Agglomeration and removal characteristics of fine particles from coal combustion under different turbulent flow fields

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Article Info
Article history:
Received 13 June 2019
Received in revised form
11 October 2019
Accepted 16 October 2019
Available online 4 November 2019

Keywords:
Fine particles
Flow field
Turbulent agglomeration
Removal
Mechanism

Abstract
Turbulent agglomeration is a promising pretreatment technology for improving the removal of fine particles in industrial flue gas, which can improve the particle removal effect of dust removal equipment safely and economically. However, due to the complexity of turbulence mechanisms, the relationship between turbulent flow fields and the agglomeration of fine particles is not known with precision, resulting a weak promotion effect for particle removal with this pretreatment technology. In this work, three kinds of turbulent agglomerators were constructed to investigate the agglomeration and removal characteristics of fine particles under different turbulent flow fields. The results demonstrated that the turbulent agglomerator with small-scale and three-dimensional vortexes in the flow field had the best effect in improving the agglomeration and removal of fine particles. Two kinds of agglomeration modes in turbulent agglomeration were proposed, one being agglomeration between fine particles in the vortex area, and the other the capture of fine particles by coarse particles. Furthermore, the motion trajectory, relative velocity and residence time of fine particles of different sizes in different flow fields were calculated by numerical simulation to investigate the interaction mechanism of particle agglomeration and turbulent flow fields. The results showed that a flow field with small-scale and three-dimensional vortexes can reduce the Stokes number (StK) and the relative velocity of particles of different sizes, and extend their residence time in a turbulent flow field, so as to obtain a better agglomeration effect for fine particles.

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Introduction
Coal is an important part of the world energy structure, which accounts for 38% of global electricity production (BP, 2018). In China, coal is also the main fuel in energy production, with a proportion of more than 60% (BP, 2018). The combustion of coal produces a large number of fly ash particles, and although most of these can be captured and removed by existing dust removal equipment, such as electrostatic precipitators (ESPs),
In order to improve the removal effect for fine particles, a variety of agglomeration pretreatment technologies have been proposed to increase their particle size before they enter dust removal equipment, including electric agglomeration (Lin et al., 2011; Thonglek and Kiatsiriroat, 2014), chemical agglomeration (Liu et al., 2016; Guo et al., 2017), heterogeneous-condensation agglomeration (Yang et al., 2010; Heidenreich and Ebert, 1995), turbulent agglomeration (Chen et al., 2016; Asanakham and Kiatsiriroat, 2016), and acoustic agglomeration (Zu et al., 2017; Zhang et al., 2018). Among these agglomeration methods, turbulent agglomeration has attracted the attention of many researchers. Turbulent agglomeration is a phenomenon whereby fine particles gain different velocities and trajectories due to the velocity gradient and turbulence pulsation in a turbulent flow field, which results in particle collision and agglomeration. Compared with other agglomeration technologies, turbulent agglomeration is a physical method to promote the growth of fine particles, which gives it the advantages of simple structure, convenient installation and construction, low failure rate and low energy consumption. Besides, it has no impact on other equipment in the system. In turbulent agglomeration, fine particles collide and agglomerate with each other under the influence of vortices in the flow field, so the properties of the turbulent flow field play an important role in the agglomeration of fine particles. However, due to the complexity of turbulence mechanisms, current studies have only focused on several common turbulent vortex sheet structures to investigate the agglomeration and removal effect of fine particles, or used turbulent agglomeration as an auxiliary means along with other agglomeration technologies (Guo et al., 2012; Sun et al., 2013; Yan et al., 2018). There are few studies on the relationships among the structure of turbulent vortex sheets, the properties of turbulent flow fields and the agglomeration characteristics of fine particles. As a result, the mechanism of turbulent agglomeration is not definitive and the agglomeration and removal efficiency of fine particles by this pretreatment technology is relatively low.

In this work, three kinds of turbulent agglomerators with different structures were designed and manufactured to investigate the agglomeration and removal characteristics of fine particles under different turbulent flow fields, so as to improve the effect of turbulent agglomeration. Different structures of turbulent vortex sheets produced flow fields with different properties, which were manifested on the vortex scale and generation dimension. The influence of flow field properties on the agglomeration and removal characteristics of fine particles by ESP were explored experimentally. Furthermore, the motion trajectory, relative velocity and residence time of fine particles with different sizes in flow fields were calculated by numerical simulation to investigate the mechanism of interaction between particle agglomeration and turbulent flow fields.

1. Materials and methods

1.1. Experimental setup

The schematic of the experimental system is shown in Fig. 1. A gas heater was employed to generate hot air flow to the system, the temperature of which could be heated to 300°C with a rated flow of 300 Nm³/hr (Nm³: gas volume in normal condition, which is 0°C and 101.325 kPa). The coal-fired fly ash particles were provided by a solid aerosol generator (SAG 410/ U, Topas Ltd, Germany), and sampled from the third ash hopper of an ESP in a coal-fired power plant. The hot air and fly ash particles were well mixed in a buffer vessel as flue gas, which was equipped with a stirrer. Then the flue gas entered the turbulent agglomeration system, the fine particles in the flue gas became larger in size after agglomeration and were removed by a subsequent dust removal device. The turbulent agglomeration system consisted of several valves and three kinds of turbulent agglomerators (#1, #2, and #3). By adjusting the valves, the flow sequence of flue gas could be conveniently adjusted, so that the flue gas could enter the three kinds of turbulent agglomerators respectively. The dust removal device was a barb-plate tube type ESP, and the applied rectifier voltage was ~40 kV. An induced draft fan was installed at the end of the experimental system, and the flue gas velocity was maintained at 10 m/sec by adjusting the fan power. Meanwhile, the flue gas temperature at the entrance of turbulent agglomeration system was set at 150°C by adjusting the power of the gas heater.

An electrical low-pressure impactor (ELPI+, Dekati Co. Ltd, Finland), which can measure the concentration and size distribution of particles under 10 μm in real time, was applied to determine the particle concentration and size distribution. The test points included the outlets of the buffer vessel, turbulent agglomeration system and ESP. An aspirated isokinetic sampler (WJ-608, Laoying Ltd, China) was employed to collect the samples of fine particles after turbulent agglomeration. The microscopic morphology of fine particle samples was observed by a field emission scanning electron microscopy (Ultra Plus, Zeiss Ltd, Germany).

1.2. Structure and flow field of turbulent agglomerators

Fig. 2 shows the structures of the three kinds of turbulent agglomerators. The turbulent agglomerators were constructed of stainless-steel pipes with square cross-section, with length of 1320 mm and width of 100 mm. In turbulent agglomerator #1, 8 pairs of vortex sheets with z-shaped cross-section were arranged alternately in 2 columns. The length of each vortex sheet along the direction of the flue gas was
52 mm, the width in the vertical direction was 30 mm, and the height was 100 mm (Fig. 2). In turbulent agglomerator #2, 16 pairs of pin fins with cross-type cross-section were arranged abreast in 2 columns, the length and width of which were both 20 mm, and the height was also 100 mm (Fig. 2). In turbulent agglomerator #3, there were also 16 pairs of pin fins of the same shape and size as in #2; the difference was that 4 incisions were uniformly arranged on each of three sides of the pins (the exception being the side toward the entrance); the depth of the incisions was 4 mm, and the width was 6 mm (Fig. 2).

Turbulent agglomerators with different internal structures had different flow field distributions, for which the streamlines are shown in Fig. 3. In the flow field of turbulent agglomerator #1, the velocity in the middle area of the two columns of vortex sheets (the main flow area) was faster than that of the inlet flue gas, and there were large-scale vortexes behind the vortex sheets, thus forming low-speed reflux areas. The streamline velocity in the reflux area was much lower than that of the main flow area, which indicated that the turbulence intensity was high in the x-y plane. However, in the direction of the z-axis, there was no obvious fluctuation of the streamlines, and...
they basically moved uniformly along the x-axis direction (Fig. 3). In the flow field of turbulent agglomerator #2, the flue gas velocity in the main flow area was also relatively high, and low-speed reflux zones were also formed behind the pin fins, but the vortex scale was smaller than in #1 owing to the small size of the pin fins. Meanwhile, the streamlines also had no observable fluctuation in the z-axis direction, and the velocity behind the pin fins was higher at the top and bottom but lower in the middle on the x-z plane, which was similar to the laminar flow moving along the x-axis direction (Fig. 3). In the flow field of turbulent agglomerator #3, the velocity distribution was similar to #2 in the x-y plane, but different in the x-z plane. It can be seen that owing to the incisions on the pin fins, there was some fluctuation of streamlines in the z-axis direction, and the velocity behind the pin fins was more uniform from top to bottom than in #2, which meant that it could generate vortexes in three dimensions (Fig. 3).

2. Results and discussion

2.1. Particle agglomeration characteristics after different turbulent agglomerators

2.1.1. Particle concentrations

In order to compare the agglomeration characteristics of fine particles in different flow fields, the concentrations of fine particles before and after the three kinds of turbulent
agglomerators were measured respectively, as seen in Fig. 4. In the original flue gas, the number concentration of particles smaller than 10 μm (PM$_{10}$) was $9.03 \times 10^6$ particles/cm$^3$. After the turbulent agglomeration systems, the particle number concentrations were decreased to $7.51 \times 10^6$, $6.91 \times 10^6$ and $6.66 \times 10^6$ particles/cm$^3$ by turbulent agglomerators #1, #2 and #3, amounting to reduction of about 16.8%, 23.5% and 26.3% compared to that in the original flue gas, respectively. Meanwhile, the mass concentration of PM$_{10}$ remained stable at about 312 mg/m$^3$ during the whole process.

### 2.1.2. Particle size distributions

The particle size distributions were also assessed to compare the particle agglomeration characteristics under different turbulent agglomerators, as shown in Fig. 5. The dN/dlog$D_p$ refers to the density of particle number concentration, in which dN is particle number concentration, and 1/dlog$D_p$ is the conventional form of aerosol distribution, which is formed by dividing the stages measured value by the logarithmic width of the stage in ELPI+. The particle size distribution in the original flue gas was a unimodal distribution with peak diameter at 0.04 μm, where the particle number concentration was about $3.40 \times 10^6$ particles/cm$^3$, and the diameters of most particles were less than 1 μm. After turbulent agglomeration, the concentration of fine particles decreased in all particle sizes, especially in the range of less than 0.1 μm. The particle number concentration at the peak decreased to $2.83 \times 10^6$, $2.57 \times 10^6$ and $2.48 \times 10^6$ particles/cm$^3$ after turbulent agglomerator #1, #2 and #3, declining by about 16.8%, 24.4% and 27.1% respectively. What’s more, the concentration was reduced by about 17.2%, 25.4% and 30.4% in the range of less than 0.1 μm, from $1.34 \times 10^7$ to $1.11 \times 10^7$, $1.00 \times 10^7$ and $9.33 \times 10^6$ particles/cm$^3$.

It can be seen from the results that turbulent agglomeration can promote collision and agglomeration between fine particles and increase the particle size, thus reducing the concentration of these particles. For the three kinds of turbulent agglomerators, the effect of #2 was better than #1, and #3 was the best, which meant that small-scale vortexes were better than large ones, and three-dimensional vortexes were superior to two-dimensional ones for fine particle agglomeration. Particles can be divided into three categories according to their size and inertia, namely zero-inertia particles, finite-inertia particles and maximum-inertia particles (Alipchenkov and Zaichik, 2001). The zero-inertia particles are idealized particles without mass, which are easily affected by vortexes and follow well with the flue gas. Maximum-inertia particles refer to the particles with great inertia, whose motion is not affected by the vortexes in the turbulence at all. Finite-inertia particles are particles with a certain size and inertia, the influence of gas flow on which is between the two kinds mentioned above. The actual flue gas contained both fine particles and coarse particles, and the fine particles had very small inertia, which was similar to the zero-inertia particles, and showed good following performance with the gas flow. Therefore, no matter how large the vortex scale was, the fine particles could be affected by turbulence and entered the vortex area, where collision and agglomeration occurred. However, due to larger inertia, the motion of coarse particles was quite different from that of fine particles. Compared with the fine particles, the coarse particles were less affected by turbulence, so they tended to maintain their original motion and had difficulty entering the vortex area. Therefore, we believed that there were two kinds of agglomeration modes in the process of turbulent agglomeration, one being the agglomeration between fine particles because of their tendency to gather in the vortex area, and the other the capture of fine particles by coarse particles because of their different motion trajectories, which both led to the growth of particle size. Meanwhile, this can also be proved from the scanning electron microscopy (SEM) images of particle samples collected after turbulent agglomeration (Fig. 6). Two kinds of morphology were observed in the aggregates, one where multiple fine particles gathered together to form large-sized aggregates (Fig. 6a), and the other where some fine particles adhered to a coarse particle to form a larger-sized agglomerate (Fig. 6b). Considering the experimental results, it can be

![Fig. 4 – Particle concentrations after different turbulent agglomerators.](image)

![Fig. 5 – Particle size distributions after different turbulent agglomerators. Inset: local enlargement for particle distributions in the range of 0.5–10 μm. dN/dlog$D_p$: density of particle number concentration; $D_p$: diameter of fine particles.](image)
inferred that turbulent agglomerator #2 with small-scale vortexes in the flow field can more effectively promote the agglomeration between fine particles and the capture of fine particles by coarse particles than #1, so the agglomeration effect in turbulent agglomerator #2 was better than that in #1. Moreover, in addition to the small-scale vortexes in the x-y plane, #3 could further generate turbulence in the z-axis direction, which caused stronger collision and agglomeration of particles in the x-z plane than #2, so the particle agglomeration effect in #3 was the best of the three turbulent agglomerators.

2.2. Particle removal characteristics by ESP after different turbulent agglomerators

2.2.1. Particle concentrations after ESP

To compare the promoting effects on the removal of fine particles, the particle concentrations and removal efficiencies after ESP with different turbulent agglomerators were measured, as seen in Figs. 7 and 8. The particle number concentrations and removal efficiencies are shown in Fig. 7. In the original flue gas, the particle number concentration was $9.03 \times 10^6$ particles/cm$^3$, which was reduced to $1.91 \times 10^6$ particles/cm$^3$ when the ESP was operating and without any turbulent agglomerators, so the number removal efficiency with ESP only was 78.8%. After the turbulent agglomeration systems were added before the ESP, the particle number concentrations decreased to $1.42 \times 10^6$, $1.12 \times 10^6$ and $9.21 \times 10^5$ particles/cm$^3$ with turbulent agglomerator #1, #2 and #3, so the particle number removal efficiency was improved to 84.3%, 87.6% and 89.8%, respectively. In addition, the particle mass concentrations and removal efficiencies were also measured, shown in Fig. 8. It can be seen that the particle mass concentration was 321 mg/m$^3$ in the original flue gas and decreased to 30.6 mg/m$^3$ after the ESP, and the mass removal efficiency was 90.2% with ESP only. After a turbulent agglomeration system was added, fine particles firstly collided and grew in size and then entered the ESP. The mass concentrations of particles decreased to 20.3, 16.2 and 13.7 mg/m$^3$ with turbulent agglomerators #1, #2 and #3, which meant the particle mass removal efficiency increased to 93.5%, 94.8% and 95.6% respectively. The results indicated that all three kinds of turbulent agglomerators can promote the ability of ESP to capture fine particles, but the promoting effects of agglomerators with different flow field properties were different. Among the three kinds of turbulent agglomerators, #3 was better than #2, and #2 better than #1 regardless of the number or mass removal effect of ESP, and the removal efficiency on the number and mass of fine particles was improved by 11.0% and 5.4% maximally with #3, which meant that three-dimensional vortexes were superior to two-dimensional ones, and small-scale vortexes better than large-scale ones.

2.2.2. Particle stage removal efficiencies

To further research the promoting effect on the removal of fine particles in the different turbulent agglomerators, the particle stage removal efficiencies were determined as illustrated in Fig. 9. In this study, the particle stage removal efficiency was defined as the ratio of particle number concentrations and removal efficiencies.
The efficiency was generally low at each channel less than 0.1, respectively. The removal efficiency was improved in all channels, especially in the range less than 1 μm. The average removal efficiency of channels 1–8 below 1 μm was increased from 79.8% to 83.8%, 86.3% and 89.1% respectively by turbulent agglomerators #1, #2 and #3. The results showed that turbulent agglomeration mainly improved the removal efficiency of particles with size less than 1 μm, thus improving the overall removal efficiency of ESP. The effect of #3 was also better than #2, and #2 better than #1, which meant three-dimensional and small-scale vortexes were more conducive to the removal of fine particles.

2.3. Interaction mechanism of particle agglomeration and turbulent flow field

2.3.1. Motion of particles in different turbulent agglomerators

As described in Section 2.1.2, there were two modes for the agglomeration of fine particles in the turbulent agglomerators: one was the agglomeration between fine particles and the other was the capture of fine particles by coarse ones. Therefore, in order to analyze the effect of different flow field properties on the growth of fine particles, the motion trajectories of particles with different sizes in turbulent agglomerators were simulated. A particle with diameter of 1 μm was selected as a fine particle, and a 10 μm particle as a coarse particle, as shown in Fig. 10, which includes the motion trajectories of particles in the turbulent agglomerators. The motion trajectories of particle groups containing multiple particles and that of a typical single particle. In turbulent agglomerator #1, the particles of 1 μm were widely distributed in the flow field, and it can be seen from the motion trajectory of a typical 1 μm particle that the fine particles were affected by vortexes after entering the agglomerator, and continuously flowed from one vortex to another, where collision and agglomeration occurred. However, most of the coarse particles with 10 μm diameter only moved in the main flow area and did not enter the reflux area behind the vortex sheets. The capture of fine particles only occurred when the fine particles entered the main flow area when flowing from one vortex to another. Therefore, it can be speculated that the main agglomeration mode of fine particles in turbulent agglomerator #1 was agglomeration between fine particles, while the agglomeration effect due to coarse particles capturing fine particles was weak. In turbulent agglomerator #2, fine particles with particle size of 1 μm were also widely distributed in the flow field, and continuously flowed from one vortex to another. However, when the 10 μm particles moved with the flue gas in the main flow area, some of them entered the reflux area behind the pin fins, thus colliding with and capturing the fine particles, and eventually forming large aggregates. Therefore, compared with that in #1, the capture effect of coarse particles toward fine particles in turbulent agglomerator #2 was enhanced. In turbulent agglomerator #3, more coarse particles entered the reflux areas than in #2, and their motion was also affected by

\[
\eta_m = \frac{N_0 - N_t}{N_0} \times 100\% \tag{1}
\]

where \( \eta_m \) is the stage removal efficiency, \( N_0 \) and \( N_t \) are the particle number concentrations at the ith channel of the ELPI+ in the original flue gas and the outlet of the ESP, respectively.

Without any turbulent agglomerator, the particle removal efficiency was generally low at each channel less than 0.1 μm, being lower than 85%, and improved with the increase of particle size. In the range of 0.1–1 μm, the removal efficiency first decreased and then increased with the growth of fine particles, and the minimum removal efficiency was only 72.1% at the 8th channel. When the particle size was larger than 1 μm, the removal efficiency improved with the increase of particle size, and was generally higher than 90%. The explanation for this phenomenon is that the number of particles below 0.1 μm was large (94.1%, seen in Fig. 5) in flue gas and the size was too small, and the capture effect of ESP on fine particles became weaker with the decrease of particle size, so the removal efficiency was low in the particle size range less than 0.1 μm. Besides, the two kinds of charging mechanisms for particles in the ESP were both weak between 0.1 and 1 μm (Ylătal et al., 1992), so the removal efficiencies were lower in this range. After the turbulent agglomerators were added before the ESP, the removal efficiency was improved in all channels, especially in the range less than 1 μm. The average removal efficiency of channels 1–8 below 1 μm was increased from 79.8% to 83.8%, 86.3% and 89.1% respectively for 1 μm.

![Fig. 8](image_url) Particle mass concentration and removal efficiency after ESP with different turbulent agglomerators.

![Fig. 9](image_url) Particle stage removal efficiencies with different turbulent agglomerators.
the vortexes, thus further enhancing the capture effect of fine particles by coarse ones. At the same time, there were more fine particles with particle size of 1 \( \mu \text{m} \) gathered behind the pin fins than in #2, indicating that their motion was more affected by turbulence, so that the collision and agglomeration between fine particles was also more intense.

The motion of a particle in turbulent flow is determined by its St\( \text{K} \) (Alipchenkov and Zaichik, 2001). St\( \text{K} \) can be defined as the ratio of the particle relaxation time scale to the characteristic time scale of the turbulent flow, which is expressed by Eq. (2)

\[
\text{St}_K = \frac{\tau_p}{\tau_K}
\]  

where \( \tau_p \) is the relaxation time scale of a particle, and \( \tau_K \) is the Kolmogorov time scale of turbulence, which can be expressed in the following equations:

\[
\tau_p = \frac{1}{18} \frac{\rho_p D_p^2}{\rho_f \mu} \tag{3}
\]

\[
\tau_K = \left( \frac{\nu^3}{\varepsilon} \right)^{\frac{1}{4}} \tag{4}
\]

where \( D_p \) and \( \rho_p \) are the diameter and density of a particle, \( \rho_f \) is the density of the fluid, \( \mu \) is the dynamic viscosity of the fluid, \( \nu \) is the kinematic viscosity of the fluid, and \( \varepsilon \) is the turbulence dissipation rate.

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**Fig. 10** – Motion of particles in different turbulent agglomerators #1, #2 and #3.
StK represents the ratio of particle inertia and diffusion. The smaller it is, the more easily the particle will follow the fluid motion, and its behavior is closer to that of zero-inertia particles. On the contrary, the larger the particle inertia is, the less obvious the particle following feature is, and the closer the behavior is to that of maximum-inertia particles. In order to explain the differences in the motion of particles in flow fields with different properties, the StK of 1 and 10 μm particles in three kinds of turbulent agglomerators was calculated, as shown in Fig. 11. The density of particles was set as 2100 kg/m³, and the turbulence dissipation rate was the average value of the whole flow field, which was 29,777.49, 17,767.93 and 11,053.81 m³/sec³ in the three turbulent agglomerators, respectively. In general, the movement of particles is mainly manifested as a local aggregation effect when StK is between 0 and 1.0, while as the particle size increases, the movement is gradually affected by the turbulent transport effect, especially above 3.0 (Wang and Maxey, 1993; Squires and Eaton, 1991; Maxey, 1987). Therefore, the motion forms of particles with particle sizes of 1 and 10 μm were completely different. In turbulent agglomerator #1, the StK of particles with diameter of 1 μm was 0.19, which was much less than 1.0, while it was 19.13 when the particle size increased to 10 μm. As a result, the fine particles of 1 μm mainly underwent local aggregation in the reflux area and the coarse particles of 10 μm were mainly affected by the turbulent transport effect in the main flow area. In turbulent agglomerator #2, the StK of particles declined to 0.15 and 14.77 with diameter of 1 and 10 μm respectively due to the reduction of the turbulence dissipation rate in the flow field. The StK of particles with diameter of 1 μm was still well below 1.0, so their motion was still similar to that of zero-inertia particles. However, as the StK of 10 μm particles decreased, the effect of turbulent transport on their motion was weakened. Therefore, some coarse particles were affected by turbulence in the flow field and entered the vortex area behind the pin fins, enhancing the capture effect of fine particles. In turbulent agglomerator #3, the StK of particles with diameter of 1 and 10 μm dropped further to 0.12 and 11.65, which indicated that more coarse particles were susceptible to the turbulence in the flow field, and the agglomeration between fine and coarse particles was stronger than that in #2. Therefore, small-scale and three-dimensional vortexes enhanced the capture effect of coarse particles toward fine particles, thus enhancing the agglomeration and removal of fine particles.

2.3.2. Relative velocity between particles in different turbulent agglomerators

Particles that collide do not always agglomerate together, and whether the particles can form large-sized aggregates after collision is also affected by the surface properties of particles, such as van der Waals force, humidity and electrostatic force (Marshall and Li, 2014; Hinds, 2012). Therefore, the collision efficiency and agglomeration efficiency are proposed as indicators to evaluate the agglomeration effect of particles. The collision efficiency (ηc) refers to the ratio between the number of actual collisions and theoretical collisions. The larger the value is, the greater the number of collisions will be under same condition, which is given by (Chi and Martin, 2002):

$$\eta_c = \left( \frac{\psi_i}{\psi_i + a} \right)^b$$

(5)

where a and b are parameters related to the Reynolds number, and ψi is the Stokes number of particles, which is used to describe the interaction between small particles and large particles, given by:

$$\psi_i = \frac{\rho_p |u_{p1} - u_{p2}| D_p^2}{18 \mu D_k}$$

(6)

where Dp is the diameter of the large particle, and |u_{p1} - u_{p2}| is the relative velocity of the small and large particles.

In addition, the agglomeration efficiency is not expressed by an exact mathematical equation, but by a judgment expression. The criterion that determines whether two particles can agglomerate together is the critical velocity, which can be obtained from the energy balance equation between particles. In turbulent agglomeration, the adhesion force between fine particles is mainly the van der Waals force, so when only van der Waals force is considered, the critical relative velocity (v_cr) can be expressed as (Chi and Martin, 2002):

$$v_{cr} = \frac{1}{D_p} \left( 1 - e^2 \right)^2 \frac{A}{\pi z_0 \sqrt{6 \rho_p \mu}}$$

(7)

where e is the energetic restitution coefficient, A is the Hamaker constant, z₀ is the contact length, and p is the material limiting contact pressure. When the relative velocity between particles is less than the critical relative velocity, it is believed that agglomeration between the two colliding particles occurs, given by

$$|\vec{u}_{p1} - \vec{u}_{p2}| \cos \theta \leq v_{cr}$$

(8)

where |\vec{u}_{p1} - \vec{u}_{p2}| is the relative velocity of the two colliding particles, and θ is the collision angle, which refers to the angle between the center line of two particles and the direction of particle movement. Therefore, the relative velocity between particles has a great influence on both the collision and agglomeration efficiency.
In order to investigate the effects of flow field properties on the collision and agglomeration of fine particles, the relative velocity between particles with diameter of 1 and 10 μm was calculated in different turbulent agglomerators, expressed by:

\[ v_r = \sqrt{(v_{x1} - v_{x2})^2 + (v_{y1} - v_{y2})^2 + (v_{z1} - v_{z2})^2} \]  

where \( v_{x1}, v_{y1}, \) and \( v_{z1} \) are the velocity components on the \( x, y \) and \( z \) axis of 1 μm particles respectively, and \( v_{x2}, v_{y2}, \) and \( v_{z2} \) are the velocity components on the \( x, y \) and \( z \) axis of 10 μm particles, which are illustrated in Fig. 12. For the particles of 1 μm diameter, the velocity components on the \( x, y \) and \( z \) axes all decreased gradually from turbulent agglomerator #1 to #3 (Fig. 12a). For the particles of 10 μm diameter, the velocity components on the \( x, y \) and \( z \) axis in turbulent agglomerator #2 were still lower than those in #1, but the velocity components on the \( y \) and \( z \) axis in turbulent agglomerator #3 were higher than in #2, and lower than in #1 (Fig. 12b). Correspondingly, the relative particle velocities of 1 and 10 μm particles gradually decreased too, from 10.12 to 7.38 m/sec (Fig. 12c). According to the above theory of collision and agglomeration efficiency, the increase of relative velocity is beneficial to improve the particle collision efficiency, but excessive relative velocity which is higher than the critical relative velocity will lead to a decrease in particle agglomeration efficiency. Combining the experimental and computational results, the lower the relative velocity between particles with diameter of 1 and 10 μm, the stronger the coarse particles’ capture effect on fine particles, and the better the agglomeration effect of fine particles. So it can be inferred that under the experimental conditions in this work, the collision efficiency between particles was high enough, and too much increase in the relative velocity between particles caused small particles to bounce off large particles due to excessive residual velocity after collision and weak van der Waals forces (Chi and Martin, 2002). As a result, in this experiment, small-scale and three-dimensional vortexes reduced the relative velocity of particles with different sizes, thus improving the agglomeration efficiency of particles, so that the agglomeration and removal effect of fine particles were improved.

2.3.3. Residence time of particles in different turbulent agglomerators

The residence time of particles in the turbulent flow field is another important factor affecting the agglomeration of fine particles. The longer the residence time, the greater likelihood of repeated collisions between particles, so as to form aggregates with larger particle size that are more easily removed by ESP. The average residence time of multiple particles with 1 and 10 μm diameters in the flow field was calculated, as seen in Fig. 13. From turbulent agglomerators #1 to #3, the residence time of particles with diameter of 1 and 10 μm both gradually became longer. The residence times of particles with diameter of 10 μm were all shorter than those of 1 μm particles in the three kinds of turbulent agglomerators, which was due to the 10 μm particles having higher \( x \)-axis velocity in the main flow area. The results showed that small-scale and three-dimensional vortexes can extend the residence time of particles, thus promoting the interaction between fine particles and improving the effect of turbulent agglomeration.

From the above discussion, it can be seen that turbulent agglomerators with small-scale and three-dimensional vortexes enhance the capture effect of coarse particles toward fine particles by reducing the StK of the coarse particles,
improving the agglomeration efficiency of particles by reducing the relative velocity between them, and promote the interaction between fine particles by extending their residence time in the flow field, so as to obtain better turbulent agglomeration effects.

3. Conclusions

In this study, in order to explore the influence of flow field properties on fine particle agglomeration and removal characteristics under turbulent agglomeration, three kinds of turbulent agglomerators with different structures were constructed, and the particle concentration and size distribution after the turbulent agglomeration system and particle concentration and stage removal efficiency after ESP were investigated respectively through experiments. The results demonstrated that the turbulent agglomerator with small-scale and three-dimensional vortexes had the best effect on improving the agglomeration and removal of fine particles, by which the agglomeration efficiency was improved to 26.3%, and the number concentration of particles below 0.1 μm was reduced by 30.4%. Besides, the number and mass removal efficiency were increased to 89.8% and 55.6% respectively, and the particle stage removal efficiency below 1 μm was significantly improved from 79.8% to 89.1%.

Moreover, the interaction mechanism for particle agglomeration and turbulent flow fields was studied by calculating the motion trajectory, relative velocity and residence time of fine particles in different flow fields. The results proved that a turbulent flow field with small-scale and three-dimensional vortexes can reduce the Stc and relative velocity of particles with different sizes, which is beneficial for enhancing the capture effect of coarse particles toward fine particles and improving their agglomeration efficiency. In addition, it extended the residence time of fine particles in the turbulent flow field, thus promoting interactions between them and improving the effect of turbulent agglomeration. This work can provide references for improving the agglomeration and removal of fine particles in various industrial processes.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (No. 2016YFB0600602), the National Natural Science Foundation of China (No. 51806107) and the Scientific Research Foundation of Graduate School of Southeast University (No. 3203009749).

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