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Particle filtration characteristics of typical packing granular filters used in hot gas clean-up

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ABSTRACT

Granular filter is a promising method in hot gas clean-up for advanced coal gasification technologies. Numerical simulations were performed in this paper for the particle filtration characteristics of granular filters with two typical packings: body centered cubic (BCC) and face centered cubic (FCC) packings. Fluid flow characteristics were investigated and pressure drop correlations for the two granular packings were obtained. The pressure drop of both packings increases linearly with the increase of velocity, and the pressure drop of the FCC packing is significantly higher than that of BCC. The discrete phase model (DPM) was employed to trace fly ash particle motion during the filtration process, and particle deposition characteristics on the granular surface, including the particle penetration, deposition distribution of different particle sizes, and deposition distribution along filter layers were determined. The deposition fraction of particles on each layer of granules decreases with the increase of row number, and the maximum deposition location is different for BCC and FCC packings. Large particles mainly deposit on the first four layers of granules, while small particles deposit over all layers. The collection efficiency of BCC and FCC packings increases with the increase of velocity, and they decrease first and then increase with particle diameter. Correlations of collection efficiency for the two granular packings are presented and they have good prediction accuracy.

1. Introduction

Hot gas clean-up plays an important role in the integrated gasification combined cycle (IGCC) and advanced pressurized fluidized bed combustion (PFBC) technologies, which promise electricity generation with substantially greater thermodynamic efficiencies and less impact on the environment [1]. Since the high temperature flue gas usually contains fly ash and dust, which can cause the fouling in heat exchangers and downstream systems, significant efficiency deterioration and system failure can result with significant economic consequence [2–4]. Hot gas clean-up is therefore necessary to ensure safe, economic and stable operation of the system and equipment.

The ceramic candle filters and granular bed filters are the two of the most promising methods in hot gas clean-up for advanced coal gasification technologies [5,6]. However the ceramic filters usually can be blocked by particles, leading to a sharp increase in pressure drop and the effectiveness of the equipment [7]. Granular bed filters can be more attractive because of their low cost and low pressure drop. Because of the advantages of granular bed filters, they are used in bio-oil production [8], water and waste-water treatment [9]. They are especially useful in filtration of hot exhaust gases containing fly ash particles and corrosive components in thermal power plants where other filters cannot be used.

The granular bed filters can be divided into three types: fixed bed, fluidized bed and moving bed. The fixed bed granular filter has high filtration efficiency, even up to 99%, however it must be stopped periodically for cleaning. The fluidized bed filter can run continuously without interruption, but it has low efficiency for removing the small particles. The moving granule bed filter can provide continuous operation with high filtration efficiency for small particles, and the pressure drop is small. Xiao et al. [10] have systematically reviewed the basic principles, characteristics and performances of the three type of granular bed filters.

As the flue gas carrying the fly ash particles flows through the granular bed, particles get deposited on the granular surface. The particle deposition process on the granules consists of two steps: transport and attachment, or bouncing. First the particles are transported towards the granular surface by the fluid. It then comes to the attachment or bouncing step, the particle can either deposit or bounce from the granular surface, which depends on the size, shape and material

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properties of the particles and granules. Mechanisms of particle deposition on granular surface include interception, inertial impaction, diffusion, gravitational settling and electrostatic attraction [10]. Diffusional and gravitational effects on the granular filter are significant only for very small particles ($d_p < 1\,\mu m$) at low velocities [11], as for the granular bed with granule diameter $D \geq 1$ mm and fly ash particle diameter $d_p \leq 50\,\mu m$, the inertial separation is generally thought to be the dominating deposition mechanism [8,12].

Owing to the low cost and numerous advantages, the granular bed filter is considered to be one of the most promising hot gas clean-up technologies, and much research has been carried out on the performance of granular bed filters in recent years. The fixed bed is the most common type device for granular filters. Carpinlioglu et al. [13] experimentally studied the pressure drop characteristics of a variety of vertical packed beds in turbulent flow of air, and a simplified correlation for fixed bed pressure drop was conducted. Kuo et al. [14] investigated the filtration and loading characteristics of granular bed filters, and the effects of the granule size and packing geometry on both pressure drop and particle penetration were studied. They also proposed a parameter, the "filter quality factor", $q_f = (-\ln P)/\Delta p$, as an indicator combining the measurements of penetration rate, P, and pressure drop, Δp, to judge the performance of the granular filters. A new kind of dual-layer granular bed filter proposed by Tian and Yang et al. [15] consists of a lower layer of fine granules and an upper layer of coarse granules and can achieve both high filtration efficiency and low bed pressure drop simultaneously. Extensive research has also been conducted on the fluidized bed filter including effects of flow rate [16], bed temperature [17], properties of particles [18], size of granules and particles [19,20] and other factors were investigated. However, the fluidized bed filter has low efficiency at removing the small particles and needs a uniform gas velocity because of its inherent fluctuating flow reduces filtration efficiency [21]. The moving granular bed is more efficient than the fluidized bed in the same situation. Zevenhoven et al. [22] investigated the removal of particles from the flue gas in a coal-fired power plant using a counter flow moving bed granular filter with an electrostatic precipitator and found that collection efficiency can reach 98%. Brown et al. [12] studied the removal performance of a counter flow moving bed filter and found that collection efficiency increased along with the granular flow rate. Chen and Hsiau et al. [23–26] proposed a novel moving bed filters with a series of flow-corrective elements, and the influence of operational parameters on the performance of filters was investigated. They found the optimal efficiency using different filtration superficial velocities and mass flow rates of filter media in the moving granular bed filter.

Existing research mainly focuses on determining empirical formulas for prediction of collection and application. However current experimental methods cannot describe and understand particle motion and deposition mechanisms inside filter. For this purpose, high fidelity computational fluid dynamics (CFD) simulations can be very useful and also can be applied to investigate the effects of a wide range of design options and operating parameters. Mohanty et al. [27] numerically studied flow through randomly packed beds using the discrete element method and CFD. Mathey [28] investigated turbulent flow and heat transfer characteristics inside randomly packed beds. Guan and Gu et al. [29,30] numerically determined ash particle penetration and deposition characteristics on the granular surface of a randomly packed granular filter, and the influences of granular bed depth, gas velocity and granular diameter on the collection efficiency were also determined.

However few experimental or numerical studies have investigated particle deposition distribution characteristics on the granular surface, as well as the particle distribution and filtration rate along bed. In experimentation, the primary difficulty is the limited optical access inside the granular bed.

In this paper, we present a numerical study of the filtration characteristics of two typical filter granular packings, the body centered cubic (BCC) and the face centered cubic (FCC) packing. Fluid flow characteristics of the two granular packings are analyzed, and correlations of pressure drop are obtained. Particle deposition characteristics on the granular surfaces, including particle penetration, deposition distribution of different particle sizes on granular surface, and deposition distribution along different layers are then determined. The effects of velocity and particle diameter on the collection efficiency are investigated, and correlations of collection efficiency for the two granular packings are obtained. Our findings are intended to lay a foundation for future research on the filtration characteristics and engineering of granular filters, and it can be beneficial to the design of high efficiency and low pressure drop granular filters used in hot gas clean-up.

2. Modeling and numerical methods

In this section, the physical and mathematical models of fluid flow and particle deposition on the granules will be first provided. Then the numerical methods and boundary conditions will be presented. Some simplifications and assumptions are considered in present work:

(1) Fluid flow is considered as a three-dimensional, viscous and incompressible turbulent flow.
(2) Fly ash particles are regarded as spheres.
(3) Particle-particle interaction and influence of particles on the flow field are neglected.
(4) The effect of deposited particles on fluid flow and further deposition of particles on granules is neglected.

2.1. Physical model

The granules inside the filter are usually packed randomly (Fig. 1a). The porosity of packing varies from 0.36 to 0.44 according to the density of packing arrangement [31]. It is difficult for the random packed granules to be reproduced, but typical packings can be chosen as simplifications to investigate filtration characteristics of granular filter. Fig. 1b shows the BCC and FCC packings with porosity 0.318 and 0.259 respectively. The BCC packing is the closest to the dense random packing in porosity, while the FCC packing is the densest packing, which can be used as the upper limit of filtration efficiency.

The physical models for granules with BCC and FCC packings are shown in Fig. 2. We consider one volumetric unit of granules because the geometry shows a periodic and symmetric characteristic. This unit volume can be extended to the entire filter by applying periodic boundary conditions on the four surfaces along x- and y- directions. As shown in Fig. 2, both BCC and FCC packings comprise 10 layers of granules. For the BCC packing, the physical model contains five completed granules and 20 quarter granules and for the FCC packing, five complete granules, 20 half granules and 20 quarter granules. The red translucent block region is the main computational domain, and the 10 layers of granules are located at the center. To maintain a uniform inlet

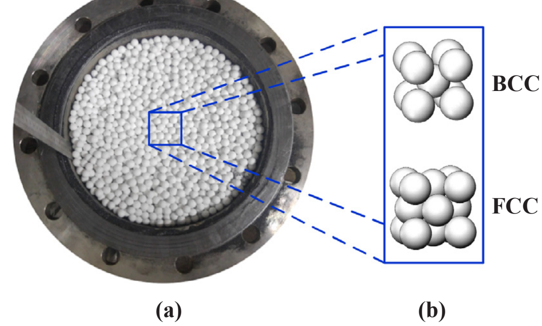

Fig. 1. Granular filters: (a) picture of a granular filter; (b) the BCC and FCC packings.