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Numerical study on the penetration of ash particles in a three-dimensional randomly packed granular filter

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HIGHLIGHTS

- A three-dimensional randomly packed granular filtration model was built.
- Increasing the gas velocity improves the efficiency of greater than 7 μm.
- Increasing the bed depth makes the efficiency reach maximum earlier.
- Granule diameter influences the “turning point one” and “turning point two”.

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ABSTRACT

The purpose of this study is to investigate the influences of granular bed depth, gas velocity and granule diameter on the grade collection efficiency in a three-dimensional randomly packed granular filtration model. The simulation results and experimental results showed the effect of granular bed depth on the overall collection efficiency and pressure drop. It is found the pressure drop approximately linearly correlates with the granular bed depth. Then, the effects of granular bed depth, gas velocity and granule diameter on the grade collection efficiency were studied using simulation method, and the results indicated that increasing the gas velocity could improve the grade collection efficiency of particles greater than 7 μm while it is useless for the particles smaller than 5 μm. Increasing the granular bed depth makes the grade collection efficiency reaches the maximum earlier and it has equal promotion for the particles of all size. The grade collection efficiency is also approximately linearly correlates with the granule diameter and the granule diameter influences the position of the “turning point one” and “turning point two”.

1. Introduction

Dust in high temperature flue gas affects the efficiency and lifetime of heat exchanger and the operation of downstream equipment. Granular filtering is a high-efficiency and environmental-friendly dust removal technology, which is regarded as one of the most promising technology of hot gas clean-up for its advantages of high temperature resistance, high pressure resistance and simple structure [1,2]. Recent researches show that the granular filter gets more attractiveness in integrated gasification combined cycle (IGCC) power generation system based on the combustion and gasification of coal [3,4].

Granular filter has been researched for a long period, and many researchers published their works about it. Typically, Tardos et al. [5] reviewed the theory of granular bed dust filtration and summarized various dust deposition mechanisms, like inertia collection, diffusional deposition. It was concluded that the dust removal efficiency has relation with the granule diameter, dust diameter, granular bed depth and gas velocity. Hsiau et al. [6] and Chou et al. [7] introduced a louver-walled moving granular bed as the simulation object and concluded the influence of louver angle on the granular flow and the internal gas velocity field. Brown et al. [8] evaluated a moving granular bed filter at the high temperature and high pressure, and obtained high collection efficiency of exceeding 99% and low pressure drop without the periodic regeneration of fresh granular filter. Jeon and Jung [9] developed the simulation method on dust cakes composed of monodisperse aerosols into a more complex and general case of cake filtration by using polydisperse aerosols and found that the adhesion and compression forces play crucial roles in the compression behavior of dust cakes. Zhao et al. [10] built their cross-flow moving granular bed model in two-dimension and investigated the optimization of bed depth

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for the system combined hot gas desulfurization and dust removal. Xiao et al. [11] discussed the fixed bed, fluidized bed and moving granular bed and indicated that the fixed bed has the highest collection efficiency. Stanghelle et al. [12] and Wenzel et al. [13] built their own granular bed filter setups and studied the effect of superficial gas velocity, deposited dust and operation time on the pressure drop. Other researchers [14–17] discussed the influence of granular flow rate, particle diameter and aerosol deposition on the performance of the granular filter.

In conclusion, the investigations on the granular filter employed experimental method and simulation method and most of them applied experimental method. Our work mainly depends on the simulation method, since the influence factors including the granular bed depth, gas velocity and granule diameter can be easily and accurately controlled and the grade collection efficiency of particles of all different diameters can be easily measured with the simulation method, and it can build a strong foundation for the further research on the complex structure both experimentally and numerically. Previous simulation works mainly focused on the collection mechanism of single granule and two-dimension filtration model, but its flow field, particle movement and passage boundary are very different from those in the practical operation, which results from that the granule distribution in three-dimension is completely different and the flow passage is more complex than that in two-dimension.

As for the existing problems, the purpose of this paper is to build a rational and effective three-dimensional filtration model and numerically study the effect of granular bed depth, gas velocity and granule diameter on the grade collection efficiency. The granular filter experimental system is built in our work and the rationality of the filtration model is verified from the perspective of overall collection efficiency and pressure drop by comparing the simulation results with the experimental results.

2. Experimental description

The experimental apparatus in this work is shown in Fig. 1. The granular filter was fixed in the middle of a vertical pipe. An air compressor supplied the flow gas. The gas flow rate in the pipe was measured by the rotor flow meter. The dust was added by the aerosol generator. The dust contained gas flowed across the granular filter and part of the dust was collected by the granular filter. The escaped dust was finally collected by the filter cartridge in the downstream of the granular filter. The pressure drop caused by the granular filter was measured by the differential manometer. The mass and particle size distribution of the dust in the filter cartridge were measured by the electronic balance and particle size analyzer respectively.

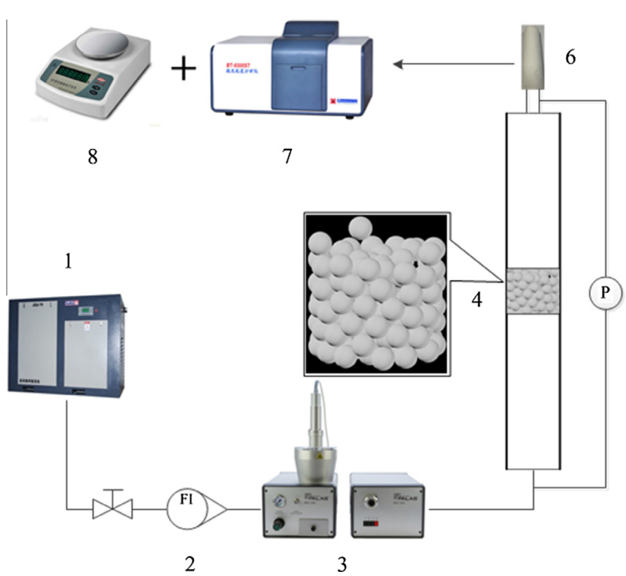

Fig. 1. Diagram of the granular filter experimental system. (1) Air compressor; (2) rotor flow meter; (3) aerosol generator; (4) granular filter and its partial enlargement; (5) differential manometer; (6) filter cartridge; (7) particle size analyzer; (8) electronic balance.

The vertical pipe had an inner diameter of 58 mm and a length of 684 mm. The gas flow rate is $3.281 m^3/h$ with a fluctuation of ±5% and the bulk gas velocity in the pipe is calculated as 0.345 m/s. The granule diameter (marked as "D") is selected as 10 mm. The height of the granular filter is 2D, 4D, 6D, 8D and 10D. The gas density is $1.205 kg/m^3$ and the dynamic viscosity is $1.81 \times 10^{-5} kg/m\,s$. The true density of ash particle is $2100 kg/m^3$ and its mass flow rate is 382 mg/min. The original particle size distribution of the dust entering the granular filter is shown in Fig. 2. In order to combine with simulation, single-trial lasts for five minutes to ensure that the granular filter is clean.

To eliminate the impact of the frictional pressure drop of pipe, the pressure drop of granular filter is obtained by subtracting the pressure drop measured without granular filter in the pipe from the pressure drop measured with granular filter in the pipe. The original particle size distribution of the dust is acquired by measuring the reference sample without granular filter in the pipe. The granular filter is taken out and cleaned after each single-trial to guarantee its cleaning, and the pipe is cleaned by large air flow. The dust is dried for twelve hours to ensure the sufficient dispersion of ash particles.

3. The foundation of filtration model

The cylindrical fixed bed is studied in this work. In order to simulate the removal process, the following assumptions are considered:

(1) Steady state operation conditions are obtained in the whole process.
(2) The gas is continuity, incompressible and isothermal.
(3) The effect of deposited particle on the flow field and the removal of particle in the gas can be neglected due to the short sampling time of five minutes.
(4) The particle is regarded as sphere to deal with.

With these assumptions, the three-dimension model is established based on particulate collecting equations.

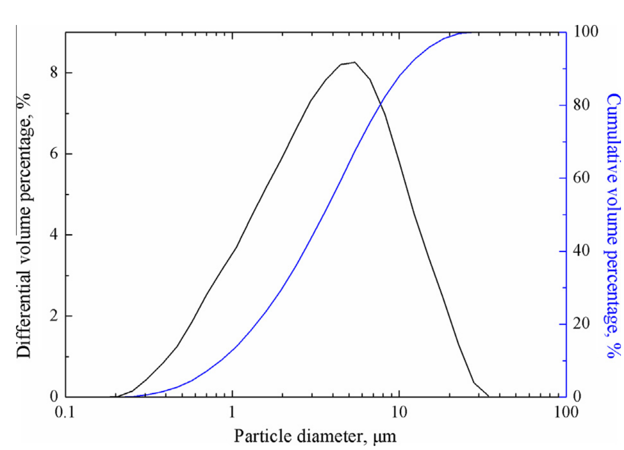

Fig. 2. Original particle size distribution of the ash particle.