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Hot gas clean-up technology of dust particulates with a moving granular bed filter

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HIGHLIGHTS

- A moving granular bed filter (MGBF) was tested in high-temperature environment.
- Filtration superficial velocity affected the removal efficiency of dust.
- Increase of operation temperature resulted in a decrease in collection efficiency.
- Collection efficiency could be promoted by optimizing operation parameters.

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ABSTRACT

The purpose of this study is to investigate the efficiency and stability of moving granular bed filter (MGBF) in high-temperature environment with various operation conditions. Experiments were carried out to study the influence of various parameters, such as test temperature, mass flow rate of filter granules and filtration superficial velocity. The experimental facilities include an air fan, flow ducts, heaters of gas and filter granules, a screw feeder of dust particulates, a measurement system for size distribution of dust particulates, a filter granules supply device, a rotary valve, and a granular bed filter filled with filter granules. The results of this study indicate that this type of method can be useful to applications in different cross-flow filter systems for gas clean-up. From the results, with the conditions of filtration superficial velocities at 0.2 and 0.35 m/s, and the mass flow rate of filter granules at 0.01 kg/s, the better collection efficiency and the smaller-sized distribution of dust particulates were obtained for the case with operating temperature of 20 °C. The experimental results show that an average increase in operation temperature of 100 °C resulted in a decrease in average collection efficiency of 1.74%. The focus in the current study is essentially the development of an MGBF that can be applied in the industrial environment. The results are expected to serve as the basis for future research.

1. Introduction

Gasification concerns the conversion of various combinations of carbon-based feedstock (e.g., coal, heavy refinery residues, petroleum coke, biomass, etc.) into syngas. During gasification, the feedstock is partially combusted with oxidants at high temperature and pressure, so the syngas is primarily a mixture of hydrogen and carbon monoxide, which can be used as a fuel for combustion turbines in advanced coal-based power generation systems, such as Integrated Gasification Combined-Cycle (IGCC) and Pressurized Fluidized-Bed Combustion (PFBC). Advanced coal-based power generation systems consist primarily of a gasification system, heat exchangers for syngas cooling, a station for fuel gas clean-up and a combined-cycle power block with gas turbine, heat recovery steam generator (HRSG) and steam turbine. Coal is a candidate feedstock to be used in IGCC and PFBC systems, which have the potential to improve power plant efficiency, as a way to reduce the cost of electricity, and to exploit technologies for reducing pollutant emissions, with special reference to carbon dioxide capture in both oxygen- and air-blown coal gasification plants. High-temperature dust particulate filtration is a key component in advanced coal-based power generation systems. Though removal of dust particulates from a gas stream can be achieved by using cyclones, electrostatic precipitators, and scrubbers [1], however, these methods are not applicable to hot gas environment.

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The questions should be considered in the dust removal devices, especially for hot gas environment, include emission, reliability and cost. The most promising alternatives seem to be ceramic candle filters and granular bed filters. Ceramic candle filters generally exhibit very high cleaning efficiency; nevertheless, at high temperature the filter elements can suffer from micro-crack formation, due mainly to thermal shock, breaking and mechanical fatigue [2–5]. For the above reasons, researchers have focused their investigation on the development of granular bed filters [6]. Granular bed filters are more attractive because they use low-cost filter media and have a constant pressure drop when the filter is operated as a moving bed [7,8]. Experimental or pilot tests of granular bed filters have been performed under IGCC conditions at the Yubari fluidized-bed test facility by the Coal Mining Research Centre in Japan, as well as in Electrified Filter Bed (EFB) Inc., Air Pollution Technology (APT), Combustion Power Company (CPC) and Siemens-Westinghouse [9]. There are primarily three types of operating processes: fixed bed, moving bed and fluidized bed [10–14]. In cross-flow moving-bed operations, the bed is comprised of a vertical layer or granular material, held in place by retaining grids or louvered walls. Raw syngas passes horizontally through the granular layer, while filter media move downwards and leave the vessel from the bottom of the moving granular bed filter (MGBF).

Most studies focus on the collection efficiency of the granular bed filter. Some of the parameters that determine the collection efficiency are as follows: superficial velocity, mass flow rate of filter media, particle size, pressure drop, operating temperature, and thickness of the dust cake. Peukert and Löffler [15] determined that a lower superficial velocity both improved collection efficiency and decreased pressure drop in the granular bed filter. Much evidence can be found in research studies that dust cake formation is crucial to achieving high collection efficiency for the filter system [16–19]. Kim et al. [20] focused on the effects of various parameters on the particulate filtration, such as the superficial gas velocity, the static bed height, the different particulates collector and distributor. Most of the studies used a particulate generator to produce mono-dispersed particulates (usually about 1 μm) and were operated at normal temperature.

However, the application of hot gas filtration using granular bed filter is rare. General principles of granular bed filters and collection efficiency at high temperature are discussed by Simeone et al. [21]. A specific application of a granular bed filter to remove soot and recover heat from diesel exhausts is reported [8]. Additionally, some simulation models are introduced by several researchers [22–25]. All the models neglect the re-entrainment of the particles from the bed to avoid complexity. However, there are queries about applying these results to really filtrate fly ash in combustion gas, since the chemical compositions, particulate size distribution of the fly ash and operating temperature are quite different for the dust used in those papers. The effect of temperature on filtration efficiency was examined in other studies. Peukert and Löffler [15] found, in their tests with fixed beds, that efficiency fell from 99.97% at room temperature to 98.6% at 800 °C. Chiang et al. [26] found that the removal of fly ash is more efficient at higher operating velocities and fixed-bed heights. Inertial impaction is the main removal mechanism in a fluidized-bed filter operated at room temperature (25 °C). When operated at higher temperature (~200 °C), efficiency of 99.4% can be achieved for submicron particles. It is believed that the diffusion mechanism is responsible for collecting such small particles, and the high temperature is a favorable condition for diffusion. Brown et al. [27] devised experiments based on the similitude theory. At a higher temperature (850 °C), the collection efficiency of the apparatus of the moving bed granular filter was high, typically exceeding 99%, with low pressure drops. The collection behavior and dust properties of the filter system at high temperature were discussed by Heidenreich [28]. This paper presents a detailed survey on hot gas filtration. High filtration temperatures were required to avoid undesirable condensation reaction, which result in the fouling and blocking of filters. Besides, high temperatures place high demands on the properties and the mechanical, thermal and chemical stability of the materials which were occurred. In the higher temperature, the structure and the porosity of the dust cake can change due to the increase of the sticking force of dust particulates. The filtration behavior of filter system was influenced by the thermal properties of the dust particulates.

In addition, in the other pollutants with high temperature filtration processing, sulfur dioxide removal occurring during convective pass sorbent injection with high temperature filtration has been studied [29]. Iron oxide waste material sorbents might also be a viable candidate for the development of low-cost regenerable sorbents for H_2S removal from hot coal gases by Xie et al. [30]. Huang et al. [31] found, SO_2 can be processed to yield sulfuric acid or elemental sulfur as saleable products thereby eliminating stack clean-up costs. Besides, Smid et al. [32,33] presents the study of the flow patterns inside a granular moving bed in a quasi-two-dimensional model of a moving granular bed filter vessel. Stagnant zones were effectively diminished, using flow-corrective insert placed in the filter vessel. The results can be applied to granular bed filters for the removal of dust particulates, acid gas, and alkaline gas in the multiple-stage moving granular bed apparatus [34,35].

Hot gas filtration by MGBF attracts the interest for this study, because a moving bed exhibits potential applications of removing not only particulates but also acid gases in flue gas. Although MGBF has potential to remove particulates at high temperature, the purification of fly ash using MGBF at high temperature was rarely studied. In this study, MGBF is utilized to filter the high-laden fly ash from a coal-fired power plant under the high-temperature conditions of 100, 200, 300, and 400 °C and the superficial filtration velocity of 0.2 and 0.35 m/s, simulating the filtration of fly ash in a real case. The differences among elevated temperatures and room temperature of 20 °C are also compared. The filtration of the fly ash is a dynamic process since the fly ash captured by the filtration media is collected from the bed. Therefore, the variations of the collection efficiency with different operation conditions are measured. The particulate size distribution and the grade collection efficiency of the fly ash are analyzed, since they are the critical parameters of the particle treatment facilities.

2. Theory

2.1. Collection efficiency

The performance of particulate filters is often expressed in terms of particulate collection efficiency η

$$\eta = 1 - \frac{C_{\text{out}}}{C_{\text{in}}}, \tag{1}$$

where C_{in} and C_{out} are the dust concentrations at the inlet and outlet of the granular bed filter, respectively.

2.2. Filter mechanisms of inertial impaction and diffusion

In principle, there are several separate mechanisms which contribute to the filtration efficiency, including inertial impaction, diffusion, gravitational settling, interception, and electrostatic attraction. In this study, the dust particulates follow the curvilinear path of gas motion and tend to move along the gas streamlines until deposited on the filter granules. The collection mechanisms considered include inertial impaction and diffusion.

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