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Calculation and Analysis of Dust Removal Efficiency of Waste Heat Boiler of Cement Kiln based on EDEM-FLUENT Coupling

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Abstract

Based on Euler Lagrange theory and edem-fluent coupling method, the flue gas in the waste heat boiler of cement kiln head is regarded as the ideal gas of continuous phase, and the flue gas dust is regarded as the discrete solid phase. The influence of particle concentration and particle velocity on the dust removal efficiency of the separation baffle of the boiler is analyzed. The results show that: (1) when the concentration is C= 2g·m^{-3}-4g·m^{-3}, the dust removal efficiency decreases with the increase of concentration; when the concentration is C= 4g·m^{-3}-6g·m^{-3}, the dust removal efficiency increases with the increase of concentration; when the concentration is greater than C= 6g·m^{-3}, the dust removal efficiency decreases linearly, and the dust removal efficiency of C= 10g·m^{-3} is 2% lower than that of C= 6g·m^{-3}. (2) At the same speed, the increase of accumulation time will reduce the dust removal efficiency; When the accumulation time is the same, the dust removal efficiency decreases with the increase of flue gas inlet velocity, because the increase of particle velocity will enhance the interaction with the air phase, increase the lift of air relative to particles, and make more particles flow out from the flue gas outlet but not into the dust collection outlet. The dust removal efficiency of V= 8m·s^{-1} is 6% lower than that of V= 4m·s^{-1}.

Keywords

Cement Kiln; Waste Heat Boiler; Coupling of EDEM-FLUENT; Dust Removal Efficiency; Gas Solid Two Phase Flow.

1. Introduction

China is rich in waste heat resources, which has become the fifth largest available resource in China. With the promotion of national energy saving and emission reduction, the energy saving technology of cement kiln waste heat boiler has been paid more and more attention, and has been widely used in industrial production. However, as the heat source of cement kiln waste heat boiler is the waste gas of cement kiln with high dust concentration, compared with other types of boilers, it is easier to produce ash deposition on the heating surface, and the serious ash deposition will greatly deteriorate the heat transfer effect and significantly reduce the heat transfer performance of the heating surface [1]. Therefore, reducing the smoke and dust is of great significance to improve the thermal efficiency of the boiler, reduce the wear of the heating surface, prolong the service life of the boiler and ensure the safe and stable operation of the boiler.

At present, domestic and foreign scholars have done some research on the improvement of the structure of cement kiln boiler, the utilization of waste heat, the corrosion of internal pipes, and the denitrification of flue gas. Maozhengdong [2] and others have made structural improvement on the

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waste heat boiler at kiln head, and changed the flue gas intake mode from "up in and down" to "up and out". The results show that this can reduce the system loss and increase the heat exchange efficiency; Duwenjing [3] and others proposed a new method for full-scale numerical simulation of boiler 3D model to two-dimensional model. Caoji [4] and others studied the mechanism of ash deposition on the heating surface, and concluded that the stronger the bond of ash deposition with the increase of temperature. Chenjianglong [5] analyzed the vibration of boiler water heater, found that the vibration was caused by pulsation in the tube screen, and put forward the corresponding suggestions and improvement measures according to the working conditions. According to the actual working condition of HRSG, Dong Chen [6] and others analyzed the flue gas flow field of denitrification system by numerical simulation of porous medium model. Ehsan Amiri rad[7] and others analyzed the waste heat of boiler by using Rankine cycle, and obtained the best pressure of boiler waste heat utilization, and the best pressure was independent of the maximum circulating temperature, ambient temperature and condenser pressure. Yong yin[8] et al. Measured and analyzed the flue gas at the kiln end. The results show that the reduction of kiln tail temperature has no effect on the removal and transformation of carbonyl compounds. Rong Jin [9] et al. Analyzed the PCN in flue gas samples and solid samples in different stages of three cement production processes, which indicated that the discharge of PCN should be controlled in the preheater and kiln tail of hydrocyclone, and the main factors affecting the formation of PCN were temperature, feed and chlorine content.

To sum up, scholars at home and abroad rarely talk about the analysis of the dust removal efficiency of waste heat boiler. Based on the actual operation and structural characteristics of the boiler, this research group uses the edem-fluent coupled numerical calculation model to analyze the dust removal efficiency of a 5000 t/d cement kiln head waste heat boiler designed by a manufacturer based on the discrete element theory.

2. Research objects

2.1 Physical model

A 5000 t/d waste heat boiler at the kiln head of cement kiln developed and designed by a boiler factory adopts the flue gas inlet mode of "lower inlet and upper outlet". The flue gas first passes through the free external dust collector, and then enters the waste heat boiler horizontally after the first dust removal. The inlet flue of the boiler is equipped with a separation baffle with a stepped structure for primary dust removal and optimization of the flue gas flow path. After the separation of the separation baffle, the flue gas is separated for 90 ° Turn, vertically upward into the V-shaped steel, and filter the dust again. The boiler is used to recover the waste heat of grate cooler and generate superheated steam for power generation. As the dust removal structure of the boiler is mainly concentrated in the lower end of the boiler, in order to reduce the amount of calculation, the lower end of the boiler is taken as the research object, as shown in Fig.1.

Fig. 2 is the grid model diagram of fluid region calculation division, which is composed of flue gas inlet, flue gas outlet, three dust collection outlets, separation baffle, V-shaped steel baffle and wall.

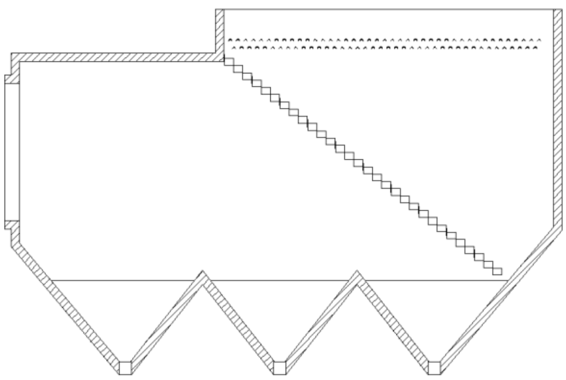

Fig. 1 Schematic diagram of cement kiln waste heat boiler structure

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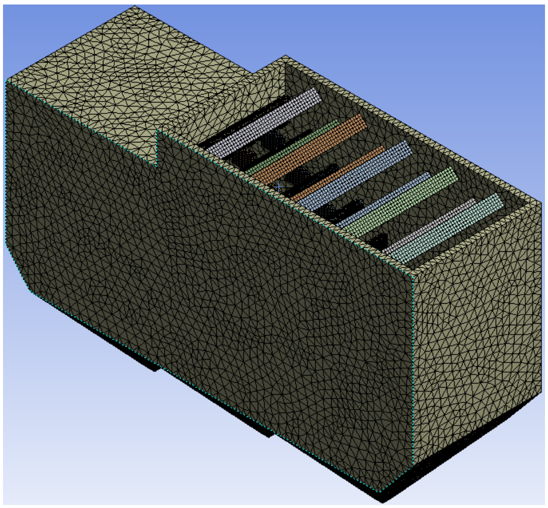

Fig. 2 Meshing

2.2 Calculation parameter setting

According to the actual working conditions of the boiler, the cement clinker medium and relevant parameters used in the calculation are shown in Table 1. Because of the separation baffle and V-shaped steel dust removal structure inside the boiler, there are a lot of collisions of cement clinker particles in the process of internal movement. The collision movement between particles and particles, between particles and baffle is one of the important factors affecting the dust removal efficiency. Referring to relevant data, the particle model of cement clinker is spherical. In the calculation of dust removal efficiency, the standard Hertz Mindlin non slip contact model is used for the contact between particles and the inner wall of boiler.

Table 1. Particle calculation related parameters

Material	Waste heat boiler	Cement clinker particles
Poisson's ratio	0.3	0.15
Shear modulus G/Mpa	35	18.91
Density /(kg·m^{-3})	7800	3200
Coefficient of restitution	0.5	0.5
Static friction coefficient k_s	0.15	0.27
Rolling friction coefficient k_r	0.01	0.01

3. Equations of motion and methods

3.1 Model governing equations

According to the data and related literature [10-13]. In the simulation calculation of boiler dust removal efficiency, the fluid control equation is:

$$\frac{\partial}{\partial t}(\alpha\rho_f)+\nabla(\alpha\rho_f u)=0 \tag{1}$$

$$\rho_f\frac{\partial}{\partial t}(\alpha u)+\nabla(\alpha\rho_f uu)=-\nabla(\alpha P)+(\nabla\alpha u[(\nabla u+(\nabla u)^T-\frac{2}{3}\nabla uI)])+\rho_f g+F \tag{2}$$

In the above formula, ρ_f, u, T, P, g, F, are the density, velocity, time, pressure, acceleration of gravity of fluid and the reaction force of particles on fluid respectively. In addition, α is the fluid volume fraction. In the calculation of boiler dust removal efficiency, Euler Lagrange method is used in the coupling simulation, which ignores the influence of cement clinker particle volume fraction. Therefore, α is equal to 1.

The motion of particle phase is solved by Newton's second law:

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$$m_p \frac{du_p}{dt} = F_{drag} + F_g + F_{VM} + F_p + F_{snff} + F_{Magn} + F_C \tag{3}$$

$$I_P \frac{d\omega_p}{dt} = \frac{\rho_f}{2}(\frac{d_p}{2})^5 C_W \Omega \tag{4}$$

$$F_{drag} = \frac{3\rho m_p C_D}{4\rho_D D_P}|u - u_p|(u - u_p) \tag{5}$$

F_{drag} is the drag force of the particle by the fluid, which can be obtained by formula (5) [13].

$$C_D = \begin{cases} 24(1 + 0.15{R_{ep}}^{0.687})({R_{ep}}^{-1}), & R_{ep} \le 1000 \\ 0.44. & R_{ep} > 1000 \end{cases} \tag{6}$$

$$R_{ep} = \rho_f |u - u_\rho| D_p / u \tag{7}$$

$$F_g = m_p g(\frac{\rho_P - \rho}{\rho_P}) \tag{8}$$

$$F_{VM} = C_{VM}\frac{\rho}{\rho_P}(u_p \nabla u - \frac{du_p}{dt}) \tag{9}$$

$$F_P = -V_p \frac{\partial p}{\partial x} \tag{10}$$

$$F_{saff} = 1.615 d_p^2 (u_f \rho_f)^{1/2} C_{saff} |\omega_c|^{-1/2} (u - u_p)\omega_c \tag{11}$$

$$C_{saff} = \begin{cases} (1 - 0.3314)\sqrt{\beta}\, exp[-\frac{R_{es}}{10}] + 0.3314\sqrt{\beta} & R_{es} \le 40 \\ 0.0524\sqrt{\beta R_{es}}, & R_{es} > 40 \end{cases} \tag{12}$$

In the above formulas, C_D, R_{ep}, F_g, F_{VM}, C_{VM}, F_P, F_{snaff}, ω, C_{snaff}, R_{es}, respectively represent drag coefficient, Reynolds number of particles, sum of buoyancy and gravity of particles, virtual mass force that cannot be ignored in gas-solid two-phase flow, virtual mass factor (default 0.5), pressure gradient force, lift generated by fluid shear force, vorticity of fluid, shear lift coefficient and Reynolds coefficient of shear flow.

$$F_{Magn} = \frac{1}{2} A_P C_{Magn} \rho_f \frac{|V|}{|\Omega|}(V \times \Omega) \tag{13}$$

$$C_{Magn} = 0.45 + (\frac{R_{e\omega}}{R_{ep}} - 0.45)\, exp^{(-0.057 R_{e\omega}^{0.4} R_{ep}^{0.3})} \tag{14}$$

$$F_C = F_{c,n} + F_{c,t} \tag{15}$$

Among them, F_{Magn}, C_{Magn}, A_P, V, Ω, $R_{e\omega}$, F_C, $F_{c,n}$, $F_{c,t}$, are the lifting force produced by particle rotation, the rotating lifting coefficient, the particle projected area, the particle linear velocity, the particle angular velocity, the rotating Reynolds coefficient, the particle impact contact force, the particle contact normal impact force, and the particle contact tangential impact force.

3.2 Calculation formula of dust removal efficiency

According to the technical specification for manual monitoring method (gravimetric method) of ambient air particulate matter (PM2.5) (HJ656-2013) and related literature [14-16], the calculation formula of dust concentration in flue gas is as follows:

$$\eta = \frac{C_1 - C_0(1 + \Delta\alpha)}{C_1} 100\% \tag{16}$$

η - dust removal efficiency; C_1 - dust concentration of inlet flue gas; C_0 - dust concentration of flue gas at outlet; $\Delta\alpha$ - air leakage rate, in the coupled simulation analysis, the simulation condition is no air leakage, so $\Delta\alpha$ = 0.

4. Calculation results and analysis

4.1 Particle movement

Fig.4 shows the position and velocity distribution of cement clinker particles in boiler at different times, and the depth and light of particle color represent the size of velocity. At 0.1 s, some particles enter the flue gas inlet, which is dispersed due to the motion of air flow and the collision between

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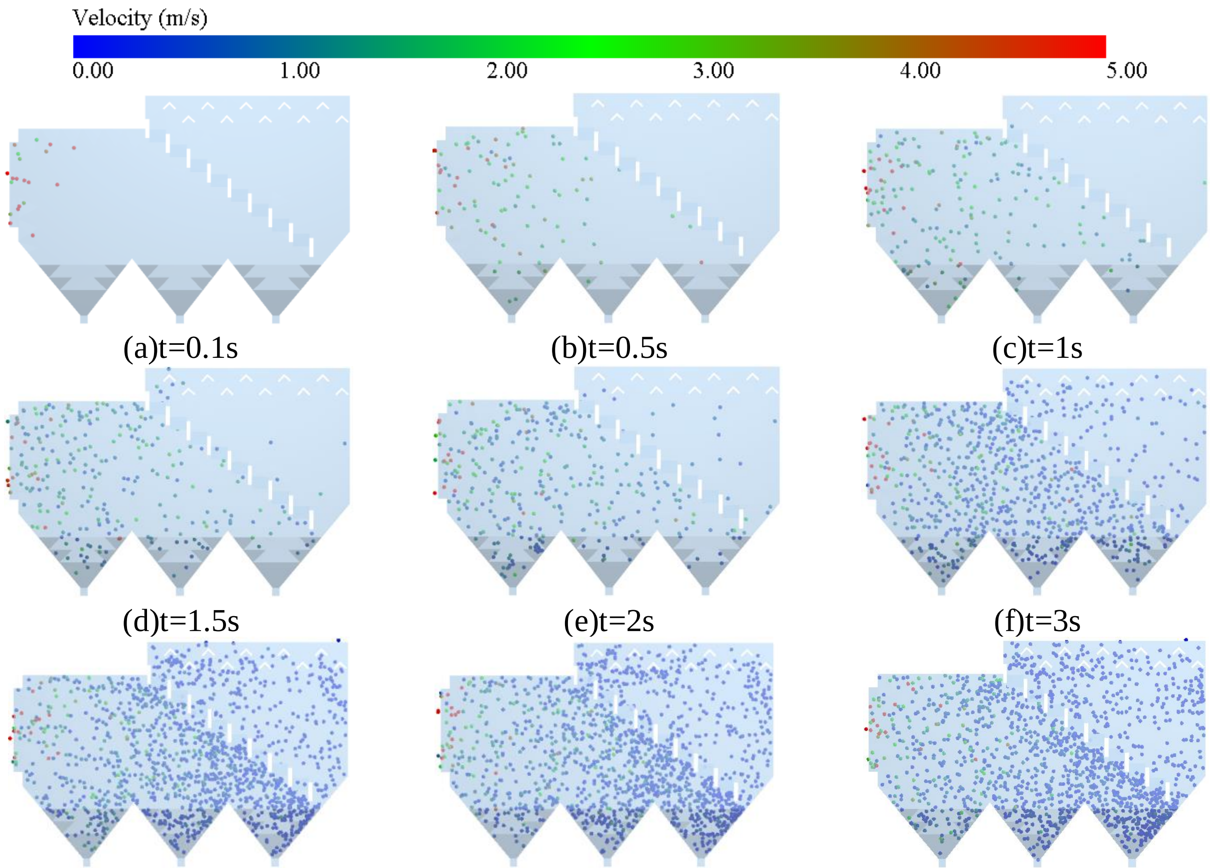
particles. At 0.5 s, the particles have moved to the first dust collecting port. A small part of particles can collide with the particles due to the collision with the upper wall of the boiler, resulting in a decrease of speed, and start to enter the bottom of the dust collection port, and the dust collection begins. At 1 s, the particles move to the separation baffle. Because the separation baffle is arranged in an oblique direction, the particles above collide with the separation baffle earlier, and the energy reduction speed decreases, and the particles fall to the three dust collecting ports below. The particles below collide with the separation baffle later, and mainly fall to the third dust collecting port. When 1.5 s, some particles passed through the separation baffle space and began to flow to the V-shaped steel baffle. At 2 s, some particles enter V-shaped steel baffle and start the second stage dust removal treatment. At 3 s, the particles at the front end of the air flow have been flowing to the outlet, and the coupling field simulation of the whole flue gas particles is completed, and the time is the starting point of the accumulated time. At 6 s, it enters a stable and regular motion state.



(a)t=0.1s (b)t=0.5s (c)t=1s

(d)t=1.5s (e)t=2s (f)t=3s

(g)t=6s (h)t=10s (i)t=20s

Fig. 3 Particle position and velocity distribution

4.2 Flow velocity distribution

Fig.5 shows the trajectory of particle streamline in the center section of boiler calculation domain. It can be seen from the figure that when t = 0.1 s, the flue gas drives the particles into the internal fluid calculation domain from the inlet, and the particles arrive at the first dust collection port. Due to the decrease of the outlet, a velocity vector vortex is formed. When t = 0.2 s, due to the continuous air intake at the inlet, the particles in the fluid domain continue to move forward, which makes the vector vortex of the first dust collection port gradually increase, and the vortex also forms at the second dust collection port. When it reaches a certain time, the third dust collector will also form a velocity vector vortex, and the vector vortices of the first two dust collectors will increase with time, and finally tend to equilibrium.

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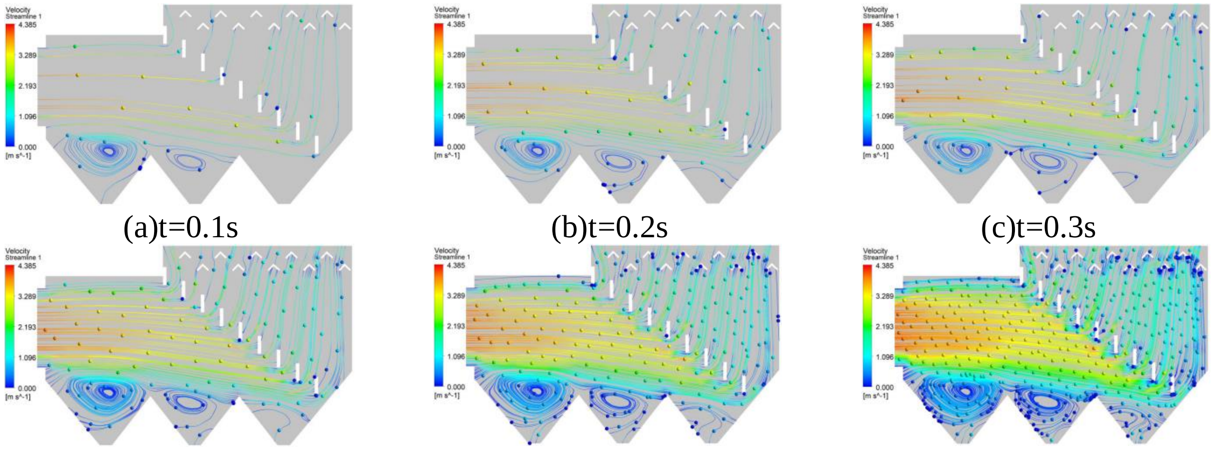

(a)t=0.1s (b)t=0.2s (c)t=0.3s

(d)t=0.5s (e)t=1s (f)t=2s

Fig. 4 Particle streamline trajectory diagram of the central section of the computational domain

4.3 Influence of inlet velocity on dust removal efficiency

Fig. 5 shows the influence of inlet velocity on dust removal efficiency with the accumulation time. The cumulative time is that the particles enter from the flue gas inlet, and the first batch of particles arrive at the flue gas outlet to start the timing. It can be seen from the figure that, with the increase of accumulated time, the dust removal efficiency generally shows a downward trend, and finally tends to be constant. When the velocity is below $v = 6\ m \cdot s^{-1}$, the dust removal efficiency increases briefly in the first 3 seconds of the accumulated time, and then it begins to decline. The reason is that the velocity is too low. When the first batch of particles reach the flue gas outlet, the particle movement has not reached the stability in a short time. When the velocity is above $6\ m \cdot s^{-1}$, the velocity increases, the particle movement will reach a stable state faster, and the dust removal efficiency decreases with the increase of the accumulated time, and finally tends to a fixed value.

Fig. 6 shows the total dust removal efficiency of the speed. It can be seen from the figure that the dust removal efficiency decreases with the increase of flue gas inlet speed, which is consistent with the analysis results in Fig. 5. The dust removal efficiency is the highest when the velocity $v = 4\ m \cdot s^{-1}$ is 93%. When the velocity $v = 4\ m \cdot s^{-1}$-$5\ m \cdot s^{-1}$, the dust removal efficiency decreases linearly, and the reduction rate is 1%; When the velocity $v = 5\ m \cdot s^{-1}$-$8\ m \cdot s^{-1}$, the dust removal efficiency is approximately parabola reduced, and the speed increases, which causes the sudden increase of the rotating lift of particles. More particles pass through the gap of separation baffle, which increases the exit particles and reduces the dust removal efficiency.

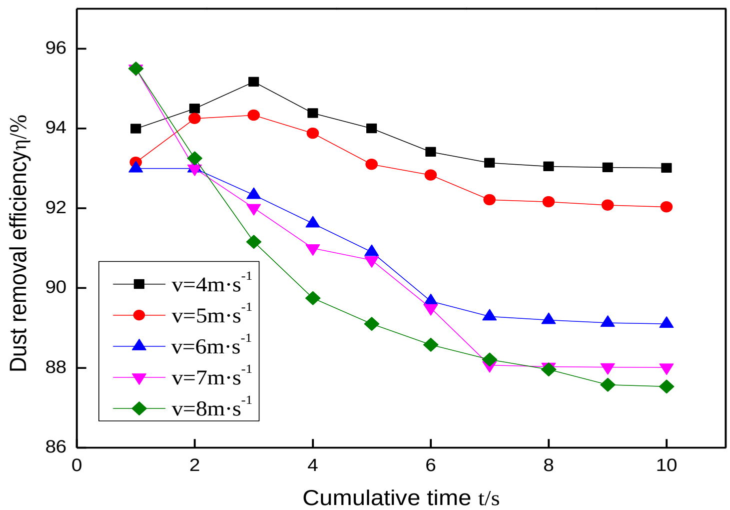

Fig. 5 The influence of different speeds on dust removal efficiency

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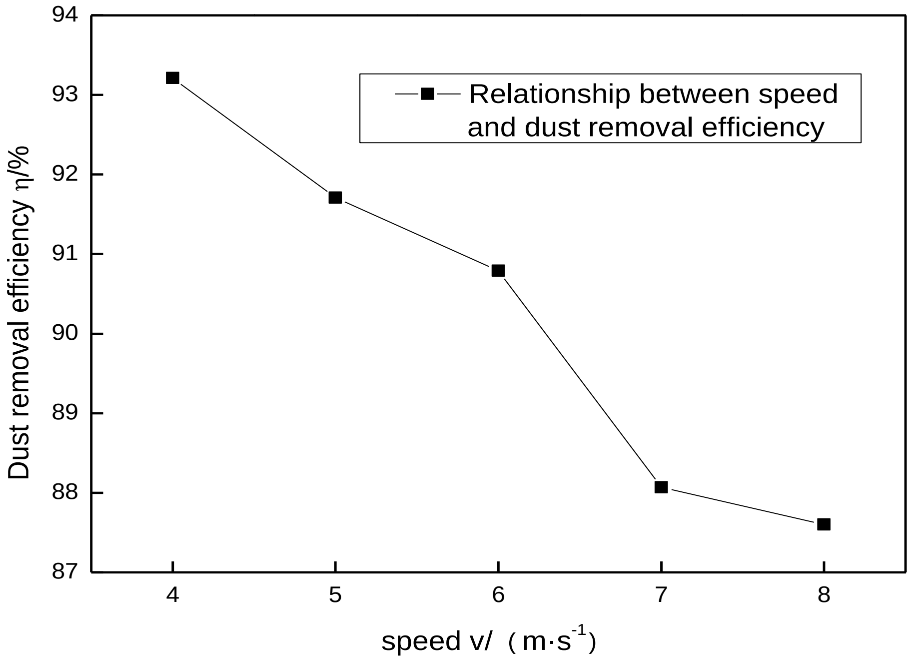

Fig. 6 Speed and total dust removal efficiency

4.4 Influence of flue gas concentration on dust removal efficiency

Fig. 7 shows the effect of inlet concentration on dust removal efficiency with accumulation time under the same other conditions. It can be seen from the figure that at the same concentration, the dust removal efficiency decreases with the increase of accumulation time. When the accumulation time is less than 5 s and the concentration C=2 g·m^{-3}-C = 4 g·m^{-3}, the dust removal efficiency increases with the increase of concentration; When the concentration C =4 g·m^{-3}-C=10 g·m^{-3}, the dust removal efficiency decreases with the increase of concentration. When the accumulation time is more than 5 s and the concentration C=2 g·m^{-3}-C =4 g·m^{-3}, the dust removal efficiency decreases with the increase of concentration; When the concentration C =4 g·m^{-3}-C =6 g·m^{-3}, the dust removal efficiency increases with the increase of concentration; When the concentration C =6 g·m^{-3}-C=10g·m^{-3}, the dust removal efficiency decreases with the increase of concentration.

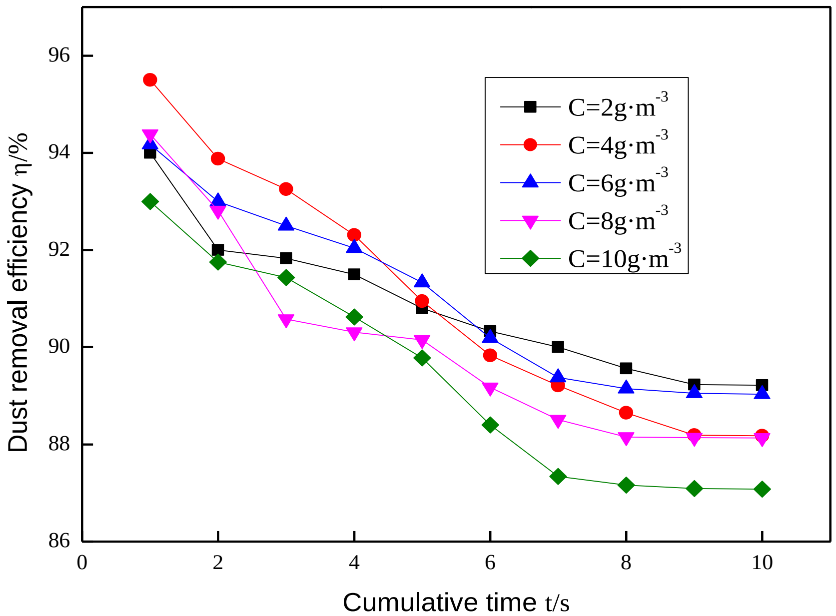

Fig. 7 Influence of different concentrations on dust removal efficiency

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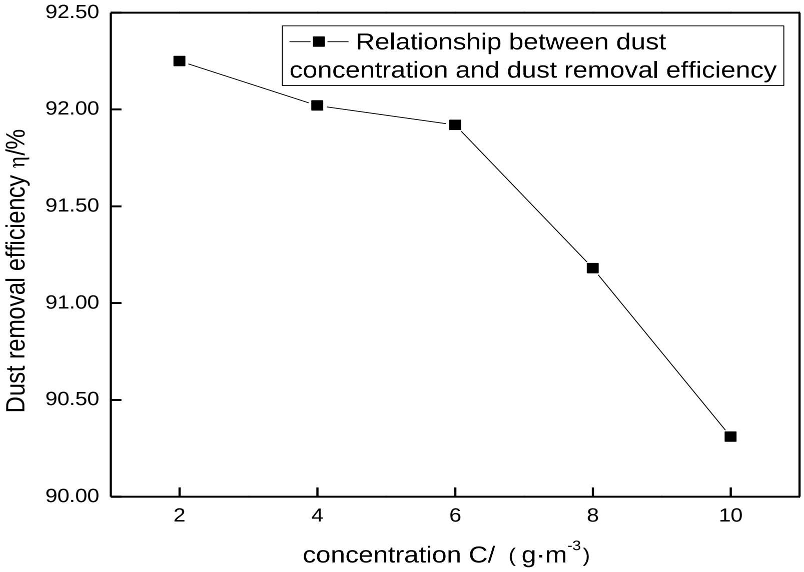

Fig. 8 Concentration and total dust removal efficiency

Fig. 8 shows the relationship between concentration and total dust removal efficiency. It can be seen from the figure that the dust removal efficiency is decreased first, but increased, and finally decreased. It is because at the beginning of C= 2g·m^{-3}, the particles are in low concentration in the calculation domain, and the internal space is relatively large, and the probability of particle collision is small. Increasing the concentration will increase the collision probability of particles, and make more particles fly out of the outlet, which leads to the reduction of dust removal efficiency. Drop the particles to the dust collection port. When C = 4g·m^{-3}, the particles are more dense in the calculation area. The collision and extrusion between particles and the wall reduces the kinetic energy of particles, and causes the particles to fall to the nearest dust collecting port. With the increase of concentration, particle collision becomes more intense when C = 6g·m^{-3}, which disturbs the flow field, which increases the shear lift and the rotating lift of particles, which leads to the increase of particles flowing out of the flue gas outlet.

5. Conclusion

EDEM-FLUENT coupling method and particle collision model are used to analyze the dust removal efficiency of the separation baffle structure of waste heat boiler at the head of cement kiln.

(1) The flow velocity inside the boiler is relatively uniform, and the streamline distribution is obviously dispersed after entering the separation baffle. Because the gas and particles enter from the inlet at the same time, the particles disperse under the influence of the air flow. With the forward flow of the flue gas, when the particles fall to the dust collection outlet, the vortex streamline is formed nearby due to the decrease of the outlet.

(2) The dust removal efficiency is reduced by increasing the flue gas inlet speed. It can be seen that at the same speed, the dust removal efficiency of boiler decreases with the increase of accumulated time, and finally tends to the total dust removal efficiency at the same speed. The longer the time, the more stable the particle movement state is in the whole process.

(3) When the concentration C= 2g·m^{-3}-C=6g·m^{-3}, the dust removal efficiency first decreases and then increases with the increase of concentration. When C= 6g m^{-3}-C= 10g·m^{-3}, the dust removal efficiency decreases linearly with the increase of inlet flue gas concentration.

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