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Original Research Paper

Structure optimization of granular bed filter for industrial flue gas filtration containing coagulative particles: An experimental and numerical study

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ABSTRACT

A numerical model for the flow and filtration characteristics of industrial flue gas in granular bed filter (GBF) was established and the local filtration efficiency for different granule layers was investigated. Numerical validation results show that the GBF structure with large size granules at the inlet region and small size granules at the outlet region can effectively improve the filtration performance of GBF and the underlying mechanism was revealed. Then an experimental system was built to validate the suitability of the optimized GBF structure for the filtration of industrial flue gas with coagulative particles. The experimental results show that the optimized GBF structure is also suitable and its superiority is more significant with the increase of filtration time. The results show that the pressure drop and filtration efficiency of the experimental system increase with the increase of dust particles concentration. The existing of coagulative particles is conducive to the growth of smaller size dust particles, the pressure drop and filtration efficiency increase significantly. In addition, the pressure drop and filtration efficiency decrease with the increase of cooling rate. The results of this study are expected to be useful for the design and optimization of industrial flue gas purification and waste heat recovery.

1. Introduction

Recently, the problems of energy waste and environmental pollution caused by the emission of a large amount of flue gas in the industrial fields of chemical engineering, building materials and metallurgy have aroused widespread concern, which thus needs to be solved urgently [1–3]. In most cases, some kinds of industrial flue gas have the characteristics of high temperature and high waste heat grade, so it is possible to reduce industrial energy consumption by recovering heat from industrial flue gas through waste heat recovery equipment. However, the composition of industrial flue gas is usually complex, it contains high content of dust particles, coagulative particles, corrosive components and toxic components and so on [4–7]. The deposition of dust particles accompanied by coagulative particles makes the surface of heat exchanger tubes easily clogged, fouled and corroded, which significantly reduces the heat transfer performance and threatens the operation stability of the waste heat recovery system. At the same time, due to the failure of heat exchanger tubes and soot blowing process, additional economic losses are also caused [8–11]. In addition, dust particles contained in the industrial flue gas can easily form inhalable particles in the atmosphere, which leads to a variety of respiratory diseases and thus threatens the survival of human beings and animals [12]. So the purification and recovery of waste heat of industrial flue gas have been widely concerned.

In the past few years, many dust removal technologies, such as dust catcher, pocket dust collector, ceramic dust collector, centrifugal dust separator and wet dust collector, have been widely used for the purification of industrial flue gas under low temperature conditions [13–15]. However, these dust removal technologies are not applicable to the high temperature environment, and it is difficult to achieve the high efficiency and low cost purification target for fine particles. As an example, ceramic filters usually have high filtration efficiency; nevertheless, at high temperatures, the filter element may suffer a lot due to thermal shock, fracture and mechanical fatigue, which lead to the formation of micro cracks [16]. The working principle of the wet dust collector is to cool down the high temperature flue gas, and a large amount of heat energy will be wasted [17].

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Granular bed filter (GBF) is considered as an excellent candidate technology for industrial flue gas purification owing to the numerous advantages, such as high temperature resistance, high pressure and corrosion resistance and low cost. As a promising technology, it has been widely used in the integrated gasification combined cycle (IGCC) and advanced pressurized fluidized bed combustion (PFBC) technologies, which has made GBF become a much more attractive filtration technology [18–20].

Many researchers have studied the filtration and resistance characteristics of GBF experimentally and numerically. Xiao et al. [21] summarized and discussed the characteristics and performances of GBF which can be designed as fixed beds, fluidized beds and moving granular beds and the results showed that the fixed beds had the highest filtration efficiency under the same conditions, and filtration efficiency can even have reached greater than 99%. Guan et al. [22] investigated the influences of granular bed depth, gas velocity and granule diameter on the grade filtration efficiency in a three-dimensional randomly GBF model. The simulation results and experimental results showed the effect of GBF depth on the overall filtration efficiency and pressure drop, the pressure drop approximately linearly correlates with the GBF depth. Chen et al. [23] investigated the characteristics of filtration and resistance of the moving GBF designed to filter out coal-fired dust particles. The results showed that the overall porosity of the filter granules decreased, but the filter resistance and the collection efficiency increased, with an increase in the amount of smaller-sized filter granules in the bed. Brown et al. [24] found that a moving GBF can operate with a high filtration efficiency, typically exceeding 99%, and low pressure drop without the need for periodic regeneration through the use of a continuous flow of a fresh granular filter medium in the filter. Fine particles are mainly filtered through the formation of a dust cake on the surface of the granular layer. Chen et al. [25] experimentally investigated the efficiency and stability of moving GBF in high-temperature environment with various operation conditions. The influence of various parameters, such as flue gas temperature, mass flow rate of filter granules and filtration superficial velocity were studied. The experimental results show that an average increase at 100 °C resulted in a decrease in average filtration efficiency of 1.74%. In our previous work [26], the structural optimization was performed for the fixed GBF and an optimized GBF structure with different granules sizes was designed. The validation results indicate that the designed GBF structure has excellent filtration and fluid flow performance compared with the traditional structure with single granules size. Under the investigated filtration superficial velocity region, the average filtration efficiency is enhanced 3.23% and the pressure drop is reduced 49.94%. However, the above literatures do not consider coagulative particles contained in the industrial flue gas, which means that the above conclusions are not suitable for the flue gas coagulative particles, and it is clearly divorced from industrial reality.

For the industrial flue gas with coagulative particles, available research has been carried out mainly to investigate the flow and heat transfer characteristics of flue gas in GBF. Wen et al. [27] experimentally studied the heat transfer of gas mixed with particles flowing through a packed GBF under the constant wall temperature conditions. Chen et al. [28] carried out an experimental study on the overall heat transfer coefficient of gas with coagulative particles flowing through a packed GBF. It was found that the heat quantity released by the concretion of coagulative particles has an improved influence on the heat transfer when the inlet gas temperature of GBF is above the melting point of the coagulative particles and outlet gas temperature is below the melting point. However, the heat quantity absorbed by the melting of coagulative particles can weaken the heat transfer when both the inlet and outlet gas temperature of GBF are above the melting point of coagulative particles.

From the above literature review, it can be found that although many researchers have studied the influence factors of GBF to improve its filtration performance, most of them are only focused on the industrial flue gas without coagulative particles. Little attention has been paid to the influence of coagulative particles on flow and filtration performance of GBF. Unfortunately, the composition of the industrial flue gas is very complex with both coagulative particles and non-coagulative dust particles. The filtration process of industrial flue gas in GBF is a multiphase transport process, which involves complex heat and mass transfer process including phase transition, agglomeration and adhesion of coagulative particles. That means the existing filtration theory of GBF is far from practical engineering application, especially for the industrial flue gas with coagulative particles.

Therefore, in this paper, the structure optimization was performed for GBF to suit the filtration of industrial flue gas with coagulative particles. An optimized GBF structure was obtained by adjusting the arrangement of granules size, its performance was validated by numerical and experimental methods, and the underlying mechanism of performance optimization is revealed by numerical simulations. The effects of geometric and operating parameters on the performance of the designed GBF were also investigated.

2. Model description and validation

2.1. Physical model

Generally, the granules are placed in a GBF in a free stacking manner in industrial applications. The complex and irregular structures are difficult to describe by conventional numerical methods. Previous studies have shown that the disordered stacking structure can be abstracted into a regular and orderly packing [29], such as simple cubic (SC), face centered cubic (FCC) and body centered cubic (BCC) structures respectively. In order to get closer to the porosity of GBF in the engineering application, the BCC structure is chosen as the physical model of the numerical simulation in the present study as shown in Fig. 1. Based on the above simplification, the geometry shows a periodic and symmetric characteristic, so the volumetric unit of granules can be extended to the whole GBF by applying periodic boundary conditions along x and y directions.

The diameter of the granules is 5 mm; the height of the bed is 30 mm, which consists of 10 layers of granules; the Al_2O_3 granules with different sizes were chosen as filter material with a density of 3.96 g/cm^3 and a melting point of 2054 °C. The diameter of the dust particles is set to 5 μm, 10 μm and 20 μm with a single size distribution. The dust concentration in the flue gas at the inlet is 2.0 g/m^3; flue gas inlet velocity is 0.1–0.5 m/s; flue gas inlet temperature is 600 °C to 1200 °C. The flue gas was regarded as air at high temperature, and its physical properties are determined by temperature. For example, when the temperature was 1000 °C, the density ρ was 0.273 kg/m^3 and dynamic viscosity μ was 5.08×10^{-5} kg/(m·s). The properties of the dust particles are determined from coal dust particles which are taken from a thermal power plant. The particle density is about 2500 kg/m^3. The computational domains for the BCC packing are shown in Fig. 1(c). In order to keep the inlet velocity uniform and prevent the backflow, additional inlet and outlet zones with a length of 35 mm are extended, which are far longer than the granules diameter. Consid-

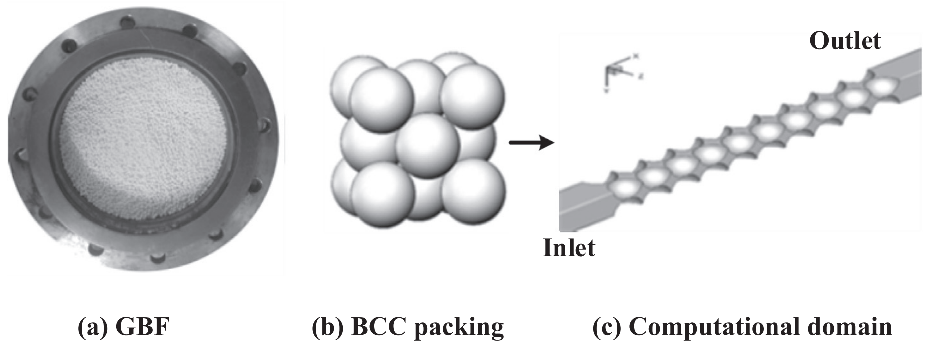

Fig. 1. Physical model.

ering that the granules are contacted as point contacts, it may be difficult to mesh and ensure grid quality in numerical solutions. In some previous studies, keeping a tiny gap or using an area-contact between the granules was used to solve the meshing problem. It is reported that there are no large differences between area-contact and direct contact treatment [29,31]. So the area-contact treatment is used in this study to keep the mesh quality in the CFD calculations.

2.2. Mathematical model

2.2.1. Continuum phase

In the discrete phase model, Euler-Lagrange model is used to describe the movement of gas and solid phases in flue gas flow. The Euler method is used to describe the incompressible flow of gas. To simplify the model, some reasonable assumptions and simplifications are involved as follows:

(1) The flue gas flow is continuous, incompressible, viscous and turbulent flow.
(2) The filter granules are regarded as regular spheres, and the dust particles are regular spherical, and dispersed in the continuous gas phase.
(3) Particle-particle interaction and influence of particles on the flow field are neglected.
(4) The effect of deposited particles on fluid flow and further deposition of particles on granules are neglected.

The governing equations of flue gas as a continuous phase is as follows:

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

$$\frac{\partial(\rho_g u_i)}{\partial t} + \frac{\partial}{\partial x_i}(\rho_g u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_g\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

where ρ_g represents the density of gas, kg/m^3; u_i and u_j are the velocity vectors of gas, m/s; p is the static pressure, Pa. The structure inside the GBF is very complicated, so the gas flow through the GBF is regarded as turbulent flow, and the standard k-ε turbulence model can well meet the requirement of computational accuracy. Besides, the kinetic energy equation and diffusion equation of turbulence are as follows:

$$\frac{\partial(\rho_g k)}{\partial t} + \frac{\partial}{\partial x_i}(\rho_g k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu_g + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k - \rho_g \varepsilon \tag{3}$$

$$\frac{\partial(\rho_g \varepsilon)}{\partial t} + \frac{\partial}{\partial x_i}(\rho_g \varepsilon u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu_g + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho_g\frac{\varepsilon^2}{k} \tag{4}$$

where μ is the turbulent (or eddy) viscosity, kg/m·s;

$$\mu_t = C_\mu \rho_g \frac{k^2}{\varepsilon} \tag{5}$$

moreover, σ_k = 1.0 and σ_ε = 1.3 are the Prandtl number related to the turbulent energy and turbulent dissipation rate respectively; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the Reynolds number constants in the k-ε equations respectively; C_μ is an empirical constant, and C_μ = 1.3, $C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92. μ_t represents the turbulent viscosity, kg/m·s; G_k is the generation term of turbulent energy due to the mean velocity gradients, which is given as:

$$G_k = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{6}$$

2.2.2. Discrete phase

The discrete phase of dust particles is described by Lagrange method, which are often used to determine the force, motion and trajectories of the dust particles. Previous studies have showed that when dust particles size is less than 100 μm, the drag force is considered as the main force affecting its motion [22,29,30]. Therefore, to simplify the calculation, the Brownian and thermophoretic forces are ignored, the influence of drag force, van der Waals force and gravity on particle trajectory is mainly considered in this paper. According to the force balance of dust particles, the equations of motion of the dust particles in the Lagrange coordinate system are established as follows:

$$m\frac{du_p}{dt} = F_{drag} + F_{vdw} - mg \tag{7}$$

$$F_{drag} = \frac{3}{4}C_D\frac{|u_g - u_p|(u_g - u_p)\rho_g(1-\delta)}{d_p}\delta^{-2.7} \tag{8}$$

$$\delta = 1 - \frac{\rho_p^{(s)}}{\rho_p} \tag{9}$$

$$F_{vdW} = A\frac{2}{3r\left[(h/r)^2 - 1\right]} \tag{10}$$

where m represents the particle mass, kg; u_P and g represent the particle velocity, m/s and the gravitational acceleration, m/s^2 respectively; F_{drag} is the drag force, N; F_{vdw} is the van der Waals force, and r is the particle radius, m; A is the Hamaker constant; J. A is selected as 10^{-19} J [21,22]; h is the distance between the center of dust particle to the granule surface. The van der Waals force is negligible when the distance between the particles and the granules surface is beyond the range from 0.4 nm to 50 μm [21–23]. And u_g is the gas velocity, m/s; d_P is the particles diameter, m; η is the local void fraction; $\rho_p^{(s)}$ is apparent density of particles, kg/m^3; ρ_p is true density of particles, kg/ m^3; C_D is drag coefficient, which is given as:

$$C_D = \begin{cases} \frac{24\left(1+0.15Re_p^{0.687}\right)}{Re_p} & Re_p \leqslant 1000 \\ 0.43 & Re_p > 1000 \end{cases} \tag{11}$$

$$Re_p = \frac{\rho_g d_p |u_g - u_p|}{\mu_g} \tag{12}$$

where the Re_p is Reynolds number of dust particles.

2.3. Numerical method and filtration model

The velocity inlet and outflow for outlet boundary conditions are applied in inlet and outlet respectively, and periodic boundaries are applied in other surfaces. Before the simulation of filtration and resistance characteristics is performed, the gas flow is first simulated, the turbulent flow is simulated by using the standard k-ε turbulence model. Previous studies have shown that when granule diameter $D \geq 1$ mm and the dust particle diameter $dp \leq 50$ μm, the inertial separation is generally considered to be the dominating deposition mechanism [24,32]. Therefore, only the mechanism of inertial separation is considered in this study.

The discrete phase model (DPM) is used to track the dust particles and describe their behavior in the gas flow at time steps of 10^{-4} s. The dust particles are injected from the inlet surface into the computation domain at each time step. Owing to the low particles mass and the small particles size, the particle-particle interaction and the effect of the particles on the fluid flow field have little effect on the result of the numerical calculation which thus are neglected. One-way coupling and frequently used random walk stochastic tracking method are applied to the particle phase [29]. Once the particle hits the wall, it is captured by the wall and removed from the flue gas [22,29,33]. The deposition number and deposition mass on the granular surface is recorded by our homemade user-defined functions (UDF) at every time step. In this way, the filtration efficiency is calculated by:

$$\eta = 1 - \frac{m_{out}}{m_{in}} \tag{13}$$

All simulations are performed using FLUENT™ software (V 14.0). The SIMPLEC algorithm is employed for velocity-pressure coupling with a second order upwind discretization scheme for the convective and diffusive terms. When the normalized residuals are less than 10^{-5} for each governing equation, the simulation is regarded as converged. When the stable filtration efficiency is reached, the calculation is completed.

2.4. Model validation

Since the quality and number of the generated grids are important for numerical accuracy, the grid independence is verified before the simulations. GAMBIT software (version 2.4) was used to generate geometric mesh and enhanced wall treatment was applied on the surface of granules. The filtration efficiency of the system is applied to grid independence verification after different sizes of grid systems are generated. Grid independence is assumed when the changes of the filtration efficiency are less than 5% with a decrease in grid size. The verification results show that the final size of independent grids is about 0.3 mm. Fig. 2 shows the simulation results of filtration efficiency under different *Stokes* numbers. It can be seen that the simulation results in this paper are in good agreement with the results of the literature [34], which shows the rationality of the selection of the model and the relative calculation method in the present study.

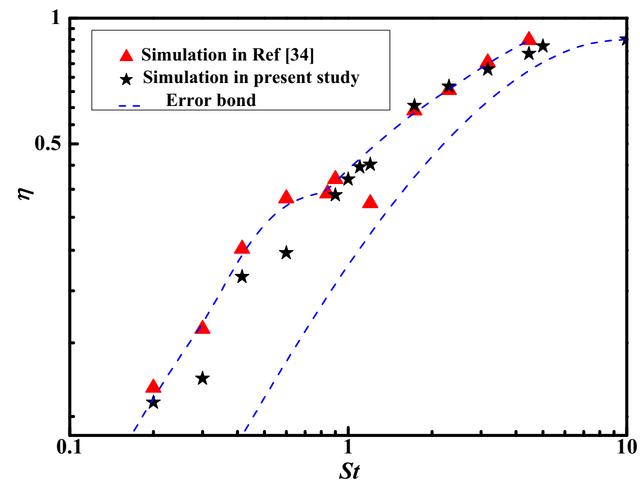

Fig. 2. Simulation model validation.

3. Numerical result and discussion

3.1. Local filtration efficiency based on different granule layers

The local filtration efficiency reflects the number of dust particles deposited on each layer of granules. It is defined as:

$$\phi = \frac{m_i}{\sum_i^N m_i} \tag{14}$$

where m_i is the deposited mass of dust particles on the granules at layer i, and N represents the total number of layers. It is a key parameter for the optimization of GBF. In the numerical simulation, before cake formation, the pressure drop of each layer in the GBF can be calculated by the Ergun formula, which can be written as [35]:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \tag{15}$$

$$\frac{\Delta P_i}{L_i} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U}{D_i^2} + 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_g U^2}{D_i} \tag{16}$$

where ΔP_i represents the pressure drop of each layer i, L_i denotes the bed height of each layer i, ε is the porosity of the GBF, μ represents the dynamic viscosity of the fluid flowing in the GBF; D_i is diameter of the granules of each layer i, and U is the superial velocity of fluid.

Therefore, firstly, numerical studies were performed to investigate the filtration efficiency on different granule layers. The simulation results are shown in Fig. 3. As it can be seen from Fig. 3, the deposition of dust particles with a single granules size of 10 μm mainly concentrates on the first few layers of GBF (e.g., 1–4 layers), even accounting for 80% of the total deposition. Therefore, it can be concluded that for the filtration process of flue gas in GBF, most of the dust particles are filtrated in the first several layers, which means the filtration and resistance performance of GBF can be optimized by adjusting the arrangement of granules with different size.

3.2. Optimization results

Based on the above results, the structure optimization was performed by the combination of different sizes of granules. The GBF with two layers made up of different granules size is proposed.

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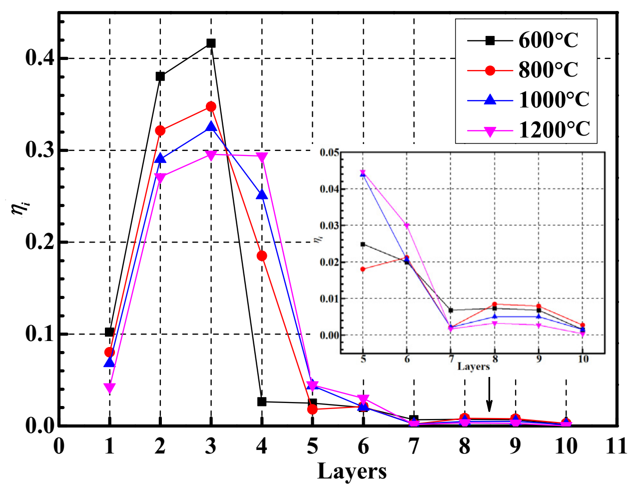


Fig. 3. Filtration efficiency of dust particles in each layer of GBF under different temperatures.

Granules size arrangements in simulation models are listed in Table 1. Model I (3 mm-3 mm) and model IV (6 mm-6 mm) are traditional GBF structures with single granules size. Model II (3 mm-6 mm) and model III (6 mm-3 mm) are the designed structure of the GBF models. The computational domain for the designed models are shown in Fig. 4. By comparing the performances of the proposed structures (Model II and III) with the traditional single granules size structures (Model I and II), the optimized GBF structure can be obtained.

The simulation results of filtration and resistance characteristics for the four models are shown in Fig. 5. The rated operation conditions are as follows: the filtration superficial velocity of 0.5 m/s or 0.3 m/s, the particle size of 5 μm, the inlet temperature of 800 °C, and the inlet dust concentration of 2.0 g /m^3. It should be noted that the size of the fluid area for different models are the same, but the arrangement of granules for different models is different. Since the filtration and resistance characteristics of a GBF are highly dependent on the flow fields in the granules, the flow characteristics of the dust particles through granules are discussed to further analyze the reason for filtration and resistance performance optimization of GBF. Fig. 6 illustrates the streamline distribution of dust particles of four different kinds of GBF with a filtration superficial velocity of 0.5 m/s. The black lines with arrows represent the dust particles path lines and flow directions. From Fig. 5, it can be seen that the filtration efficiency of Model I and II are equivalent; this is because the deposition of single particle size dust mainly concentrates on the first few layers as shown in Fig. 3. The two models have the same physical structure of granules in the first few layers of GBF, so they have similar filtration efficiency. For model III, the dust particles, which are not captured by the layers packed with granules of 6 mm, will move more centrally to the layers packed with granules of 3 mm as shown in Fig. 6. So it enhances the probability of inertial collision between dust particles and then be captured by layers packed with granules of 3 mm. Therefore, the filtration efficiency of model III is higher

Table 1
Granules size arrangement in simulation models.

Simulation model	Granules size (mm)	
	1(upper)	2(lower)
Model I	3	3
Model II	3	6
Model III	6	3
Model IV	6	6

than model I. Compared to Model II, the filtration efficiency of Model III is improved by 20%, and the pressure drop is reduced by 82.35%. The results indicate that the performance of the GBF can be significantly improved by arranging larger granules at the inlet and smaller granules at the outlet.

In addition, the filtration efficiency of different layers of the Model III were analyzed, which is shown in Fig. 7. It can be seen from the figure that the dust particles with larger size are mainly captured in the first few layers packed with larger granules, and the smaller dust particles which are not captured will then be trapped in the next few layers packed with smaller granules. Based on the results, it can be concluded that the designed GBF structure of model III (6 mm-3 mm) has the best filtration and pressure drop performance in industrial applications.

4. Experimental description

In the purification process of flue gas with coagulative particles using a GBF, the coagulative particles will condensate or solidify on granule surface due to the heat transfer between coagulative particles and the packed granules. Therefore, the coagulative particles are easier to be trapped and congealed on the surface of the first several layer granules compared to the traditional dust particles. In order to validate the suitability of the optimized GBF structure to the filtration of flue gas with coagulative particles, an experimental system was built and the effects of operating parameters on the filtration and fluid flow performance were investigated.

4.1. GBF structure

The optimized structure of the GBF used in the experiment is shown in Fig. 8. The filter granules in the GBF are arranged in three layers. From the top to bottom along the direction of flue gas flow, the granules sizes are 8 mm, 5 mm and 3 mm with a machining accuracy of 0.1 mm respectively, the granules material is also Al_2O_3 as mentioned above. There is a supporting plate and a copper cooling coil with a diameter of 10 mm and a wall thickness of 1 mm (±0.1 mm) between different layers. The granules are filled in GBF with random packing. The upper part of GBF is arranged with a uniform velocity distributor to make the velocity distribution of the flue gas entering the GBF evenly distributed. The outer side of the GBF is coated with aluminum silicate cotton to reduce the heat loss in the experiment, its thickness is about 15 mm. During the filtration process, the flue gas with high temperature containing coagulative particles and dust particles enters the GBF from the upper part of the GBF, and then the dust particles collide with the granules and deposit on the surface of the granules. In this way, the filtration target can be realized. The circulating cooling water flows into the GBF from the lower entrance of the copper cooling coil and flows out from the upper outlet. After heat exchange process between the cooling water and granules and hot flue gas, the cooling water is cooled by the cooling tower and then flows into the GBF again. At the same time, the temperature of the granules is significantly reduced and the coagulative particles are solidified and adhere to the surface of the granules.

4.2. Filtration system for flue gas containing coagulative particles

The schematic diagram and physical drawings of the experimental system are shown in Fig. 9. The experimental system mainly includes the air heating part, the flue gas generation part, the GBF part, the post-processing part and the data acquisition part. During the operation of the experimental system, the air driven by a fan is heated to 310–400 °C through the electric heater, and the gas mass rate is controlled by adjusting the opening of

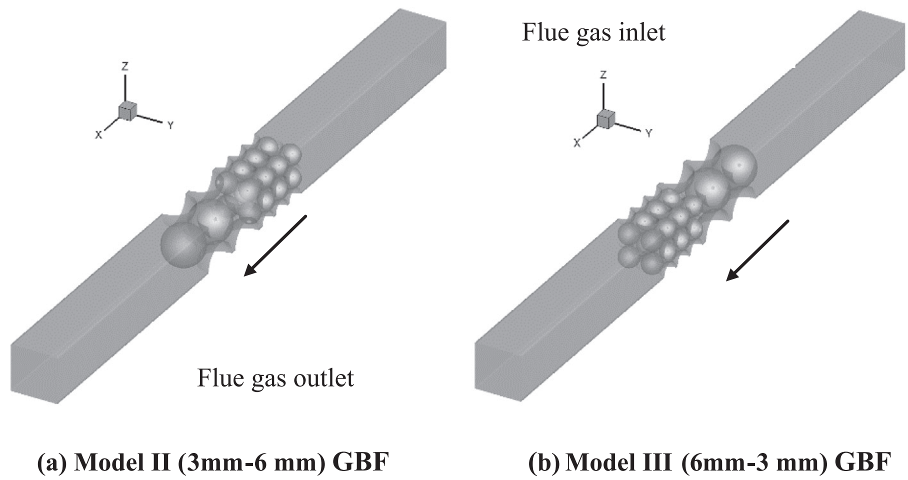


Fig. 4. Optimized simulation model of GBF structure.

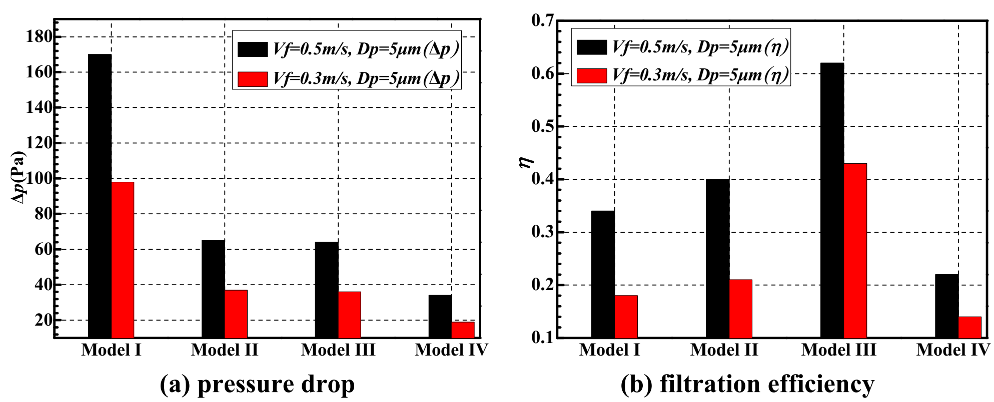


Fig. 5. Simulation results of different optimized models of GBF structure.

the valve. The vortex flowmeter with the uncertainty of 1.5% is adopted to obtain the mass flow rate. The flow rate of cooling water is measured by LZS plastic tube rotator flowmeter with the uncertainty of 4% and the k-type thermocouples with an uncertainty of 0.5 °C are adopted to obtain the temperature of flue gas and cooling water. All the data is acquired by Keithley 2700. During the experimental process, the dust particles and coagulative particles are delivered from a uniform speed feeder, the dust particles was taken from a coal-fired power plant in Xi'an, Shaanxi, China. The original size distribution of dust particles was analyzed by a particle size analysis system (STP2000), and it was found that the corresponding dust particle sizes are 10.47 μm, 57.97 μm and 228 μm when the cumulative volumes were 10%, 50% and 90% respectively [26,36]. The XRD and SEM experiments were also carried out to analyze the microscopic morphology and chemical composition of the dust particles, and the detailed results can be found in our previous work [36]. Then the dust particles and coagulative particles are mixed with hot air in an 80 cm length mixed cavity to ensure that the distribution of dust particles in flue gas is uniform. The different inlet dust particles concentration is realized by adjusting the speed of uniform speed feeder. The cooling water conveyed by a pump from a cooling tower enters into the cooling coil from GBF bottom, and then flows out from the upper part. The coagulative particles are cooled by the cooling granules and solidified on the surface of granules. After the filtration process, the clean flue gas comes into the post treatment device from the bottom of the GBF, and then is retreated again to meet the environmental requirements and finally flows into the atmosphere. The coagulative particles selected in the experiment are $FeCl_3$, its melting point is 306 °C, and the concentration is 99.5%, and its average particle size is about 200 μm. It is mainly produced by the steel plant after the flue gas of pickled steel strip in the industry. Based on the isokinetic sampling method, the concentration of the dust particles in the experiment is measured by the flue gas analyzer. The volume of the flue gas V (The measuring accuracy is 0.5%) during the sampling time Δt (the accuracy of measurement is 1 s) was obtained by measuring the volume flow Q of flue gas. The quality of the dust is measured by the precision balance (The measuring accuracy of measurement is 0.1 mg), and the formula of the concentration C of the import and export is as follows:

$$C = \frac{|m_1 - m_2|}{V} = \frac{\Delta m}{Q\Delta t} \tag{17}$$

The formula for calculating the filtration efficiency is [19,25]:

$$\eta(\%) = \left[1 - \left(\frac{C_{out}}{C_{in}}\right)\right] \times 100\% \tag{18}$$

where C_{in} and C_{out} are the concentration of dust particles at the inlet and outlet of the GBF. The inlet and outlet pressure drop P is measured by a U tube pressure gauge (The measuring range is 2000 Pa and the measuring accuracy is 0.05%). When the filtration and resistance characteristics vary with time, the pressure drop and filtration efficiency are recorded every 5 min. After each experiment, the particle bed is fully back blown by adjusting the opening of the valve in the pipeline with high temperature air to make the GBF basically do

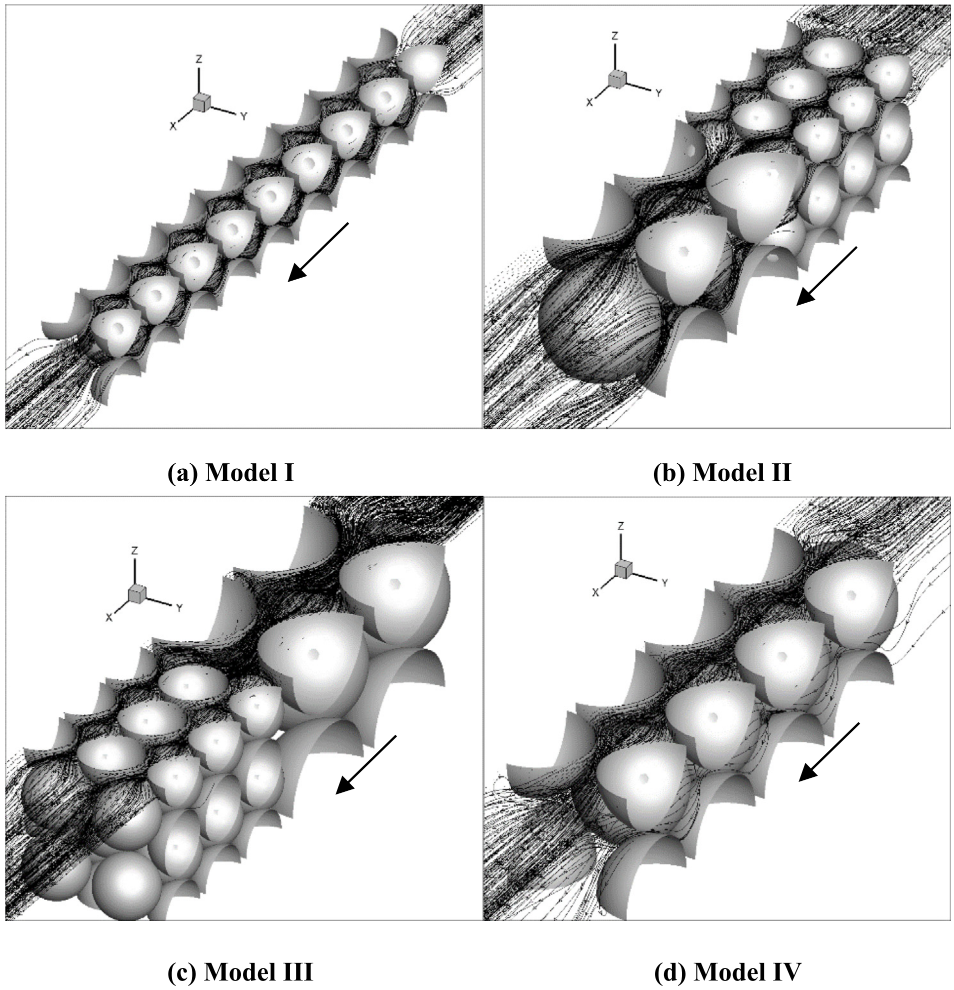


Fig. 6. Streamline diagram of different simulation optimized models of GBF structure.

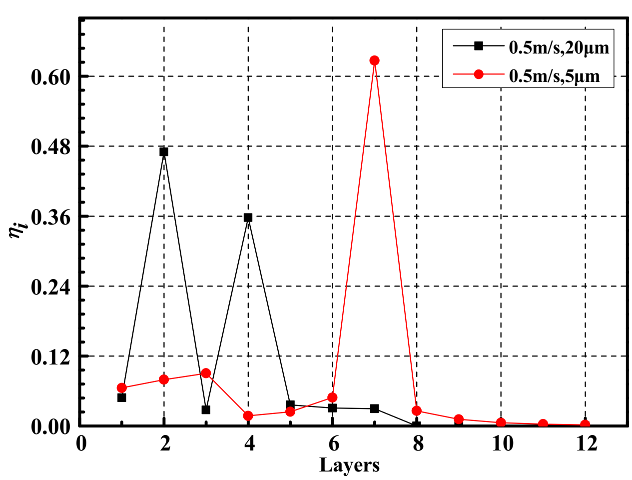


Fig. 7. Filtration efficiency of dust particles with different sizes in each layer of GBF.

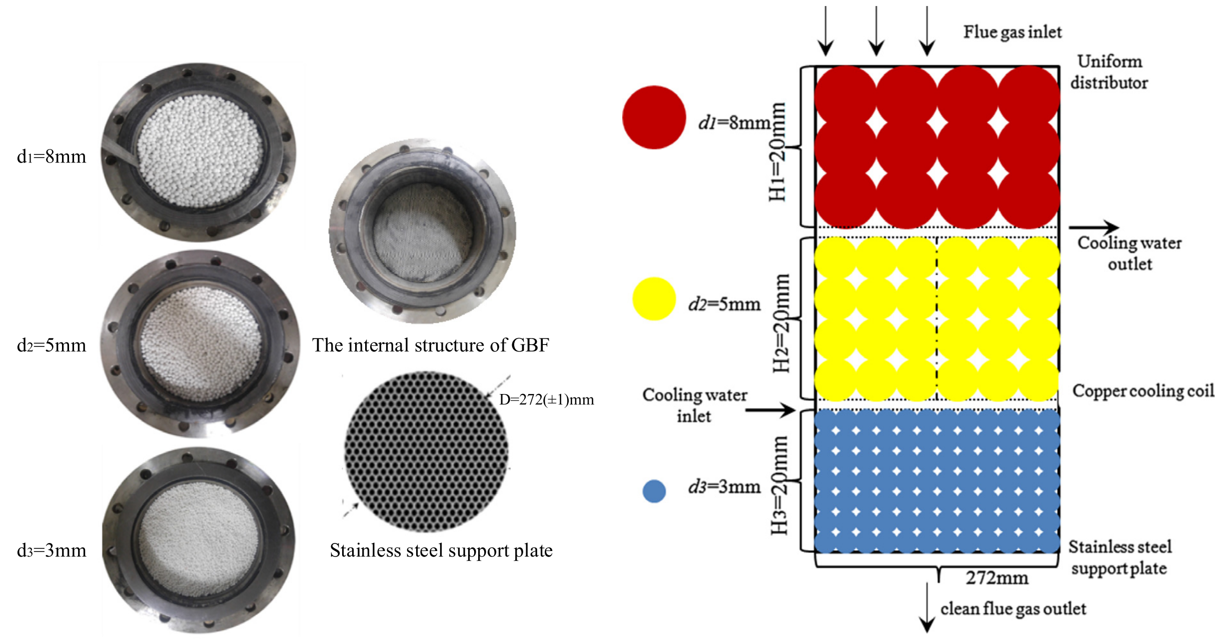
not exist residual dust particles or coagulating particles. Thus, the error of the experimental data is reduced.

4.3. Optimization design arrangements

In order to improve the filtration performance of GBF for industrial flue gas with coagulative particles, three layer structures are designed in the experiment, which are named model B (3 mm-5 mm-8 mm) and model C (3 mm-5 mm-8 mm) respectively as shown in Table 2. For model B, the granule size varies from 3 mm to 5 mm and 8 mm along the fluid flow direction and for model C the granule size is arranged in the reverse direction. Model A (3 mm-3 mm-3 mm), model D (5 mm-5 mm-5 mm) are traditional GBF structures with single granules size. The performances of the proposed structure are compared with performance of single granules size structures to obtain the optimized granular bed structure.

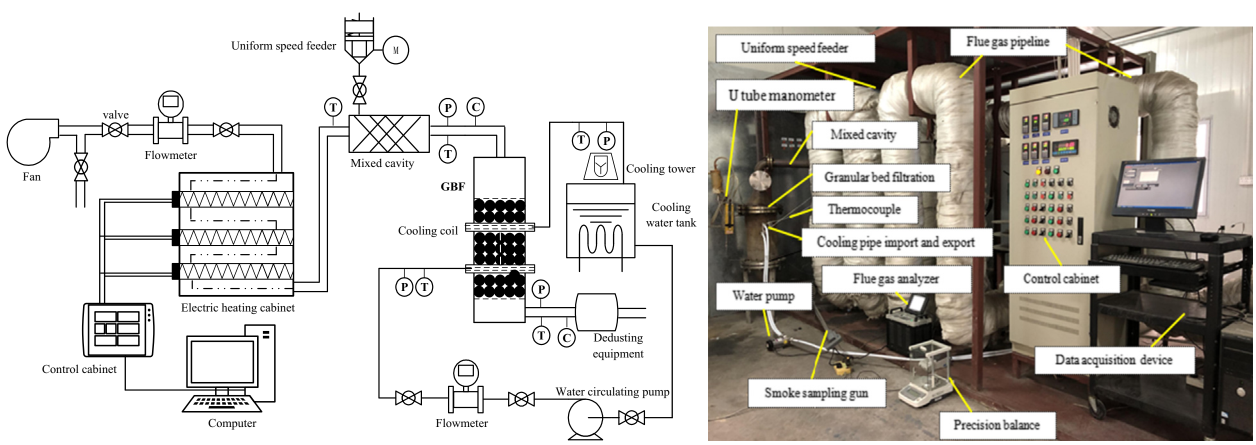
4.4. Uncertainty analysis of the experiments

Usually, we use the difference between the experimental value and the real value to reflect the deviation of the measurement result from the real value. However, in the actual measurement process, the real value is often unknown and difficult to obtain. Therefore, it is an effective evaluation method to measure the deviation of the experimental value from the true value under the local conditions such as the experimental environment and the state of the instrument by using the uncertainty of the experiment. The uncertainty of an effective evaluation method is closely related to the accuracy of instruments and instruments. As mentioned above, the filtration efficiency of the system is mainly determined by the concentration of dust particles at the inlet and outlet, and the concentration is mainly obtained by sampling the flue gas at the inlet and outlet. So the filtration efficiency can be obtained



(a) physical map of GBF (b) schematic diagram of GBF structure

Fig. 8. Schematic diagram GBF with optimized structure.



(a) schematic diagram (b) physical diagram

Fig. 9. Experimental platform for high efficiency and low resistance filtration of flue gas containing dust particles and coagulative particles.

Table 2
Granules size arrangement in experimental models.

Experimentalmodel	Granules size (mm)		
	1(upper)	2(middle)	3(lower)
Model A	3	3	3
Model B	3	5	8
Model C	8	5	3
Model D	5	5	5

by Eq. (17) and Eq. (18). The uncertainty of concentration can be calculated by Eq. (19) as follows:

$$\frac{\delta_C}{C} = \sqrt{\left(\frac{\delta_{\Delta m}}{\Delta m}\right)^2 + \left(\frac{\delta_Q}{Q}\right)^2 + \left(\frac{\delta_{\Delta t}}{\Delta t}\right)^2} \tag{19}$$

The above formulas can be simplified to:

$$\delta_C = \pm\sqrt{a_{\Delta m}^2\delta_{\Delta m}^2 + a_Q^2\delta_Q^2 + a_{\Delta t}^2\delta_{\Delta t}^2} \tag{20}$$

$$\begin{cases} a_{\Delta m} = \frac{\partial C}{\partial \Delta m} = \frac{1}{Q\Delta t} \\ a_Q = \frac{\partial C}{\partial Q} = -\frac{\Delta m}{Q^2\Delta t} \\ a_{\Delta t} = \frac{\partial C}{\partial \Delta t} = -\frac{\Delta m}{Q\Delta t^2} \end{cases} \tag{21}$$

where C is the concentration of dust particles, Δt is the sampling time, Q is the flow rate of sampling flue gas. $a_{\Delta m}$, a_Q and $a_{\Delta t}$are all uncertainty coefficients.

The expanded uncertainty of filtration efficiency of the system can be obtained by the uncertainty propagation analysis, as shown in the following equation:

$$\frac{\delta_\eta}{\eta} = \sqrt{\left(\frac{\delta_{C_{in}}}{C_{in}}\right)^2 + \left(\frac{\delta_{C_{out}}}{C_{out}}\right)^2} \tag{22}$$

$$\delta_\eta = \sqrt{a_{out}^2 \delta_{C_{in}}^2 + a_{in}^2 \delta_{C_{out}}^2} \tag{23}$$

$$\begin{cases} a_{C_{in}} = \frac{\partial \eta}{\partial C_{in}} = \frac{C_{out}}{C_{in}^2} \\ a_{C_{out}} = \frac{\partial \eta}{\partial C_{out}} = -\frac{1}{C_{in}} \end{cases} \tag{24}$$

Similarly, we simplify the formula by introducing uncertainty coefficients a_{in} and a_{out}. In addition, $\delta_{\Delta m}$, δ_Q and δ_t are 0.01 mg, 0.5% and 1 s respectively. In order to accurately calculate the uncertainty of filtration efficiency tested in the present study, one of the experimental conditions was selected for analysis and calculation of the uncertainty, and it was obtained that the uncertainty of the experimental measurement for filtration efficiency is 0.8%, which was calculated by Eq. (19)–(24).

As for the uncertainty of pressure drop, since the minimum pressure drop in the experiment is 211 Pa, so the maximum uncertainty of pressure drop can be obtained from the following formula:

$$\left(\frac{\delta_{\Delta P}}{\Delta P}\right)_{max} = \frac{2000Pa \times 0.05\%}{211} = 0.47\% \tag{25}$$

From the above analysis and calculation, it can be concluded that the uncertainty of experiments meets the requirement of the requirements of engineering application.

5. Experimental result and discussion

5.1. Optimization result validation

In the filtration experiments of flue gas containing coagulative particles and dust particles, the inlet temperature of the flue gas is 340 °C, the concentration of dust particles is 3.6 g/m^3, the concentration of the coagulative particles is 2.4 g/m^3, and the cooling water flow rate is 240 L/h. Firstly, the variations of filtration efficiency and pressure drop of the system with time were studied when the filtration superficial velocity is 0.98 m/s. The experimental results are shown in Fig. 10. It can be figured out that the filtration efficiency and pressure drop of the system increase with the increase of filtration time. At the initial time, the pressure drop for model A, model B, model C and model D are 514 Pa, 482 Pa, 452 Pa and 368 Pa respectively. Besides, the filtration efficiencies for model A, model B, model C and model D are 0.7365, 0.7002, 0.7114 and 0.6890 respectively. It can be found that model A has the highest filtration efficiency. Compared with model A, the pressure drop of model C is reduced by 12.06%, and the filtering efficiency is reduced by 3.41%. However, when the filtration process goes up to 120 min, the pressure drop of model C is only 34.05% of that for model A, the filtering efficiency is equivalent with that of model A. From this, it can be concluded that with the increase of filtration time, the proposed optimized structure model C has better filtration performance, which can significantly reduce the pressure drop while ensuring high filtration efficiency. As mentioned in our previous studies [26,36], the size distribution of dust particles has a significant effect on filtration efficiency, considering the particle size distribution of dust particles we selected in the present study, the size distribution of dust particles has a significant effect on the excellent performance filtration of model C, it is mainly because the dust particles with larger size distribution were filtered in filtration section with larger porosity due to random accumulation of larger granules. At the same time, the dust particles with smaller size distribution escaped to the subsequent filtration section and then they were filtered by granules accumulated by smaller particles with lower porosity. This is consistent with the results drawn from numerical simulation, and further validates the simulation conclusion.

Under the above experimental conditions, the filtration and resistance characteristics of different filtration superficial velocities in the same time (30 min, 60 min, 90 min and 120 min) were compared and analyzed, which are shown in Fig. 11. It can be found that with the increase of the filtration superficial velocity, the filtration efficiency significantly reduced, but the pressure drop increased. Model A has the highest filtration efficiency at 30 min and 60 min, moreover it is also accompanied by the highest pressure drop at 30 min, 60 min, 90 min and 120 min. However, the filtration efficiency of model C exceeded that of model A at 90 min in the case of the filtration superficial velocity lower than 0.64 m/s. Here, it was 0.47% higher than that of model A at filtration superficial velocity of 0.54 m/s, the pressure drop is reduced by 18.37%. It can be attributed to the superiority of the GBF structure proposed based on gradient control of granules size distribution, which significantly increases the dust content of GBF. Compared with the traditional single granules structure, the increase rate of porosity of the GBF decreases significantly with time. Therefore, the optimized structure model C has excellent performance for the filtration of industrial flue gas containing coagulative particles and dust particles, and with the increase of filtration time, the performance advantages are more obvious.

5.2. Effect of parameters on filtration and resistance characteristics

Based on the optimized GBF structure (Model C), the effects of operating parameters on filtration and resistance characteristics

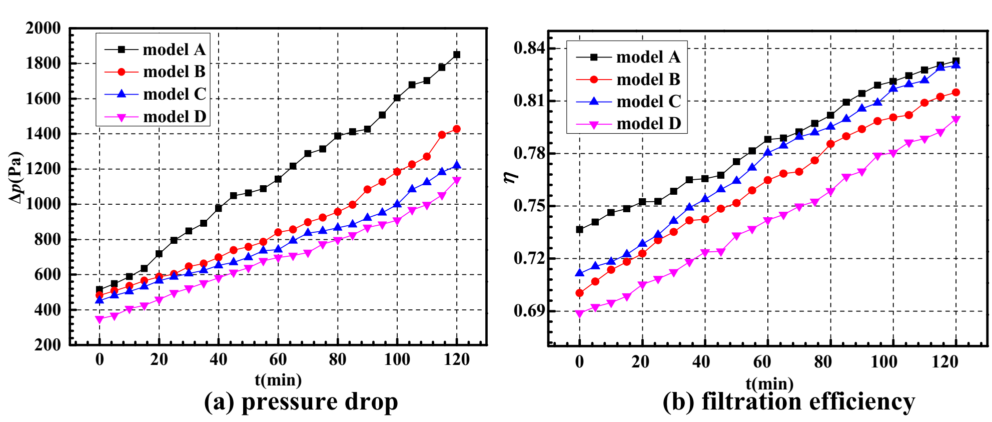


Fig. 10. Variation of pressure drop and filtration efficiency with time of different GBF structures.

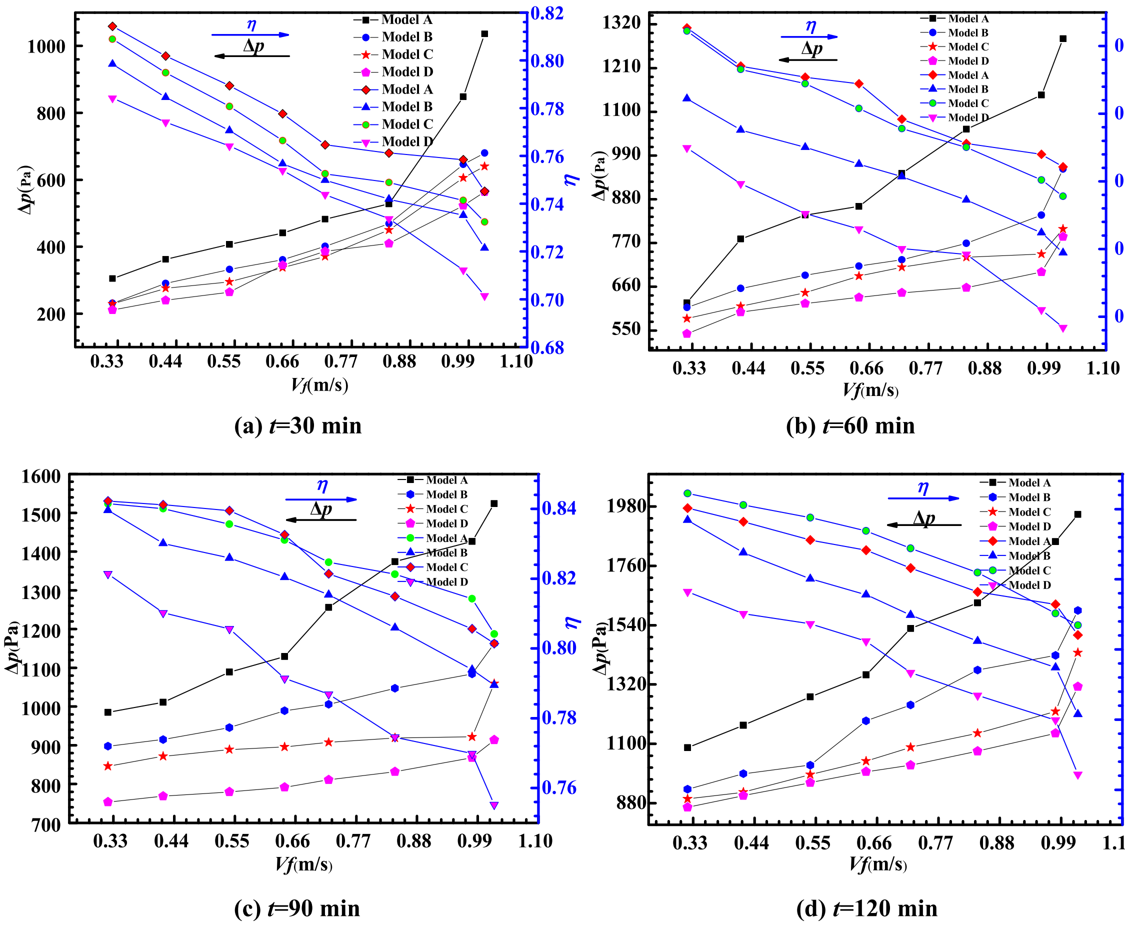


Fig. 11. Variation of system pressure drop and filtration efficiency with filtration superficial velocity.

of the flue gas containing coagulative particles and dust particles are further investigated by experimental methods. Fig. 12 illustrated the morphology of the granules before and after the filtration. We can clearly see the solidification and adhesion of the coagulative particles on the surface of the granules, and the distribution of the particles in the GBF is uniform, which indicates that the operation of the cooling system is effective.

5.2.1. Effect of dust particles concentration

It has been pointed out by many researchers that the concentration of dust particles has a significant effect on the performance of GBF [19,21,26]. In the present study, to study the effect of dust particle concentration on filtration and resistance characteristics of GBF, several parameters such as the inlet temperature of the flue gas (340 °C), the concentration of the coagulative particles (1.2 g/m^3), filtration superficial velocity (0.98 m/s) and the cooling water flow rate (240 L/h) were all held constant. Only the concentration of dust particles was set to 3.6 g/m^3, 4.8 g/m^3 and 6 g/m^3, respectively. The experimental results are shown in Fig. 13. It can be seen from Fig. 13 that in the filtration process, more and more dust particles were gathered in the GBF with the filtration process ongoing, which leads to the pressure drop and filtration efficiency rising gradually. At the same time, the pressure drop and filtration efficiency of the system all increase with the increase of dust concentration, which is due to the increase of dust concentration that increases the amount of dust captured by the particles in the

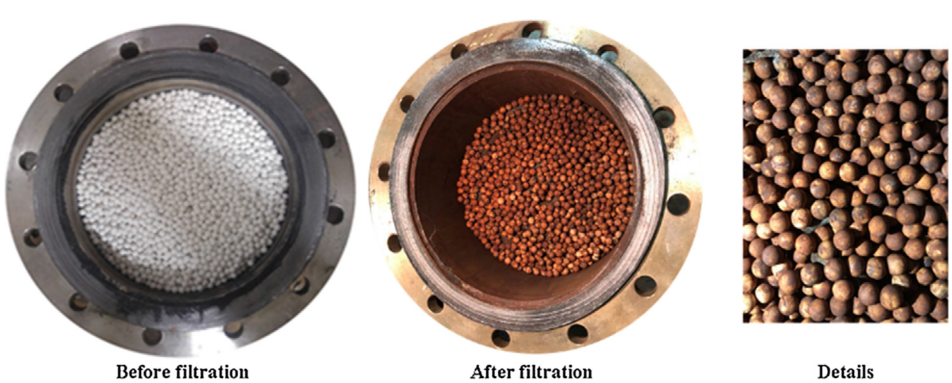
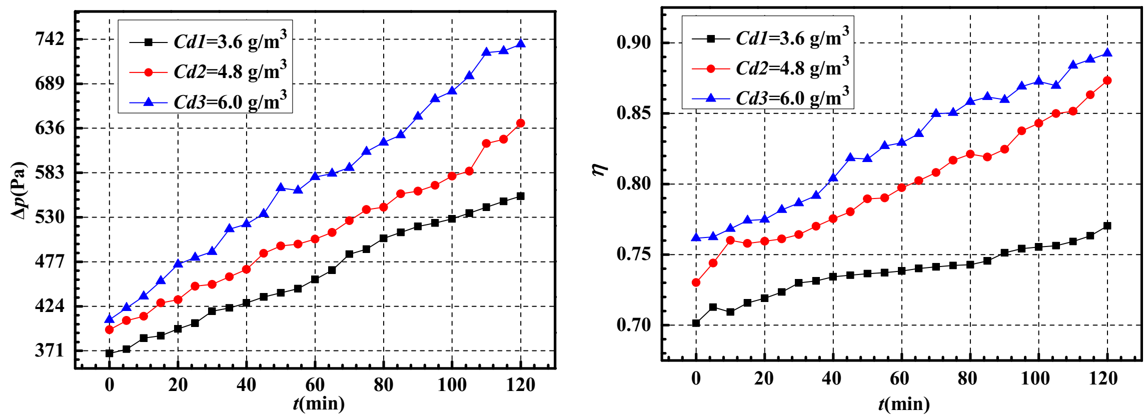


Fig. 12. The morphology of the coagulative particles deposited on the surface of granules.



(a) pressure drop (b) filtration efficiency

Fig. 13. Variation of pressure drop and filtration efficiency with time under different concentrations of dust particles.

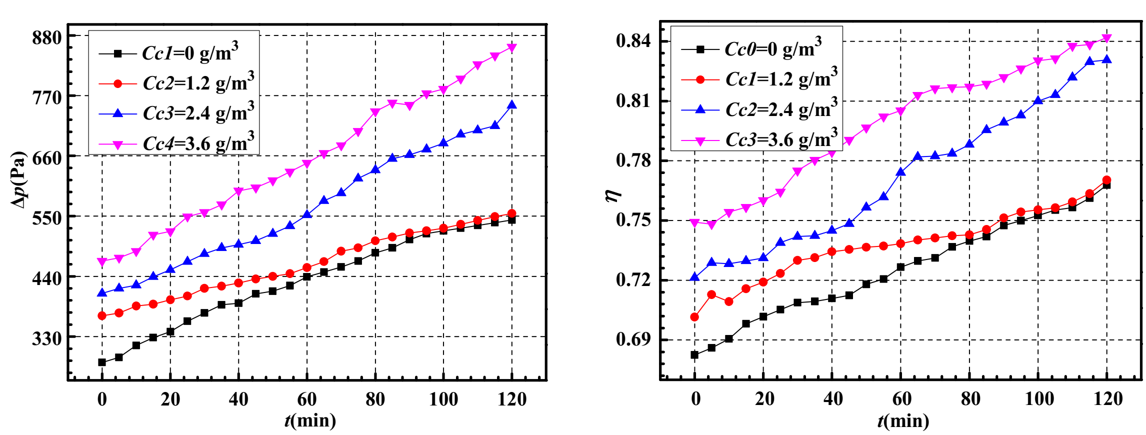
GBF within a unit time, resulting in a significant decrease in the porosity of the granular bed. With the increase of dust concentration, the increase of pressure drop and filtration efficiency is more significant. When the filter was carried out from the initial time to 120 min, the pressure drop increased by 50.8%, 62.1% and 80.39% respectively when the dust concentration was 1.2 g/m^3, 2.4 g/m^3 and 3.6 g/m^3 respectively, while the filtration efficiency increased by 9.8%, 19.6% and 17.2, respectively.

5.2.2. Effect of coagulative particles concentration

In the study of the effect of coagulative particles concentration on the filtration and pressure drop characteristics of the GBF, other operating conditions are consistent with the influence of dust particles concentration. When the dust particles concentration is 3.6 g/m^3, the concentration of coagulative particles is changed to 0, 1.2 g/m^3, 2.4 g/m^3 and 3.6 g/m^3 respectively. Fig. 14 illustrates the variation of pressure drop and filtration efficiency with time under different coagulative particles concentration. The existing of coagulative particles leads to the adhesion of dust particles around the coagulative particles in the industrial flue gas, which is beneficial to the growth of smaller size dust particles and causes the pressure drop and filtration efficiency increasing. Therefore, both the filtration efficiency and pressure drop for the flue gas with coagulative particles are higher than that without coagulative particles. When the concentration of coagulant dust is low, the pressure drop and filtration efficiency increase slightly. With the increase of the coagulative particles concentration, the pressure drop and filtration efficiency increase more significantly. Compared to the operating condition without coagulative particles, when the concentration of the coagulative particles is 1.2 g/m^3, 2.4 g/m^3 and 3.6 g/m^3, the pressure drop increases by 2.2%, 38.5% and 58.2%, respectively, the filtration efficiency increased by 0.3%, 8.2% and 9.7%, respectively.

5.2.3. Effect of cooling rate

In this section, the operating conditions are set as follows: the industrial flue gas inlet temperature is kept at 340 °C, the filtration superficial velocity is 0.98 m/s, the dust concentration is 3.6 g/m^3, the concentration of the coagulant dust is 1.2 g/m^3. The cooling water flow rate is 0 L/h, 240 L/h, 280 L/h and 320 L/h respectively to investigate the influence of cooling rate on the filtration process. The pressure drop and filtration efficiency are shown in Fig. 15. It can be seen from Fig. 15 that when the GBF is not cooled, the filtration efficiency and pressure drop are lower than the condition of the GBF is cooled. Besides, with the more increase of cooling water flow rate, the pressure drop and filtration efficiency decrease. This phenomenon can be attributed to that for coagulative particles, the increase of the nucleation rate is faster than the growth of the crystal nucleus with the increase of the super cooling. Thus, the finer grain of the coagulative particles can be obtained, which is easy



(a) pressure drop (b) filtration efficiency

Fig. 14. Variation of pressure drop and filtration efficiency with time under different concentration of coagulative particles.

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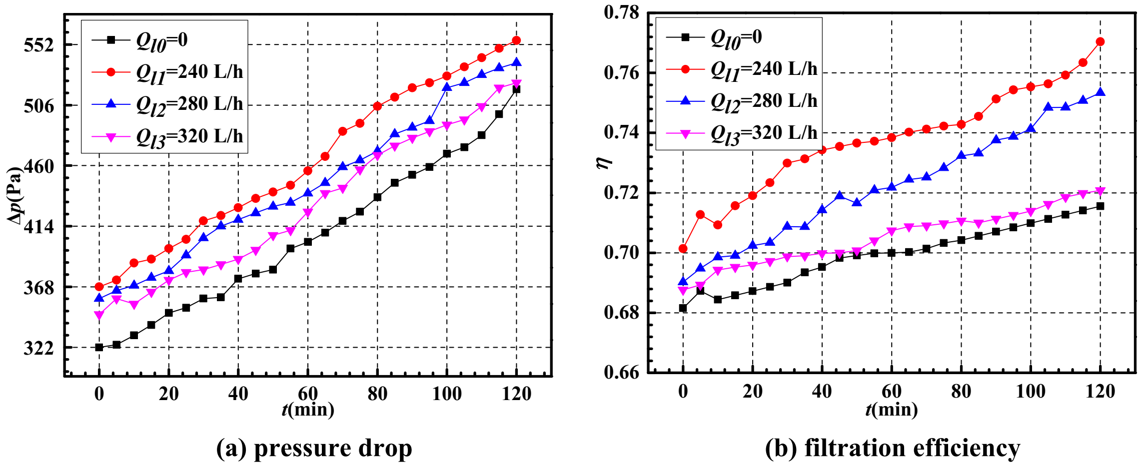

Fig. 15. Variation of system pressure drop and filtration efficiency with time under different cooling rates.

to be blown away. Therefore, the porosity of the GBF increases, which leads to the decrease of pressure drop and filtration efficiency.

6. Conclusions

In this paper, experimental and numerical methods were adopted to study the filtration and resistance characteristics of a GBF used for the purification of industrial flue gas with dust particles and coagulative particles. The local filtration efficiency of GBF for different layers was investigated, based on that the optimized GBF structure was designed by adjusting the granules size along flue gas flow direction. The numerical and experimental validation results show that the designed GBF structure has excellent filtration and resistance performance. After that, the effects of operating parameters on the filtration and resistance performance of the designed GBF were further studied, which is expected to contribute to the design and optimization of high temperature flue gas purification and waste heat recovery technology. The main conclusions can be drawn as follows:

(1) The numerical model developed in the present study can effectively predict the filtration efficiency and pressure drop of GBF, and the local filtration efficiency was obtained to optimize the performance of GBF.
(2) Numerical simulation results reveal the underlying mechanism of the performance optimization of GBF, which is that most of the dust particles deposit on the surface of the first several layers. Therefore, increasing the granule sizes at the inlet region of the GBF and decreasing the granule size at the outlet region is beneficial for performance enhancement of GBF.
(3) The designed GBF structure (Model C and Model III) has the best filtration and resistance comprehensive performance, it is mainly because the dust particles with larger size distribution were filtered by larger granules in the entrance. The dust particles with smaller size distribution were filtered by subsequent smaller granules. In addition, With the increase of time, the superiority of filtration performance becomes more significant.
(4) The pressure drop and filtration efficiency of the experimental system increase with the increase of filtration time and dust particles concentration.
(5) The existing of coagulative particles is conducive to the growth of small size dust particles, which is beneficial to the filtration of dust particles. When the concentration of coagulative particles is low, the pressure drop and filtration efficiency increase slightly. With the further increase of the concentration of coagulative particles, the pressure drop and efficiency increase more significantly.
(6) A small cooling rate is helpful for the filtration of industrial flue gas with coagulative dust particles. However, when the cooling rate increases more, both the pressure drop and filtration efficiency decrease, which deserves further study to find the optimal cooling rate.

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