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Clean coal technology for removal dust using moving granular bed filter

Yi-Shun Chen [a, b], Chia-Jen Hsu [a], Shu-San Hsiau [a, b, *], Sheng-Ming Ma [a]

[a] Department of Mechanical Engineering, National Central University, Jhongli City, Taoyuan County, 32001, Taiwan, ROC
[b] Graduate Institute of Energy Engineering, National Central University, Jhongli City, Taoyuan County, 32001, Taiwan, ROC

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ABSTRACT

An international joint research project into advanced hot gas cleaning in high-efficiency coal and solid waste power generation processes using a granular bed filter has been developed. The goal of this study is to evaluate the filtration performance of a moving granular bed with baffle designs. A series of experiments are performed at room temperature to demonstrate the flow patterns of filtration technology (i.e., the moving granular bed filter) under different operational parameters. Pressure drops and collection efficiency are measured as performance indices and analyzed through a series tests. The important parameters taken into consideration include the mass flow rates of filter granules and filtration superficial velocities.

The experimental results show that the best collection efficiency is 99.87%, which is obtained using a baffle, a mass flow rate of the filter media of 600 g/min, and a filtration superficial velocity of 40 cm/s. Furthermore, the test results from this new method can be applied to moving granular bed filters or other filtration systems for a high-temperature environment of industry.

1. Introduction

Coal has many characteristics that allow it to be utilized for multiple purposes including electricity generation, steel production, and conversion to gaseous fuels. Its low cost, abundance, and broad distribution makes it appealing for power production. According to the report of IEA, coal consumption is projected to increase 24% by 2035, compared to 2015. One such technology is that used in advanced coal-fired power generation plants. Among the advanced clean coal technologies for electric power generation, pressurized fluidized bed combustion (PFBC) and integrated gasification-combined cycles (IGCC) are the dominant processes under development.

In IGCC and PFBC systems, particulates must be removed before the raw gas is burned in a gas turbine to protect the turbine blade and control particulate emissions. It is also important to note that the incorporation of high-temperature gas cleanup for optimization of the IGCC and PFBC systems necessitates a process for removing particulates. Hence, to raise the filtration temperature and obtain a higher system efficiency, new filtration technologies and materials must be developed. In order to remove particulates from hot gas, a number of filters have been designed. Filtration systems being developed include ceramic filters, granular bed filters, ESP, dry or wet scrubbers, and various types of barrier filters [1,2].

An international joint research project into advanced hot gas cleaning in high-efficiency coal power generation processes using a ceramic filter has been supported. However, ceramic filters quickly become clogged with collected gas-entrained particulates, resulting in an unacceptable increase in the pressure drop across the filter and requiring a means of cleaning the filter's surface. These have led to concerns over the future exploitation of this technology. In addition, a significant number of ceramic filters have broken in various experimental and demonstration devices, particularly during long-term testing of the candle filter system at the Tidd station. 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. Although beds of granular solids have been employed for many years for the collection of dust, the subject has only recently become prominent as these beds are seen as a possible means of simultaneously removing fly ash and sulfur dioxide from powerhouse flue gases at high temperatures. In granular bed filter systems, the filter medium flows downward

* Corresponding author. Department of Mechanical Engineering, National Central University, Jhongli City, Taoyuan County, 32001, Taiwan, ROC
E-mail address: sshsiau@cc.ncu.edu.tw (S.-S. Hsiau).

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through the bed via a channel with louvers and flow-corrective elements. These elements are placed in such a way as to be very helpful for diminishing the stagnant zones of the filter media along the louvers [3,4]. Such filters are more attractive than conventional technologies because they use low-cost filter media, higher filtration efficiency, and longer operating lifetime when the filter is operated as a moving bed [5]. Some important parameters that determine the performance of a moving granular bed filter include the filtration superficial velocity, mass flow rate of the filter media, filter granules size, dust cake, bed depth, and properties of the gas and dust particulates [6].

Zevenhoven et al. [7] studied the removal of particulates from gas in a coal-fired power plant using a counter-flow moving bed granular filter in conjunction with the use of an electrostatic precipitator for improving collection efficiency. The efficiency of the filter was 98% when operated at 850 °C and 10 bar. A counter-flow arrangement was proposed by Brown et al. [8]. Up to 86% particulate removal in the granular moving bed filter occurs at this design, where a prominent filter cake occasionally forms. In addition, Brown et al. [8] concluded that the collection efficiency increased along with the granular flow rate. In 2007, Bai et al. [9] investigated the performance of a circulating cross-flow moving bed granular filter with conical louvre plates in terms of collection efficiency by varying the mass flow rate and the size of the filter media, as well as the type of dust/collector particles. They reported a maximal collection efficiency of 99.5% when applying a cyclone as the dust/collector particle type. They also reported that the dust collection efficiency was related to the effects of the solid mass flow rate, collector particle size, separator type, and pressure drop. Peukert and Löffler [10] determined that a lower superficial velocity both improved collection efficiency and decreased pressure drop in the granular bed filter. Chen et al. [11,12] found the optimal collection efficiency using different filtration superficial velocities and mass flow rates of filter media in a moving granular bed filter. Both Chen and Hsiau [13] and Lee et al. [14] showed that the buildup of a layer of dust particulates on filtration surfaces, known as dust-cake formation, could improve the collection efficiency by acting as a filter medium of smaller pore size (higher porosity).

Paenpong et al. [15] elucidated the influences of the size and mass flow rate of filter media in a counter-flow moving-bed granular filter. The increase in the filtration stage number was found to decrease the bio-oil yield, while not affecting the filtration efficiency. Guan et al. [16] investigated 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. It is found the pressure drop approximately linearly correlates with the granular bed depth. Pressure drop is a parameter that irrigation engineers must know to properly design and manage filters because it is related to fluid and energy consumption as well as filter efficiency [17]. This study determined that the pressure loss occurs in the filter bed. Several researchers have employed external electric field in granular filtration to enhance the particulate removal efficiency. In this case, the electrostatic attraction effect is likely to increase the collision chance of particles and consequently filtration efficiency [18]. Hsu and Hsiau [19] showed that the better filtration efficiency of up to 98.55% can be obtained by using a baffle length of 170 mm, and a baffle angle of 50°. The experimental results show that the filtration efficiency is enhanced when the gas flow becomes more uniform in the gas inlet.

All of the previous works showed that the gas flow rate, dust cake, and granular mass flow rate influenced the collection efficiency of the moving bed's granular filters. Nevertheless, the effect of the number of filtration stages, which is another important process parameter, upon the performance of a moving bed granular filter is not well understood, especially in the case of a cross-flow device.

In this study, we design a louver-walled apparatus with a series of flow-corrective elements, which is very helpful for diminishing the stagnant zones among the filter granules [20,21]. This is an effective method for removing dust particulates from a dusty gas passing through a moving granular bed filter. Another novel aspect of this work is the development of an inlet baffle device with a filter system that has been practiced. Several parameters are taken into consideration, including uniform gas flow, filtration superficial velocity, and the mass flow rate of the filter granules, in order to understand the performance of the new filter system.

2. Filtration mechanism

2.1. Specific resistance

The overall pressure drop over the filter ΔP_T is the sum of the pressure drop over the filter medium ΔP_F and over the filter cake ΔP_C:

$$\Delta P_T = \Delta P_F + \Delta P_C \tag{1}$$

Using Darcy's law and applying k_1 as the specific resistance of filter medium and k_2 as the specific cake resistance, ΔP_T is defined as follows:

$$\Delta P_T = k_1 V_f + k_2 V_f M \tag{2}$$

where M is the mass of dust cake deposited and V_f is the filtration superficial velocity.

2.2. Collection efficiency

The outlet dust concentration is simultaneously measured by the sampling probe. The performance of the particulate filters is often expressed in terms of particulate collection efficiency, η:

$$\eta = 1 - \frac{C_{out}}{C_{in}}, \tag{3}$$

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

2.3. Collection principle of filter granules

In principle, there are several separate mechanisms which contribute to the collection efficiency, including inertial impaction, diffusion, gravitational settling, interception, and electrostatic attraction. In this study, the collection mechanisms considered include inertial impaction and diffusion. For the granular bed filters, inertial impaction is generally considered to be the most important filtration mechanism. In this study, the Stokes number St is defined as:

$$St = \frac{\rho_p d_p^2 V_f C_m}{9 \mu d_m} \tag{4}$$

where ρ_p is the dust particulate density, d_p is the average dust particulate diameter, C_m is the Cunningham's correction factor for molecular slip, μ is the gas viscosity, d_m is the average filter medium diameter, and V_f is the filtration superficial velocity. Generally, the collection efficiency exceeds 90% for a granular bed filter when