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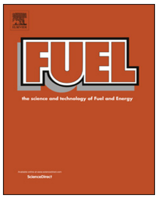

Full Length Article

Real-time particle filtration of granular filters for hot gas clean-up

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ABSTRACT

A real-time filtration model is developed in this paper, and numerical simulations are presented for filtration performance of a randomly packed granular filter. Fluid flow characteristics and filtration performance at the initial state are first investigated. Correlations of initial filtration efficiency and initial pressure drop are obtained with good prediction accuracy. Particle filtration characteristics on the granule surface show that the real-time filtration model can well predict particle deposition and accumulation characteristics on the granule surface. The particle deposition fraction in the filter decreases with filter depth, and for longer filtration time, inhomogeneity appears in the axial deposition fraction. Correlations of filtration efficiency and pressure drop versus time are presented and both are of sufficient accuracy for engineering purposes. The expression of the cleaning time is obtained, which can be used to determine the optimized cleaning time for economic operation of granular filters.

1. Introduction

Integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion (PFBC) technologies are the contemporary advanced coal-based power generation systems, which promise electricity generation with substantially greater thermodynamic efficiencies and less impact on the environment [1]. However fly ash unavoidably exit in the flue gas and cause fouling and erosion in heat exchangers resulting in significant reduction of operating efficiency and possible system failure [2–4]. Therefore hot gas clean-up and high-temperature dust filtration are necessarily key system components to ensure safe, economic and stable operation.

Due to the hot gas environment, cyclones, electrostatic precipitators, and scrubbers are not applicable, and the most promising filtration methods appear to be ceramic candle filters and granular beds [5,6]. At high temperature, ceramic candle filter elements can suffer from micro-crack formation owing to thermal shock, breaking and mechanical fatigue [7–9]. The granular bed filters can be divided into three types: fixed bed, fluidized bed and moving bed, and they can be more attractive because of their low cost of filter media and constant pressure drop when the filter is operated as a moving bed [10,11]. Xiao et al. [12] have systematically reviewed the basic principles, characteristics and performances of the three type of granular bed filters.

Much research has been carried out on the performance of granular filters in recent years. Carpinlioglu et al. [13] experimentally investigated the pressure drop characteristics of a variety of fixed beds in turbulent flow, and a simplified correlation for fixed bed pressure drop was conducted. Kuo et al. [14] investigated the filtration and loading characteristics of granular filters, and the effects of the granule size and packing parameters on both pressure drop and filtration efficiency were investigated. Tian et al. [15] proposed a new kind of dual-layer granular filter, which consists of a lower layer of fine granules and an upper layer of coarse granules, and the results shows it can achieve both high filtration efficiency and low pressure drop simultaneously.

Riefler et al. [16] numerically investigated the particle deposition and detachment processes in a random sphere packing. Guan et al. [17,18] numerically investigated the filtration characteristics in a random packed granular filter, and the effects of granular bed depth, gas velocity and granule diameter on the filtration efficiency were also determined. Much evidence can be found that dust cake formation is crucial to achieving high filtration efficiency for the filter systems [19]. The particles deposit and accumulate on the granule surface to form the dust cake. The dust cake will affect the fluid flow by reducing the cross sectional area of flow and clogging the granular filter, then the pressure drop and filtration efficiency will both increase with the formation of dust cake. Wingert et al. [20] developed a numerical model to predict clogging of a granular bed filter, which can describe the changes to filtration efficiency and pressure drop using equivalent collector diameters. High temperature filtration characteristics of typical packed granular filters were investigated in our previous work [21].

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The filtration process and particle accumulation on granular surfaces usually take hours, and it is unrealistic to simulate them entirely. It is necessary to make an extrapolation by some methods. Tong et al. [22] proposed a time ratio to convert the simulation time to the real time in their numerical study of fouling process on tubes. The authors previously investigated the fouling performance of H-type finned tube heat exchangers and also proposed a magnification fouling time ratio with which the simulation time and results can be enlarged to the real time scale [23,24].

In summary, the granular bed filter is considered to be one of the most promising hot gas clean-up technologies, and much research has been carried on its filtration performance. CFD simulation is a good choice to investigate filtration performance and to determine deposition characteristics inside the filter. However prior numerical work has been focused on initial filtration performance, but the effect of deposit growth on the filtration efficiency and pressure drop have been neglected. Few studies have investigated cleaning time which is important to the economic operation of granular filters.

A real-time filtration model is developed and filtration characteristics of a random packed granular filter is investigated. Fluid flow characteristics are analysed, and correlations of initial filtration efficiency and pressure drop are first obtained. Particle filtration characteristics on the granule surface at different times with different inlet velocities and particle diameters are then determined. Effect of deposit growth on the filtration efficiency and pressure drop are investigated, and the correlations of filtration efficiency and pressure drop with time are obtained. The optimized cleaning time is also obtained, which is beneficial to the economic operation of granular filters.

2. Model description and numerical method

2.1. Physical model

Fig. 1 shows a picture of random packed granular filters. The granules are usually dropped into a bed and form a granular filter, which is considered a loose random packing in which the average porosity of this packing varies from 0.40 to 0.41 [25].

Granular spheres of with 5 mm DIA are loaded into a bed to a height of 30 mm to create the filter (Fig. 1). An elementary volume element with a 25 mm × 25 mm cross section is chosen as the physical model (Fig. 2). The granular layer domain in Fig. 2 is taken to be computational domain, and additional inlet and outlet domains are extended to maintain a uniform inlet velocity and prevent backflow from the outlet. Geometric parameters and simulation conditions investigated in this paper are listed in Table 1.

2.2. Mathematical model

2.2.1. Continuum phase

The governing equations of continuity and momentum for the continuum phase (gas phase) are,

$$\nabla \cdot U = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + \rho U \cdot \nabla U = -\nabla p + \mu \nabla^2 U \tag{2}$$

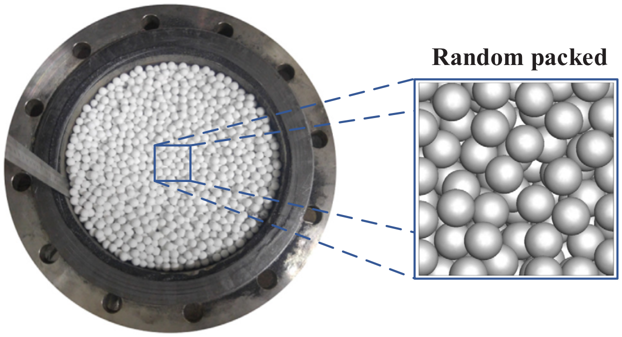

Fig. 1. Random packed granular filters.

The SST k-ω turbulence model is applied to calculate the turbulence flow, and the turbulence kinetic energy k and the specific dissipation rate ω are governed by,

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(U_i \rho k) = \frac{\partial}{\partial x_j}\left(\mu_k \frac{\partial}{\partial x_j} k\right) + \widetilde{P}_k - \beta^* \rho \omega k \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(U_i \rho \omega) = \frac{\partial}{\partial x_j}\left(\mu_\omega \frac{\partial}{\partial x_j} \omega\right) + P_\omega - \beta \rho \omega^2 + 2\rho(1 - F_1)\frac{1}{\omega}\frac{1}{\sigma_{\omega,2}}\frac{\partial}{\partial x_j} k \frac{\partial}{\partial x_j} \omega \tag{4}$$

The effective viscosities are,

$$\mu_k = \mu + \mu_t \frac{1}{\sigma_k} \tag{5}$$

$$\mu_\omega = \mu + \mu_t \frac{1}{\sigma_\omega} \tag{6}$$

where μ_t is the modified turbulent viscosity, and σ_k and σ_ω are diffusion constants of the model. In Eq. (3), P_ω is the rate of production of ω and is given by,

$$P_\omega = \gamma \left[2\rho S_{ij} \cdot S_{ij} - \frac{2}{3}\rho \omega \left(\frac{\partial}{\partial x_j} U_i \right) \delta_{ij} \right] \tag{7}$$

where γ is a model constant and δ_{ij} is the Kronecker delta. Additional detail on the SST k-ω turbulence model can be found in [26–29].

2.2.2. Discrete phase

Fly ash particles in flue gases are the dispersed phase, and a Lagrangian method is employed to predict the motion and trajectories of them. Since the particle size considered here is larger than 1 μm, the drag force is at least one order of magnitude larger than other forces [30]. Therefore, gravitational, thermophoretic, Brownian and other forces on particle are ignored. The force balance on particle is,

$$\frac{du_p}{dt} = F_D(u - u_p) \tag{8}$$

where $F_D(u - u_p)$ is the drag force of the particle, and F_D is,

$$F_D = \frac{3\mu C_D Re_p}{4\rho_p d_p^2} \tag{9}$$

C_D is the non-linear drag coefficient and Re_p is the relative particle Reynolds number,

$$C_D = \begin{cases} \frac{24(1 + 0.15 Re_p^{0.687})}{Re_p}, & Re_p \le 1000 \\ 0.43, & Re_p > 1000 \end{cases} \tag{10}$$

$$Re_p = \frac{\rho \, |u - u_p| \, d_p}{\mu} \tag{11}$$

and u and u_p are the fluid and particle velocity respectively, ρ_p is the particle density, μ is dynamic viscosity of fluid, d_p is the diameter of particle.

2.3. Filtration model

The granular filters investigated in this paper are used in high temperature flue gas clean-up, where the gas temperature is usually 1000 °C or higher. The fly ash particles at such a high temperature are in either the molten or semi-molten state, and particles will be regarded as captured (removed) once they hit the granule surface [17,18].