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Technical note

Filtration and loading characteristics of granular bed filters

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ABSTRACT

The purpose of this study was to investigate the filtration and loading characteristics of granular bed filters. Stainless steel holders (diameter 71.6 mm, height 70 mm) were fabricated to accommodate 500 g of zirconium oxide (ZrO_2) beads, as the packed media of granular bed. Monodisperse ZrO_2 granules (0.3, 0.8, 2 and 4 mm in diameter) were used to demonstrate the effect of the granule size and packing geometry on both pressure drop and aerosol penetration. From the filter quality perspective, the selection of the 'best" filter is complicated. Assuming a low face velocity (e.g., 0.58 cm/s), large granule size is more cost-effective because of the higher filter quality factor. The phenomenon implies that the gain in filtration efficiency due to larger surface area (of small granules in the filter) did not compensate for the increase in air resistance. After the cake formation point, the dust cake on glass fiber filter became compressed. This dust cake compaction caused the pressure to drop precipitously and intermittently. In contrast, the rate of increase in pressure drop of the dust cake formed on the granular bed filters decreased with time probably due to the pinhole channels in the increasing mass load. The size and density of the pinholes are determined by the granule size, the face velocity and the size of the challenge aerosols.

1. Introduction

Air filters are commonly used to remove liquid or aerosol particles, from gases. Fibrous filters, made of soft pads of fibers, have long been used for protection against airborne contaminants, and are popular because of their high porosity (up to 99%), and consequent low air resistance. Fiber sizes normally range from less than 1 μm to several hundred micrometers. Investigations on aerosol filtration of fibrous filters have been extensive (Brown, 1993; Hinds, 1999; Lee, 2001; Spurny, 1998) and are too numerous to cite individually. Classical filtration theory begins with an isolated fiber, and the collection efficiency of a fiber is defined as the ratio of the inlet height of the limiting particle trajectory to the fiber diameter. Modern single fiber theory takes into account the effect of adjacent fibers. The theoretical aerosol penetration of a particle through a filter is normally expressed in terms of total single fiber efficiency. The aerosol filtration mechanisms will be briefly discussed below.

In addition to fibrous filters, other types of filters include fabric filters, membrane filters and granular bed filters. Fabric filters, made from textile fibers which are processed into a relatively compacted form by weaving or felting, are integral to some of the most popular air pollution control devices in a variety of industries today. Membrane filters are made of perforated material or highly compacted fibrous material. The porosity of a membrane filter is normally lower than 85%,

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and can be in the range of 5–10% for the straight-through pore membrane filters. Granular bed filters are frequently used to remove both particulate and gaseous pollutants, simultaneously (Tien, 1989). The possibilities of using granular bed filters at high temperatures and pressures make this filter type especially attractive when specialized applications are needed. The aerosol penetration through porous granular bed filter under cyclic flow was found to be a function of particle size (Gebhart & Heyder, 1985).

Unlike broad porosity range of fibrous filter and low porosity of membrane filter, granular bed filters are quite constant in porosity, especially when the granule size is monodisperse. Another advantage of granular bed filters is their cleanability and reusability, which make them ideal for scientific investigations of the effect of collector size on the aerosol penetration, pressure drop across filter media, and filter quality factors. The reusability of the granules reduces their variability and leads to good quality experimental data. The principal goals of this work were to study the filtration and loading characteristics of granular bed filters, and to examine the relationship between the pressure drop across the filters, during the dusk cake and pinhole formation.

2. Filtration mechanisms

Similar to single fiber theory applied in fibrous filter (Hinds, 1999), classical filtration theory of granular bed filter begins with a collector (sphere). The single collector (sphere in this work) efficiency is defined as the ratio of the number of aerosol particles captured by a single collector to the number of aerosol particles flowing toward the collector in a circular tube of cross-sectional area (Gutfinger & Tardos, 1979; Tardos, 1997). The total efficiency is an exponential function of the filter thickness and can be expressed by the equation (Gal, Tardos, & Pfeffer, 1985; Schmidt, Gieseke, Gelfand, Lugar, & Frulong, 1978):

$$\eta = 1 - \exp\left[-1.875(1-\varepsilon)\left(\frac{L}{D_b}\right)E_t\right]$$

where ε is the porosity of the granular bed filter; L the thickness of the filter; D_b the collector size; E_t the total single collector efficiency and can be expressed as:

$$E_t = 1 - (1 - E_R)(1 - E_D)(1 - E_G)(1 - E_I)$$

where E_R is due to interception and E_D due to diffusion (Pfeffer, Tardos, & Pismen, 1981; Tardos, Gutfinger, & Abuaf, 1976); E_I due to impaction (Gal et al., 1985; Gutfinger & Tardos, 1979); E_G due to gravitational settling (Tardos & Pfeffer, 1980).

The above equation (calculating E_t) is an approximation based on the assumptions that the electrostatic attraction does not present, and all individual filtration mechanisms are independent. It is assumed that the interaction terms between the individual mechanisms are not within the scope of the present study. A spreadsheet (Microsoft Excel) was used to calculate and integrate the filtration efficiency by each individual filtration mechanism. The in-depth information of all individual filtration mechanisms has been summarized previously (Tardos, 1997) and is not reiterated here.

3. Materials & methods

Stainless steel holders (inner diameter 61 mm, height 70 mm) were fabricated to accommodate 500-g zirconium oxide (ZrO_2) beads of different sizes (0.3, 0.8, 2 and 4 mm in diameter), as the packed media of granular bed filter. The schematic diagram of the test system is shown in Fig. 1. The test chamber was made of Plexiglas and operated at room temperature. The basic granular bed properties and operation parameters are listed in Table 1.

Potassium sodium tartrate (PST) was used as the challenge aerosol for penetration tests. Monodisperse 10-μm acrylic powder was used for aerosol loading experiments for its' spherical geometry, smooth surface, uniform size, rigidness, and low cost. For the aerosol penetration test, a constant output nebulizer (model 3075, TSI Inc., St. Paul., MN, USA) and an ultrasonic atomizing nozzle (model 8700-120, Sonotek Inc., Highland, NY, US) were used to generate submicrometer-sized and micrometer-sized PST particles, respectively. Penetration test was done at the initial stage of the experiment when change in pressure drop was still negligible, in order to avoid aerosol loading effects. For the aerosol loading test, a dust feeder (RGB 1000, Palas Gmbh, Karlsruhe, Germany) was used to generate monodisperse 10-μm acrylic powder.

In order to avoid a particle charge effect, the particles were passed through a 25-mCi Am-241 radioactive source to neutralize the aerosol particles to the Boltzmann charge equilibrium. The aerosol output was then dried and diluted by aerosol-free air flow of 100 L/min. The size distributions and number concentrations upstream and downstream of the granular bed filter were measured using a scanning mobility particle sizer (SMPS, model 3934, TSI Inc.) and an aerodynamic particle sizer (APS, model 3321, TSI Inc.). The SMPS measured particles smaller than 0.7 μm, while the APS measured particles larger than 0.7 μm. Monodisperse acrylic powders (ten sizes, ranging from 0.15 to 10 μm) were used to check and calibrate size channel of these two instruments. Face velocities from 0.58 to 14.6 cm/s were used to study the flow dependency. All the filtration tests were repeated 5 times. The pressure drop across the filter was monitored by using a pressure transducer, which was calibrated against an inclined manometer. A fibrous filter (Grade 653, Whatman International Ltd., Maidstone, England) was used in loading test to demonstrate different loading characteristics.

A best-performing filter not only removes aerosol particles but also induces the least air resistance. Therefore, it is essential to use the "filter quality factor" (q_f), an indicator combining the measurements of penetration rate (P) and