Parameter study of filtration characteristics of granular filters for hot gas clean-up

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\textbf{A B S T R A C T}

Granular filters are a promising technology in hot gas clean-up for coal-based power generation systems. Numerical simulations are presented for the filtration characteristics of randomly packed granular filters. The effect of filter height is first investigated to obtain a unit height which can predict filtration characteristics of the entire filter, and it is found that the unit height should be at least 10 times the granule diameter. The filtration performance, including filtration efficiency, pressure drop and deposition uniformity are analyzed, and the effect of gas velocity, particle diameter and granule diameter are then investigated. The results show that the pressure drop increases rapidly with the increase of gas velocity and decrease with granule diameter. Increasing the gas velocity and particle diameter leads to increased filtration efficiency and decreased deposition uniformity. The effect of Stokes number on filtration efficiency and deposition uniformity can be divided into three regimes, and filter height and granule diameter need to be optimized according to Stokes number. A correlation of initial filtration efficiency is obtained for use in filter design and structural optimization.

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1. Introduction

With the increasing consumption of fossil energy, the global environmental crisis has become one of the most pressing problems in recent years [1,2]. In coal-based power generation systems, the high temperature flue gas unavoidably contains fly ash and dust which causes fouling and erosion problems in heat exchangers and downstream systems [3–5] resulting in significant loss of efficiency and system failure [6–9]. The development of hot gas clean-up and high-temperature dust filtration is therefore important to ensure safe, economic and stable operation of systems and also to meet environmental emission requirements.

Common particle filtration technologies, such as cyclones, electrostatic precipitators, and scrubbers are not applicable in hot gas clean-up owing to the high temperature environment. Ceramic candle filters and granular bed filters are considered two of the most promising methods in hot gas clean-up [10,11]. However the ceramic candle filter elements can easily suffer from micro-crack formation due to thermal shock and mechanical fatigue [12–14]. Therefore, granular bed filters can be more attractive because they are inexpensive and more stable in high temperature environments. Because of the advantages of granular bed filters, they are widely used in bio-oil production [15], water and waste-water treatment [16–18] in addition to application in coal-based power generation systems. Granular bed filters can be operated in three forms: fixed bed, fluidized bed and moving bed. Xiao et al. [19] have systematically reviewed the basic principles, characteristics and performances of the three type of granular filters.

Filtration efficiency and pressure drop are the two main performance metrics for granular filters. Influence factors on performance include granular packing, granule diameter, filter height, temperature, and operating conditions including gas velocity, the property, size and concentration of fly ash particles.

We previously investigated filtration characteristics of granular filters with two typical packings: body centered cubic (BCC) and face centered cubic (FCC) [20]. The filtration efficiency and pressure drop of FCC packing are significantly larger than that of the BCC packing. Guan et al. [21,22] numerically investigated the filtration characteristics of a random packed granular filter, and the effects of granular bed depth, granule diameter and gas velocity on the filtration efficiency were determined. Kuo et al. [23] experimentally investigated filtration and loading characteristics of granular filters, and the effects of the granular size and packing parameters on both pressure drop and filtration efficiency were investigated. Chen et al. [24] experimentally studied the efficiency and stability of moving granular bed filter in high-temperature environment with various operation conditions. Chen and Li et al. [25] experimentally investigated the heat transfer of gas with coagulative particles flowing through a packed granular bed filter, and two modified correlations are proposed to give the Nusselt number. It was found that reducing the granule diameter can effectively improve...
the filtration efficiency. Tian et al. [26] consequently 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 show it can simultaneously achieve both high filtration efficiency and low pressure drop. Yu et al. [27] experimentally investigated the performance of a fixed granular filter, and proposed a three-layer granular filter, which can improve the filtration efficiency by 3.2% and reduce the pressure drop by 5%. Temperature also affects the performance of the granular filter. Peukert et al. [28] found that the filtration efficiency falls from 99.97% at room temperature to 98.6% at 800 °C.

Much evidence can be found that particles which deposit and accumulate on the granular surface will form a dust cake, and the dust cake growth leads to a gradual increase of pressure drop. Although much research has been carried out on the performance of granular filters, it has been focused on filtration efficiency and pressure drop, and few studies have investigated particle deposition uniformity inside the drop. Peukert et al. [30] developed a numerical model to predict clogging of a granular filter. Peukert et al. [31] experimentally investigated the performance of granular filters, it has been focused on filtration efficiency model [33–35] is employed to describe the effect of turbulence flow. The transport equations for turbulent kinetic energy $k$ and the specific dissipation rate $\omega$ are,

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i} (\rho U_i k) = \frac{\partial}{\partial x_j} \left( \mu_k \frac{\partial k}{\partial x_j} \right) + \rho \omega k - \beta \rho \omega k$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i} (\rho U_i \omega) = \frac{\partial}{\partial x_j} \left( \mu_\omega \frac{\partial \omega}{\partial x_j} \right) + P_{\omega} - \beta \rho \omega^2$$

$$+ 2\rho(1-F_1) \left( \frac{1}{\alpha_1} \frac{\partial}{\partial x_j} \frac{\partial}{\partial x_j} \right) k \cdot \frac{\partial}{\partial x_j} \omega$$

where $\mu_k$ and $\mu_\omega$ are the effective viscosities,

$$\mu_k = \mu + \frac{1}{\alpha_k}$$

$$\mu_\omega = \mu + \frac{1}{\alpha_\omega}$$

$\mu_k$ is the modified turbulent viscosity, $\alpha_k$ and $\alpha_\omega$ are diffusion constants.$ P_{\omega}$ is the rate of production of $\omega$,

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

$\gamma$ is a model constant, and $\delta_{ij}$ is the Kronecker delta.

2. Model description and numerical method

2.1. Discrete filter model

Fig. 1 is a schematic of a randomly packed granular filter. The EDEM software (V 2.6) [32] is applied to generate the granules. Granules with diameter $D$ are loaded into a bed to a height of $L$ to create the filter. An elementary volume element with a $3D \times 3D$ cross section is chosen as the physical model. Owing to periodicity and symmetry, the unit volume can be extended by applying symmetry boundary conditions on the four surfaces along x- and y-directions. To maintain a uniform inlet velocity and prevent backflow from the outlet, the inlet and outlet domains are extended by 4D and 10D respectively. Fly ash particles are loaded at the inlet boundary and leave the domain from the pressure outlet boundary. The filtration characteristics of the filter are then determined with the geometric parameters and simulation conditions listed in Table 1.
Fly ash particles are the disperse phase, and a Lagrangian method is employed to predict their motion and trajectories. The forces acting on fly ash particles in fluids mainly include drag force, gravity, thermophoretic force, Brownian force, Saffman lift, Basset force, etc. The fly ash particle size ranges from 1 to 5 μm in this work (Table 1). According to Ref. [36], the drag force of particles within this size range is at least one order of magnitude larger than the other forces. Therefore, only the drag force is considered when calculating the motion of fly particles in the fluid. The force balance on a particle is,

\[
\frac{du_p}{dt} = F_D(u - u_p)
\]

where \(F_D(u - u_p)\) is the drag force, and \(F_D\) is,

\[
F_D = \frac{3\mu D_C Re_p}{4 \rho_p d_p^2}
\]

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

\[
C_D = \begin{cases} \frac{24(1 + 0.15 Re_p^{0.6})}{Re_p}, & Re_p \leq 1000 \\ \frac{0.43}{Re_p}, & Re_p > 1000 \end{cases}
\]

\[
Re_p = \frac{\rho/u_p d_p}{\mu}
\]

\(u\) and \(u_p\) are the fluid and particle velocity respectively, \(\rho_p\) is the particle density, \(\mu\) is dynamic viscosity of fluid, and \(d_p\) is the diameter of particle.

### 2.3. Filtration model

The mechanisms of particle deposition on the granular surface include interception, inertial impaction, diffusion, gravitational settling and electrostatic attraction [19]. The electrostatic attraction are not considered in this work. The gravitational settling usually dominates for large particles when the gas velocity is <0.01 m/s. In present work, the gas velocity ranges from 0.2 to 1 m/s, and the fly ash particle size ranges from 1 to 5 μm. Thus, the gravitational settling can be ignored in this work. While the effect of diffusion increases slowly as the particle size falls within submicron ranges and is dominated by nano-particles [19], so the diffusion can also be neglected in our work. As for interception, it occurs when the radius of particle exceeds the distance between its trajectory and the granules, and its influence decreases with the increase of clearance size. In this paper, the granule diameter ranges from 1 to 5 mm, and it’s 1000 times larger than that of fly ash particle size, so the interception can also be neglected. It is reported that the inertial separation is generally thought to be the dominating deposition mechanism when the particle diameter \(D > 1\ \text{mm}\), and fly ash particle diameter \(d_p \leq 50\ \mu m [15,37]\). Therefore, only inertial impaction is considered in present work.

Besides, the granular filter investigated in this paper are used for high temperature flue gas clean-up, and it usually works at temperature higher than 1000 °C. In such high temperature, the fly ash particles are in a semi-molten state, and they can be sticky enough and will be captured once they hit the granular surface. Besides, in practical application, regular blowing and cleaning is required for fixed bed granular filters, while for moving bed granular filters it is also necessary to replace the fouled granules with clean ones. Therefore, we mainly focus on the initial stage of the filtration progress and the detachment of deposited particles in the later stage are not considered in present work. Most of the theoretical and simulation works in existing literatures [19,21,22,38] are also based on such simplification, and it leads to satisfactory results.

In our simulation, the particle deposition mass flow rate \(\dot{m}_d\) on the granular surface is recorded at the end of each time step in the solution. The filtration efficiency is defined,

\[
\eta = \frac{\dot{m}_d}{C m_{in}}
\]

where \(C\) is the concentration of injected particles, and \(m_{in}\) and \(S_m\) are inlet velocity and inlet surface area, respectively.

The particle deposition fraction along the filter, \(\varphi\), is monitored,

\[
\varphi = \frac{m_x}{\int_0^L m_{in} dx}
\]

where \(m_x\) is the deposition mass at \(x\) position along the granular filter (\(0 \leq x \leq L\)).

The dust holding capacity is an important performance for a granular filter, which represents the mass of dust retained by the filter until attainment of the specified final pressure drop increase. It is conceived as a test property serving as an indicator of a filter’s service life or service period. The filter with higher dust holding capacity has a longer service life (service period). However, there is no formula for calculating the dust holding capacity. It is easy to understand that, the greater deposition uniformity, the smaller increase of pressure drop caused by deposition of dust of the same quality, so the dust holding capacity will be higher. Therefore, in this paper, the deposition uniformity is employed to evaluate the dust holding capacity of granular filters.

The index, \(\gamma\), is introduced to evaluate the degree of uniformity of the particle deposition characteristics along the filter,

\[
\gamma = 1 - \frac{1}{2n} \sum_{i=1}^{n} \sqrt{\frac{(m_i - \overline{m})^2}{\overline{m}}}
\]

where \(m_i\) is the deposition mass of each observation section (Fig. 2), and \(\overline{m}\) is the average deposition mass for all observation sections. The uniformity index, \(\gamma\), varies from 0 to 1, and a larger \(\gamma\) represents the better uniformity.

### 2.4. Numerical method and boundary conditions

The computational (Fig. 1) includes six boundaries: velocity inlet, pressure outlet, and symmetric boundaries for the four side surfaces. Additional inlet and outlet domains are extended by four and ten times granule diameters, respectively, to maintain a uniform inlet velocity and prevent the backflow from outlet.

![Fig. 2. Schematic representation of the uniformity index.](image-url)
The flue gas components are: N\textsubscript{2} 75.07%, O\textsubscript{2} 5.85%, CO\textsubscript{2} 8.88% and H\textsubscript{2}O 10.2%, which keeps the same with our previous work [31]. A typical high temperature (1000 °C) flue gas from a copper smelting process is selected as the continuum phase, and density and viscosity are calculated according to the volume fraction of each component: \( \rho = 0.27 \text{ kg/m}^3 \) and \( \mu = 4.9 \times 10^{-5} \text{ kg/(m·s)} \). The material of the fly ash particles is regarded as Bi\textsubscript{2}O\textsubscript{3}, which usually exists in the flue gas of both copper and lead smelting processes. The density of fly ash particles is 8900 kg/m\textsuperscript{3}, and the typical particle loading concentration is 2000 mg/m\textsuperscript{3}.

Fly ash particles are loaded at the velocity inlet boundary and leave the simulation domain from the pressure outlet boundary. For the particles hit on the granular surface, they will deposit on the wall and be removed from the computational domain. The discrete phase model (DPM) is used to track particle behavior in the fluid flow. Because the particle mass loading is quite low and the particle size is small (Table 1), the particle-particle interaction and effect of the particles on the fluid flow field are neglected. Thus, one-way coupling is employed for the particle phase with random walk stochastic tracking [39].

The effect of filter height on filtration characteristics is first investigated to obtain a unit height which can well predict the filtration efficiency of a whole filter. After the unit height is obtained, the effect of granule diameter and flue gas velocity are investigated. The pressure drop, filtration efficiency, particle deposition fraction and the deposition uniformity index along the filter are all monitored at each time step.

All simulations are performed with FLUENT (V 18.0) [40]. The filtration model, calculation of particle deposition fraction and the uniformity index along the filter, as well as the monitoring procedure are all written in form of user-defined functions. The SIMPLE algorithm is employed for the velocity-pressure coupling, with a second order upwind discretization scheme for the convective and diffusive terms. It can be regarded as converged when the normalized residuals are <10\textsuperscript{-4} for each governing equation.

### 2.5. Numerical validation

The grid independence validation is first conducted before simulation. The actual point contacts between granules usually leads to the meshing problems and poor mesh quality. So the area contact treatment between granules is applied in this paper, because it is more accurate than the tiny gap treatment and also can maintain mesh quality and economy in the CFD calculations [41]. Fine meshes are applied near the granular surface, while the mesh size in the inlet and outlet zones are properly enlarged to decrease computing time. Additionally, polyhedral meshes have been applied which can reduce the number of grids. For example, the case with a granule diameter of 1 mm and filter height of 10D, different sizes of grid systems are generated. The pressure drop and collection efficiency are calculated for grid independence validation. When changes in pressure drop and collection efficiency are <5% with the increase in grid number, the results are regarded as grid independence, and the final adopted grid number is ~350,000. The same grid size and mesh generation method are applied to other cases with different filter heights and granule diameters to ensure that all cases are grid independent.

A numerical validation of initial pressure drop is conducted for filters with a height of 10D, gas velocity from 0.2 to 1 m/s, and granular diameter from 1 to 5 mm. All simulation conditions and methods are kept the same as Section 2.4. The Ergun equation [42,43], which can be used to determine the pressure drop of packed bed, is employed to compare with the simulation results,

\[
\Delta p = \frac{150 (1 - \varepsilon)^2 \mu U}{\varepsilon^2 D} + 1.75 \frac{1 - \varepsilon \rho U^2}{\varepsilon^2 D}
\]

The comparison is shown in Fig. 3 where the simulations for different cases fit well with the predict results of Ergun equation. The maximum deviation is within 6%, which indicates the reliability of the simulation. Additional validation for different random packing models and filtration efficiency can be found in our previous work [20,31] and are not presented here for brevity.

### 3. Results and discussion

As the pressure drop, filtration efficiency and deposition uniformity are changing with time, and the changing characteristics are related to the gas velocity, particle diameter and the filter structures. It is difficult or even impossible to obtain correlations to well describe the filtration performance of the granular filter in the later stage. In present work, we mainly focus on the initial stage of the granular filter, and investigate each factors on the filtration performance.

#### 3.1. Effect of filter height

The effect of filter height on pressure drop and filtration efficiency is first investigated to obtain a unit height which can predict the filtration characteristics of a whole filter. For \( u_{\text{in}} = 0.2 \text{ m/s} \) and \( d_g = 1 \text{ μm} \), for example, the filtration characteristics with filter heights of 5D - 50D are obtained. Fig. 4 shows the effect of filter height on initial pressure drop.

![Fig. 3. Comparison of initial pressure drop.](image-url)

![Fig. 4. Effect of filter height on initial pressure drop at \( u_{\text{in}} = 0.2 \text{ m/s} \).](image-url)
3.2. Effect of $u_{\text{in}}$ and $D$ on initial pressure drop

For each granule diameter, the initial pressure drop increases linearly with filter height, which means any height can be used as a unit height to predict the pressure drop across the whole filter.

Fig. 5 shows the effect of filter height on the initial filtration efficiency. The efficiency results of filter height $5D$, $10D$ and $20D$ are used to predict the efficiency of other heights according to,

$$\eta = 1 - \left(1 - \eta_0\right)^{L/D}$$

where $\eta_0$ represents the filtration efficiency of a filter with height of $L_0$. It can be seen from Fig. 5 that the initial filtration efficiency increases with filter height, while the growth rate gradually decreases. Filtration efficiency will finally reach a constant value (100%) when the filter height is large enough. We also see that the $5D$ prediction results are higher than the simulation results, while the $10D$ and $20D$ prediction results agree well with the simulation results. Therefore, the unit height should be at least $10D$, and we choose $10D$ as our unit height to predict the pressure drop and filtration efficiency of the filters with different heights.

3.3. Effect of $u_{\text{in}}$ and $D$ on initial pressure drop

The fly ash particle diameter does not affect the initial pressure drop of the granular filters. To investigate the effect of gas velocity $u_{\text{in}}$ and granule diameter $D$ on the initial pressure drop, the filter height is fixed at $10D$ (unit height), and the gas velocity is varied from 0.2 to 1 m/s at 0.2 m/s steps. Fig. 6 shows the effect of gas velocity on the initial pressure drop of filters with different granule diameters. Pressure drop increases with gas velocity and can be explained well according to Eq. (15). With the same filter height and granule diameter, pressure drop increases quadratically with gas velocity. It also can be seen from Fig. 6 that the smaller the granule diameter, the faster the pressure drop grows with gas velocity, and for each gas velocity, pressure drop increases rapidly with a decrease of granule diameter. The smaller the granule diameter, the larger the specific surface area, which leads to a rapid increase in pressure drop.

3.4. Effect of $u_{\text{in}}$, $d_p$ and $D$ on initial filtration efficiency

Figs. 7 and 8 show the effect of gas velocity $u_{\text{in}}$ and particle diameter $d_p$ on the initial filtration efficiency of filters with different granule diameters, respectively. For each particle size (Fig. 7), filtration efficiency increases with gas velocity, and the larger the particles are, the faster it increases. In Fig. 8, we can see that the efficiency also grows rapidly with particle diameter. The similar pattern occurs with different granule diameters, and the smaller the granule diameter, the faster the efficiency grows.

The reason why efficiency increases with gas velocity and particle diameter can be explained appealing to the Stokes number, $Stk$. The Stokes number characterizes the behavior of the particle suspended in the fluid, defined as the ratio of particle inertia to the fluid drag,

$$Stk = \frac{t_0 u_{\text{in}}}{D} = \frac{\rho_D d_p^2 u_{\text{in}}}{9 \mu D}$$

It can be seen that with the same granule diameter, the increase of gas velocity and particle diameter will both lead to the increase of particle’s Stokes number. Particles with larger Stokes number have larger inertia and longer relaxation time $t_0$ (the time constant in the exponential decay of the particle velocity due to drag), which makes them less influenced by the flow. Thus a larger number of particles will tend to impact the granules and thus increase efficiency.

Increasing the granule diameter will also increase the filter height, because the filter height is fixed at $10D$ (unit height). Fig. 9 shows the effect of Stokes number on initial filtration efficiency at the same relative height $L/D = 10$. It can be seen from Fig. 9 that efficiency generally shows an upward trend with Stokes number. There are deviations along the upward trend, and the deviation decreases with an increase of Stokes number.

Fig. 9 can be divided into three particle regimes. Regime I corresponds to particles with $Stk \leq 0.01$. In this regime, the efficiency is relatively low, and the growth trend is slow. This is because the particle Stokes number is small, and the corresponding inertia and relaxation time are also small, which makes the particles easily moved with the
flow with few particles deposited on the granular surface. In the second regime, $0.01 < \text{Stk} < 0.05$, filtration efficiency increases rapidly with Stokes number. Particles with large Stokes number have high inertia and kinetic energy and are more likely to break away from the flow field, leading to a higher deposition rate. In the third regime, the Stokes number is $>0.05$, and the growth trend of efficiency gradually slows down, tending to 100%.

With the same relative filter height, $L/D = 10$, Fig. 10 shows the effect of granule diameter $D$ on initial filtration efficiency in the three regimes. It can be seen that the filtration efficiency for regimes II and III decreases with granule diameter even if the filter height increases. While for regime I, efficiency increases with granule diameter. Therefore, in the application process, when the Stokes number is located in regime II, reducing the granule diameter can significantly increase efficiency and reduce the filter size (height). When the Stokes number is located in regime I, the granule diameter will slightly decrease the efficiency with the same relative filter height. However, for the same filter height, reducing the granule diameter will significantly increase efficiency and pressure drop, and thus optimization is needed. For Stokes number located in regime III, the efficiency is close to 100% and does not change much with the granule diameter. Therefore, in this case appropriately increasing the granule diameter can significantly reduce the pressure drop while ensuring the efficiency does not change much.

### 3.4. Effect of $u_\infty$, $d_p$ and $D$ on particle deposition uniformity

In our previous work [20,31], we found that the particle deposition fraction decreases with filter depth and shows large spatial inhomogeneity. Inhomogeneity of the particle deposition can cause a decrease in dust holding capacity. When the front part of the filter is clogged by the accumulated particles, pressure drop increases significantly, and it is necessary to either shut down the filter system or replace the fouled granules. Therefore, the uniformity of the particle deposition plays an important role in the economic operation of the filter.

The effect of gas velocity $u_\infty$ and particle diameter $d_p$ on deposition uniformity are shown in Fig. 11 and Fig. 12. For larger particles, deposition uniformity decreases with gas velocity, and the larger the particles are, the faster it decreases. While for small particles, e.g., $d_p = 1$ μm, deposition uniformity slightly increases with gas velocity in large granule diameter filters. Larger particles have large inertia, and as gas velocity increases, the Stokes number increases, which makes them more easily deposited in the front part of the filter. Thus deposition uniformity decreases. Small particles are more strongly advected with the flow, and increasing the gas velocity may cause them run farther in filters with large diameter granules, thus the deposition uniformity slightly increases. Deposition uniformity decreases rapidly with particle diameter in different granule diameter filters (Fig. 12).

With the same relative filter height $L/D = 10$, Fig. 13 shows the effect of Stokes number on the deposition uniformity, where the deposition uniformity decreases with Stokes number. The graphs in Fig. 13 also can be divided into three Stokes-number regimes. In regime I, $\text{Stk} < 0.01$, and deposition uniformity does not strongly vary with Stokes number and remains at a high value. In regime II, $0.01 < \text{Stk} < 0.2$,
deposition uniformity decreases rapidly with the increase of Stokes number. When $Stk > 0.2$ (regime III), the downward trend gradually decreases.

To show the inhomogeneous deposition distribution of fly ash particles in the filter, we choose three cases for Stokes numbers in each of the three regimes. The probability density function of particle deposition fraction along the three filters are shown in Fig. 14 wherein the particle deposition fraction decreases with filter depth for all the cases, and the inhomogeneity of deposition become pronounced with larger Stokes number. Fig. 14a shows the case with $Stk = 0.004$ (regime I). Particles deposit along the whole of the filter, and overall deposition uniformity is relatively good with $\gamma = 0.65$. Fig. 14b shows the case with Stokes number located in regime II, where the particle deposition fraction shows a more pronounced peak than in Fig. 14a. For regime III (Fig. 14c), almost all of the particles deposit in the first half part of the filter with the dust holding capacity of the latter half part not utilized.

With the same relative filter height, $L/D = 10$, Fig. 15 shows the effect of granule diameter $D$ on deposition uniformity in the three regimes. Deposition uniformity for all cases increases with granule diameter, which means increasing the granule diameter can significantly increase the deposition uniformity and the dust holding capacity of the filters. Combining the results in Figs. 10 and 15, the efficiency is ~100% for large Stokes number ($Stk > 0.05$), and increasing the granule diameter at the same relative height $L/D$ improves deposition uniformity, reduces pressure drop and ensures that the filtration efficiency does not vary much. For medium and small Stokes number ($Stk < 0.05$) at the same filter height $L$, reducing the granule diameter can significantly increase the filtration efficiency, but it also will decrease deposition uniformity and increase the pressure drop. Thus for filter design purposes, optimization is needed.

4. Multiple correlation

The simulation results for initial filtration efficiency can be represented in compact form via correlation. The Reynolds number, $Re$, Stokes number, $Stk$, and dimensionless diameter, $d_p/D$ are the dimensionless groups used in correlation to describe the effects of gas velocity, particle diameter and granule diameter. Recall that we fixed the filter height at $10D$ (unit height) and have investigated the effect of each factor on the initial efficiency. The correlation form of initial efficiency for the filter with unit height, $L_0$, is assumed to be,

$$
\eta_{L_0} = 1 - \exp \left[ -C_1 - C_2 \cdot Re + C_4 \cdot \left( \frac{d_p}{D} \right) \right] 
$$

The four coefficients $C_1$, $C_2$, $C_3$ and $C_4$ are determined by means of multiple linear regression using the simulation results. The correlation is,

$$
\eta_{L_0} = 1 - \exp \left[ -0.453 - 6.286 \cdot Re - 0.206 \cdot \left( \frac{d_p}{D} \right)^{-1.405} \right] 
$$
5. Conclusions

A numerical investigation has been carried out on the filtration performance of randomly packed granular filters used in hot gas clean-up. Our main conclusions are,

1. A unit filter height of 10 times the granule diameter (10D) can sufficiently well predict the filtration characteristics of the entire filter.

2. Pressure drop increases rapidly with an increase of gas velocity and decrease of granule diameter.

3. Filtration efficiency increases with gas velocity and particle diameter. Reducing the granule diameter increases filtration efficiency at a given filter height.

4. Particle deposition uniformity increases with the decrease of gas velocity and particle diameter. Increasing the granule diameter improves deposition uniformity and consequently increase the dust holding capacity of the filter.

5. The effect of Stokes number on efficiency and deposition uniformity can be divided into three regimes dependent on Stokes number. For medium and small Stokes number (Stk < 0.05), the filter height and granule diameter need to be optimized for design purposes.

6. A correlation of initial filtration efficiency is obtained, and can be useful in the design and structural optimization of granular filters.

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