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Visualization of airborne nanoparticle deposits onto spherical collectors

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ABSTRACT

Knowing the morphology of deposit onto collectors is a key objective for predicting the performance of a granular bed during clogging. In this study, deposits of nanoparticles onto spherical collectors were visualized with digital microscopes, in predominant Brownian diffusion conditions. An original device using axially magnetized beads was developed to guarantee that the flow rate around the collectors and thus the structure of the nanoparticle deposits was not disrupted by any support. Visualizations of the clogging of a collector line exhibited a homogeneous ellipsoidal deposit all around the beads. The deposit thickness increased linearly irrespective of the bead point, and was maximal at the top and minimal at the contact points. Moreover, microscope viewings of a collector layer during its clogging by nanoparticles were carried out. Results highlighted that the pressure drop increased as a function of the pore closure degree, similarly for all generated agglomerates, and consequently independently of the porosity and the localization of the deposit. These observations were confirmed by theoretical modelling, and suggested that the airflow rate passes mainly through open zones, and not through particle deposits.

1. Introduction

With a view to develop predictive models of granular bed clogging by nanostructured aerosols, i.e. to estimate the temporal evolutions of pressure drop and collection efficiency, the importance of knowing the deposit morphology of particles onto collectors is prime. The single-collector based filtration model was developed for a clean collector and the shape of deposits may modify the internal flow, and consequently affect the performances of the depth filtration process. Despite this, only a few experimental studies have paid attention to visualization of micron-sized particle deposits onto spherical collectors, and none have concerned the deposit of nanoparticles.

Payatakes et al. [1] were among the first group to develop an experimental device for the visualization of deposition and pore clogging in the depth filtration regime. They observed that 2 µm latex particles suspended in a liquid solution were collected mainly on the first one or two layers of the granular bed. Depending on operating conditions, clogging may be characterized by re-entrainment, due to shear stress acting on collected particles, leading to clogging of the narrower pores. On the collector scale, Kusaka et al. [2] observed the formation, and morphology, of deposits of spherical latex particles (1 and 3.6 µm in diameter) on a 0.2 mm-diameter sphere. These deposits were generated in a liquid solution for various flow rates. Visualization results showed that the deposits formed at low velocity were quasi-uniform all over the collector surface, except at the rear face. In contrast, with increasing velocity, deposits with columnar morphology were observed on the collector face front to the flow direction.

From a theoretical point of view, Chang et al. [3] conducted a study to estimate the deposit of 1 µm-diameter particles on a spherical collector with a diameter of 0.1 mm. Their simulations showed the formation of a non-uniform deposit consisting of dendrites. However, this work based on the simulation of particle trajectories only focused on the deposit formation during the first moments of the filtration process. In another study, Chang et al. [4] resolved the particle trajectory equations to simulate the deposit of the same kind of particles in a constricted tube. Their results highlighted the formation of dendrites mainly located at the entrance of this constricted tube, which is comparable to the space between two non-joined spherical collectors. These studies dealt with the collection of micron-sized particles in liquid solutions and the results were consequently difficult to extrapolate to the collection of nanostructured aerosols.

Concerning deposits of airborne particles, Kasper et al. [5] studied the structure and density of monodispersed polystyrene

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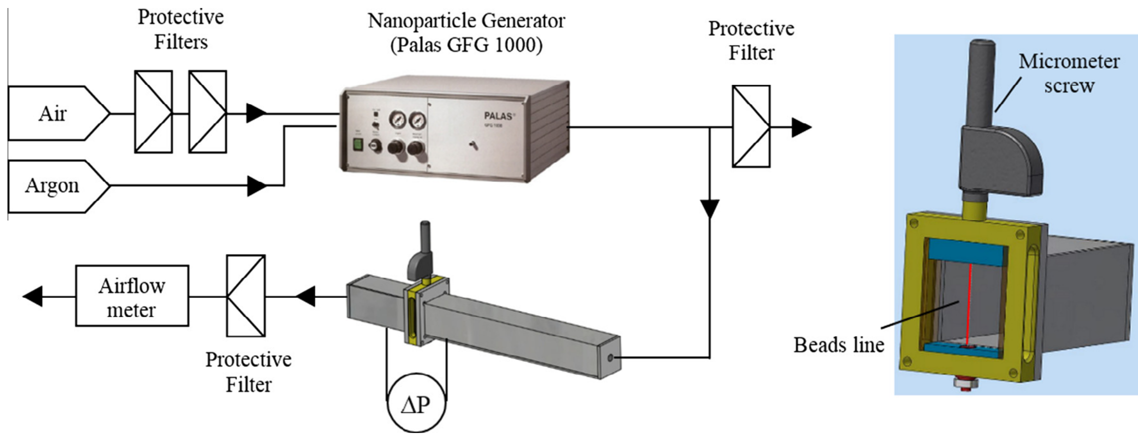

Fig. 1. Experimental set-up for visualization of nanoparticle deposits onto spherical collectors.

micron-sized particles (1.3–5.2 μm), deposited on an individual and isolated stainless steel fiber (8 or 30 μm). This work was not restricted to the early stages of particle deposition, and described the structural changes occurring during the deposition of thousands of particles per millimeter of fiber. The authors observed an upstream facing dendritic growth, and a modification of the deposit density depending on operating conditions (flow velocity, particle diameter and fiber diameter). These observations were consistent with those of Kanaoka et al. [6] who showed that predominant inertia conditions led to compact deposits facing the flow. Furthermore, Kanaoka et al. [6] highlighted that predominant Brownian diffusion conditions induced a homogeneous deposit of particles all around the fiber. Two or three-dimensional numerical studies have also been carried out on the deposit of airborne particles onto fibers [7–11]. These simulations mainly concerned deposit build-up in inertia- and interception-dominated regimes. Elmoe et al. [12] used Langevin dynamics to describe the morphology and time-evolution of a deposit of nanoparticles through a straight capillary. They emphasized that, even if the deposition occurred inside of a capillary, the majority of nanoparticles were collected at the capillary inlet and formed a cake which progressively reduced the capillary surface available for fluid to pass.

As experimental and numerical studies on the deposit morphology of airborne nanoparticles onto spherical collectors are currently unavailable, the aim of this article was to examine the structure of this kind of deposit on both a bead line and a bead layer. Deposit visualization on the bead line will give information about the structure and morphology of nanoparticle deposits on a spherical collector, and on the influence of neighboring collectors. On the layer configuration, specific attention will be paid to the kinetics of nanoparticle deposition. In addition to observation of the growth of a nanoparticle deposit, the pressure drop will be monitored over time to correlate this parameter with the pore surface covered by the deposit.

2. Materials & methods

The experimental set-up was mainly composed of a square channel (60 × 60 × 1000 mm) within which a line or a layer of spherical collectors was placed (cf. Fig. 1).

These collectors were exposed to nanostructured agglomerates generated by evaporation/condensation with a Palas® GFG1000 generator, and comprised of primary particles with a mean diameter close to 9, 3, and 2 nm, for graphite, titanium, and iron agglomerates, respectively [13]. The particle number size distributions of graphite, titanium, and iron agglomerates presented respectively a median diameter of 68, 38, and 32 nm (expressed in mobility equivalent diameter) with a geometric standard deviation close to 1.55, whatever the agglomerate material (cf. Fig. 2).

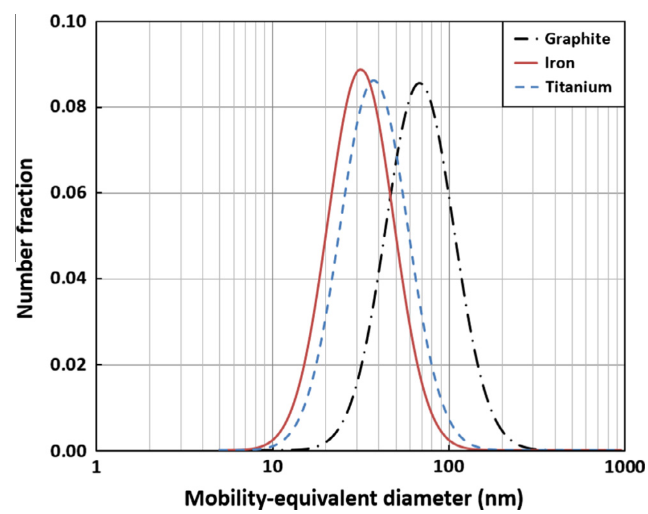

Fig. 2. Particle size distributions of the three agglomerates generated.

The bead line was composed of 60 Neodymium (NdFeB) 1 mm-diameter balls axially magnetized with double Nickel coating (Ni/Cu/Ni). A micrometer screw allowed the line to be tightened to its maximum and to ensure that the beads were joined. This set-up, inspired by that of Kasper et al. [14] (implemented for the observation of deposits onto fibers), was developed for the visualization of nanoparticle deposits onto a spherical collector with two adjacent collectors. The device can support not only a line, but also a layer made up of the same magnetic beads placed side by side to form a rectangle (22 × 17 mm) with a porosity of 0.476 (for this regular square arrangement). This configuration allowed us to observe the growth of nanoparticle deposits in the space between four beads, and to register the evolution of the pressure drop. Using magnetic beads allowed us to ensure that the flow-rate around the collectors, and thus the structure of the nanoparticle deposit was not disrupted by any support.

The deposition of nanoparticles onto spherical collectors is visualized with two different digital microscopes (Dino-Lite®). A magnification of 470 was used for the observation of the deposits onto the bead line. For the layer configuration, magnifications of 25 and 470 were used, respectively, for visualizations of nanoparticle deposits on almost the whole layer (corresponding to the black frame of Fig. 3) and on 9 different spaces distributed across the layer (blue frames[1]).

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.