive spread factor: σ_a

Those two parameters are discussed in the following two subsections.

2.2.1. Mean adhesion force

The adhesion force is often calculated using a reduction factor, f', which is defined as a ratio of the actual force to the theoretical value computed for a smooth surface. The rationale here is to reverse the role of the particle and a surface asperity. The reduction factor is viewed as a ratio of the mean surface asperity radius, $\langle r_{as} \rangle$, (typically: 10^{-8}–10^{-7} m) to the radius of the deposited particle, $(D_p/2)$, (typical value 10^{-6} m). Therefore:

$$f' = \frac{\langle r_{as} \rangle}{D_p/2} \sim 0.01 \div 0.1 \quad (1)$$

In the Vainshtein et al. (1997) model the following adhesion forces are given for a smooth surface:

- for small hard particles: $F_a = \pi \cdot \Delta\gamma \cdot D_p$
- for large soft particles: $F_a = (3/4) \cdot \pi \cdot \Delta\gamma \cdot D_p$

Here D_p is particle diameter and $\Delta\gamma$ is the adhesive surface energy. For example, if the value of $\Delta\gamma$ is 0.15 J/m^2, as used by Vainshtein et al. (1997), then:

- for small hard particles: $F_a = 0.47 \cdot D_p$
- for large soft particles $F_a = 0.35 \cdot D_p$

Fig. 1 shows the adhesion forces calculated for small hard particles, with:

$$f' = 0.01$$
$$f' = 0.1 \quad (2)$$

For comparison, adhesion force models in two computer codes, CÆSAR (Hontanon et al., 2000) and SPECTRA (2017), are discussed. The adhesion model in the CÆSAR code is described by Hontanon et al. (2000). The model predicts that the particle–surface adhesive force is proportional to the particle diameter and inversely proportional to the surface roughness. The adhesion force shown by Hontanon et al. (2000) for three values of surface roughness, R:

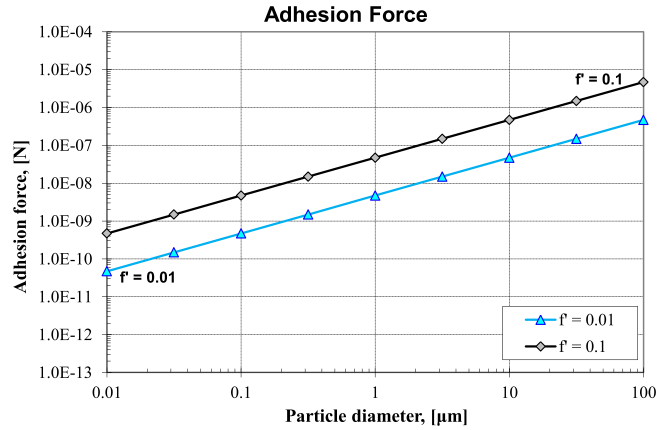

Fig. 1. Adhesive forces defined by reduction factors.

- smooth surface
- $R = 0.5$ μm
- $R = 5$ μm

is reproduced in Fig. 2. Biasi et al. (2001) proposed correlations for f' and σ_a. They observed that the correlation for f' ($f' = 0.016 - 0.0023 \times (D_p/2)$, $D_p < 30$ μm) agrees well with the CÆSAR prediction for a roughness size of $R = 0.07$ μm.

The adhesion model in the SPECTRA code is described in (SPECTRA, 2017). The van der Waals force is calculated in SPECTRA from the following correlation:

$$F_a = \frac{A_1}{R^{x_1}} D_{eff} \quad (3)$$

In the above formula, D_{eff} is the effective particle diameter, [m]; R is the surface roughness [m], while A_1 and x_1 are user-defined constants, with default values equal to $A_1 = 5.0 \times 10^{-10}$, $x_1 = 1.0$. The effective particle diameter is equal to:

$$D_{eff} = \frac{1}{\frac{1}{D_p} + \frac{1}{2r_{as}}} \quad (4)$$

Typically, the particle diameter is much larger than the asperity radius, $D_p, \gg r_{as}$. Therefore $D_{eff}, \approx 2r_{as}$. The reason for using this effective diameter is, as explained by Stempniewicz et al. (2009), that the assumption that $D_p, \gg r_{as}$, may not be applicable for different particle sizes.

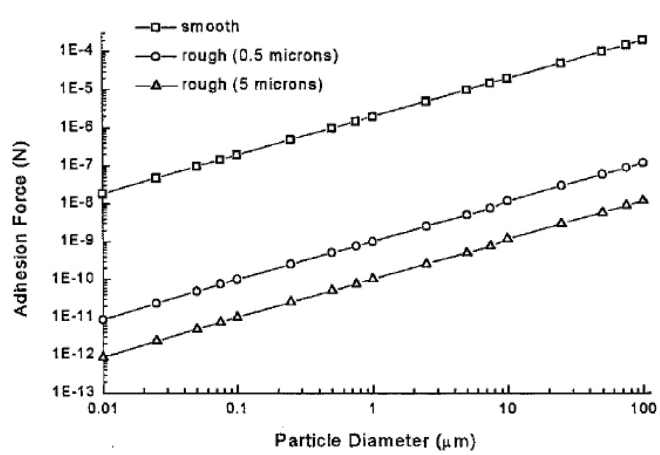

Fig. 2. Adhesive force, CÆSAR code (Hontanon et al., 2000).