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Multi-staged granular beds applied to the filtration of ultrafine particles: An optimization of collector diameters

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ABSTRACT

Granular beds exhibit interesting performances, in terms of ultrafine particle collection efficiency, hot gas cleaning, low cost and robustness. Nevertheless, some authors highlighted that ultrafine particle deposit is essentially located in the first layers of the granular bed. Thus, only a small depth is useful thereby reducing both the operation time between two uncloggings and the process yield. Our improvement approach consists in reducing the pressure drop increase while maintaining high collection efficiency by using a granular bed presenting a collector diameter gradient. Performances of this improved granular bed and of a conventional one were compared during their clogging with particles generated by thermal spraying. Since the collection efficiency is a decreasing function of the collector size, this improved configuration permits to firstly clog the downstream layers of the granular bed. Although there is a 20% decrease of the initial efficiency for this new type of bed compared to the conventional one, this gap is rapidly reduced during the clogging process. At the same time, the results highlight a lower pressure drop increase of the modified granular bed. A predictive clogging model was also developed in order to find an optimized configuration of collector diameter gradient to ensure a contribution of the whole granular bed depth.

1. Introduction

A large amount of ultrafine particles are generated by manufacturing processes such as surface processing (thermal spraying), machining (drilling, grinding…), combustion, welding and cutting of metals, … The development of suitable protection systems therefore appears crucial in order to protect the persons and the environment. The most efficient and widely used de-dusting methods for separating the particles from a carrier fluid are currently pleated fiber filters. These fibrous media are initially very efficient but generate a strong increase in pressure drop because of a quick and sometimes irreversible clogging as well as an extra cost resulting from their replacement. Following these observations, we propose to investigate the potential of other methods that could be applied to ultrafine particle collection. Among them, granular beds exhibit interesting performances, as far as ultrafine particle collection efficiency is concerned, and a higher resistance to mechanical and thermal stresses comparatively to fibrous filters. Moreover, another advantage of granular bed filters is their cleanability and reusability in opposition to the difficulty of unclogging the particles deposited on fibrous filters. This specificity is even more important because the reusability of the granules reduces the variability of pressure drop and collection efficiency in research investigations and of process performances in industrial applications.

Aerosol collection in granular beds has been the subject of many theoretical and experimental studies since 1970 and a thorough review of those can be found in Tien's book [1]. Experimental studies focused mainly on the overall performances (pressure drop and collection efficiency) of a granular filter by changing the filter construction parameters, superficial gas velocity [2], temperature [3], bed depth and porosity, granular collector characteristics [4], …

Results highlight that an optimization of the granular bed parameters (collector diameter, granular bed thickness, face velocity of the effluent, magnetic stabilization, etc.) could bring this technique to become a viable filtration method for ultrafine particles. However, all of these studies were limited to the characterization of granular beds in their initial state and the evolution of their performances during the particle loading, i.e. during the accumulation of particles within the bed, is much less examined. Moreover, these studies were dedicated to the performances of granular beds towards micronic and submicronic particles and consequently results do not guarantee the performances of such granular bed filters towards ultrafine particles, nanostructured or not.

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Furthermore, Bémer et al. [5] showed that ultrafine particle deposit is essentially located in the first layers of a granular bed. Thus, only a small depth is useful thereby reducing both operation time of granular beds between two uncloggings and the process yield. In order to optimize the performance of granular beds, Thivel et al. [6] emphasized that it may be interesting to use a magnetically stabilized bed because it combines high dust collection efficiencies with a reduced energy cost. In more recent studies, special attention has been devoted to the regeneration of the filter granules. In this way, moving granular bed filters, in countercurrent [7,8] or cross-currents configurations [9–11] use a continuous flow of fresh collectors to limit the formation of a filtration cake and maintain a low and constant pressure drop, without the need for a periodic unclogging. However, moving granular beds have some drawbacks related to the transport of collectors and present a lower collection efficiency as dust cake is continuously re-entrained. Moreover, operating principle of panel beds is somewhat different and based on a periodic renewal of the granular bed surface. Hence, these panel beds mimic fabric filters by taking advantage of the high collection efficiency of a particle cake. To decrease the pressure drop, a cyclical offline puff-back induces the fall of this filtration cake and of the first layers of collectors which are replaced with fresh ones [12–15].

Our optimization approach is quite different and consists in increasing the time between two unclogging operations by reducing the pressure drop increase while maintaining a high collection efficiency. Tian et al. [16] applied this approach, using a dual-layer granular bed for the filtration of micron-sized ash particles. Nevertheless, the very thick, and consequently very efficient, upper stage implemented in this study reduces the interest of the lower stage. Indeed, during the clogging, the deposit is mainly located in the first layers of collectors which render the remaining thickness of the upper stage unnecessary. With this in mind, a granular bed with a gradient of collector sizes was proposed. From a theoretical standpoint, as the collection efficiency is a decreasing function of the collector size in a diffusional regime, a granular bed with decreasing collector sizes in the depth should permit to firstly clog the lower stages of the granular bed and consequently delay the pressure drop increase (cf. Fig. 1). To limit the experimental constraints, we chose to study the simplest "gradient" granular bed, consisting in only three stages. Each stage is composed of beads satisfying the condition that a given stage must be filled with smaller beads than those of the previous upper stage. Moreover, it was decided to limit the thickness of each stage given that only the first layers of collectors are effective in a conventional granular bed, i.e. a granular bed composed of beads with given diameter.

2. Experimental approach

Experiments were achieved using a three-stage 40 mm-diameter column filled with stainless steel beads. The performances of a multi-staged granular bed composed of 1 mm-diameter beads in the first stage, 0.8 mm in the second and 0.5 mm in the third were compared to those of a conventional one, i.e. a granular bed with bead diameter of 0.5 mm in the three stages. For the reasons mentioned above, the depth of each granular bed stage was chosen to approximately 11 mm. To ensure that the porosity was as close as possible to the one of a random close packing of spheres, the granular beds in each stage were packed by applying vibrations until reaching a relative gap lower than 5% between the experimental pressure drop and the one predicted by the Kozeny-Carman's law. Static differential pressure sensors were mounted upstream and downstream of each stage allowing the monitoring of the pressure drop evolution during the clogging.

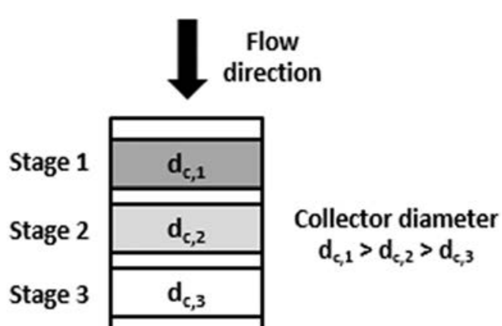

Fig. 1. Schematic view of the multi-staged granular bed.

The particles, composed of 85% of zinc and 15% of aluminium, were generated by thermal spraying of metal using an electric arc gun (Margarido® M25). These particles were then directed towards a sharp cut cyclone (BGI® SCC 1.829) to collect the micron-sized fraction of the produced aerosol and clog the granular bed only with the fine fraction. The particle size distribution of the resulting particles of Zn—Al was measured with a Scanning Mobility Particle Sizer (SMPS 5.400 Grimm®) and presented a median number diameter, expressed in equivalent electric mobility, of 78.3 nm with a geometric standard deviation of 1.6. The total number concentration was approximately 2.10^8 particles/cm^3. The total mass concentration, measured by a gravimetric method after sampling on glass fiber filters, was close to 72.5 mg/m^3. The air flowrate was controlled by a sonic nozzle and measured by a mass flowmeter (TSI® 4100). It was set to 15 L/min corresponding to a superficial velocity of 0.2 m/s.

The particle number size distributions were measured upstream and downstream of each stage using a Nanoscan analyzer (SMPS Model 3910, TSI®) after a dilution stage (VKL100, Palas®). These sequential measurements, called cycles, consisted of three scans of 1 min upstream of each stage followed by three scans downstream. The three scans of a same sampling cycle were averaged to obtain the mean upstream and downstream fractional number concentrations ($C_{n,i}$) which were converted according to Eq. 1 into fractional mass concentrations ($C_{m,i}$). It was therefore possible to obtain the fractional mass collection efficiencies and finally the total mass collected at each time step for each stage.

$$C_{m,i} = \frac{\pi \cdot \rho_P}{6} \cdot C_{n,i} \cdot d_{V,i}^3 = \frac{\pi \cdot \rho_{e,i}}{6} \cdot C_{n,i} \cdot d_{m,i}^3 \tag{1}$$

$$\rho_{e,i} = 40.24 \cdot d_{m,i}^{-0.91} \tag{2}$$

where ρ_p is the density of the raw material (5740 kg/m^3 for the Zn—Al), $d_{v,i}$ the volume equivalent diameter, $d_{m,i}$ the electric mobility equivalent diameter, $C_{n,i}$ the measured fractional number concentration and $\rho_{e,i}$ the effective density of the Zn—Al agglomerates. The effective density, defined as the ratio of agglomerate mass to equivalent mobility volume, allows converting the volume equivalent diameter into an electric mobility equivalent diameter and consequently calculating the fractional mass concentrations. It should be noted that in the Eq. 2, providing the relationship between the effective density of the agglomerates and the electric mobility equivalent diameter, the diameter is expressed in nm and the effective density in g/cm^3 [17]. Furthermore, this equation is only applicable for electric mobility equivalent diameters higher than the diameter of the primary particles constituting the agglomerates, i.e. 9 nm for Zn—Al primary particles; otherwise the effective density will become higher than the raw particle material.

The performances of the two configurations were compared in terms of global mass efficiency and pressure drop as function of the collected mass (cf. Fig. 2). As collection efficiency is a decreasing function of the collector size, the results show a lower initial efficiency for the multi-staged granular bed compared to the conventional one. But, this gap is rapidly reduced during the clogging process. At the same time, a lower pressure drop increase of the multi-staged granular bed is shown by the results. Indeed, the pressure drop is quite three times lower than the one of the conventional bed when the total mass efficiency reaches a value close to unity.

The bar chart representing the mass collected according to time and stage confirms that the deposition in a conventional granular bed